Real-Time Cooperative Behavior for Tactical Mobile Robot Teams

Final Report / A003

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1. TECHNICAL APPROACH SUMMARY

Our technical approach to achieving intelligent tactical behaviors for TMR robots is described in this section. We have specific technical approaches in three research areas:

- Fault-tolerant multi-robot behaviors,
- Mission specification and user interface, and
- Real-time resource management.

(Originally, communication minimization was also a research topic, but was deleted early in the program at government request.)

We envision that the nature of military operations in urban terrain (MOUT) can fundamentally change by empowering the personnel in these units with multiple mobile robot assets that extend their ability to perceive and act within the battlefield without increasing their exposure. It is insufficient merely to deploy these assets; they must be controlled and configured in a meaningful way by average soldiers. This is no mean feat, but if this vision is realized it can provide significant force multiplication capabilities and extended reach within the battlespace (force projection). This must be accompanied by feedback and control methods that do not overload the operator of the system and yet can provide uniform control of multiple advanced robotic systems while simultaneously increasing the unit's overall situational awareness. The impact of this system will be manifested in several ways:

- Reactive behavioral configurations for robot teams that support fault-tolerant operations typically found in the battlefield, to increase immunity against electronic countermeasures and individual agent failure.
- Team teleautonomy providing command and control capabilities for entire groups or subgroups of battlefield robots without producing cognitive overload on the operator.
- The ability of a military operator to expand his influence in the battlespace, dynamically controlling in real-time his deployed robotic team assets in a context-sensitive manner.

Throughout the program, our research focused on the generation of mission-specific designs created specifically for TMR operations that can be readily tailored by an easily trained operator for the situation at hand. These tools have been shown to be effective in the hands of students and military personnel, through the use of visual programming, information hiding, and reusable software components.

We have applied our expertise to develop the following innovative research results for tactical mobile robot teams:

1. A suite of new fault-tolerant reactive behaviors,
2. A reusable mission specification system including team communication protocols,
3. Sound and predictable real-time processing and communication,
4. Major demonstrations of usability and tactical effectiveness,

5. A skills assessment study for human-robot operator interfaces, and
6. A usability study based on experiments with human subjects.

2. SYSTEM AND SOFTWARE DESCRIPTION

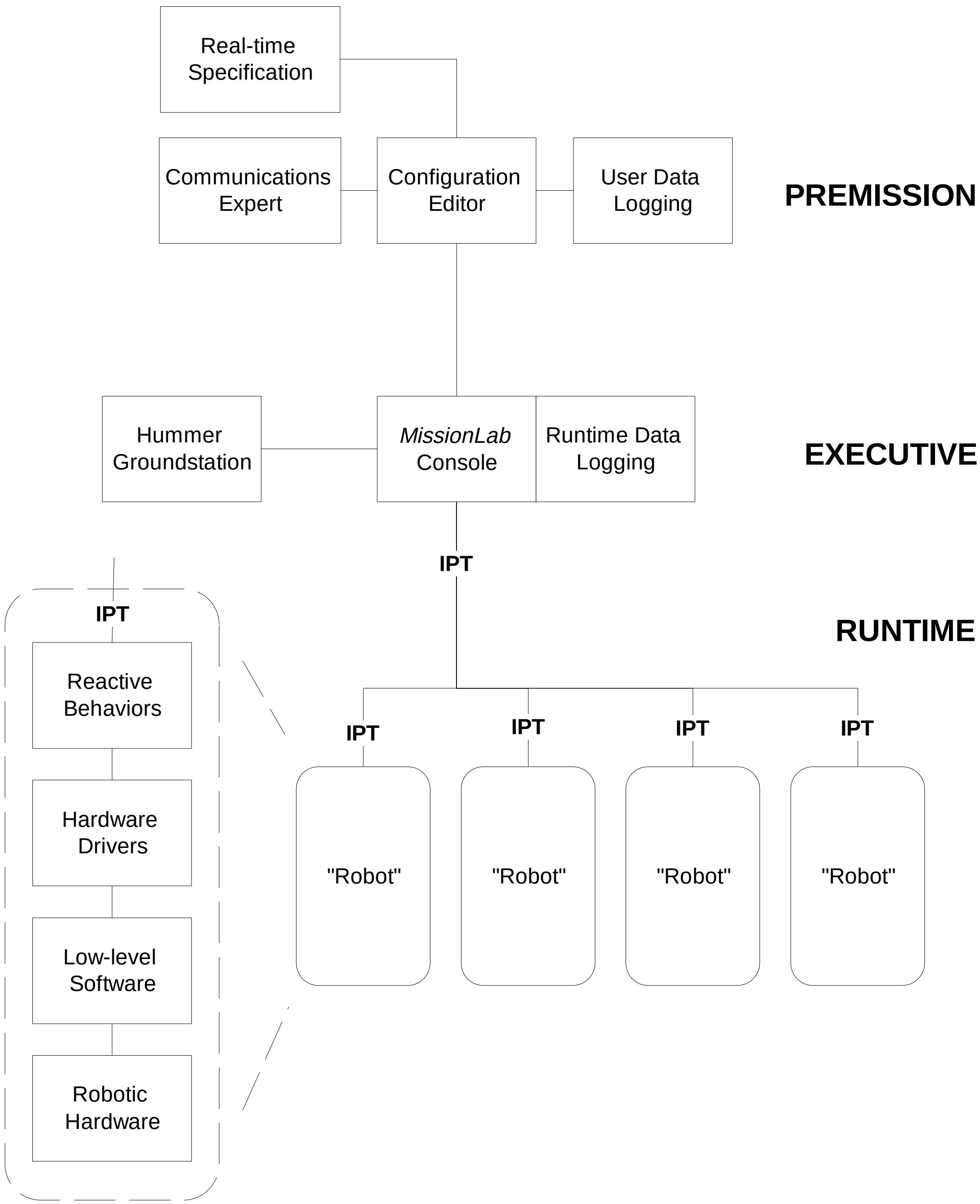

Figure 1: System Architecture

Figure 1 depicts the overall system architecture developed for this effort. It contains 3 major subsystems: Executive, Premission, and Runtime. The executive subsystem is the major focus for operator interaction. It provides an interface to both the runtime simulators and actual robot controllers, as well as the premission specification facilities and the physical operator groundstation itself. The premission subsystem's role is to provide an easy-to-use interface for designing robot missions and a means for evaluating overall usability. The runtime control system, which is located on each active robot, provides the execution framework for enacting reactive behaviors, acquiring sensor data and reporting back to the executive subsystem to provide situational awareness to the team commander. Additionally, a separate support system is provided for inter-process communications.

In Figure 1, typical communication paths between components are shown. Wherever separate threads of execution exist, this communication is implemented with IPT, to be described later. In other cases, communication may take the form of dedicated point-to-point links or conventional parameter-passing during the invocation of processes.

The figure shows a "robot" as the combination of reactive behaviors, appropriate hardware drivers, both actuator-specific and sensor-specific low-level software, and the robot hardware itself. This assemblage of components provides a uniform, hardware-independent interface to the executive subsystem which is equally suitable for simulated robots. The runtime system consists of one or more instances of these assemblages, with four shown in this particular case.

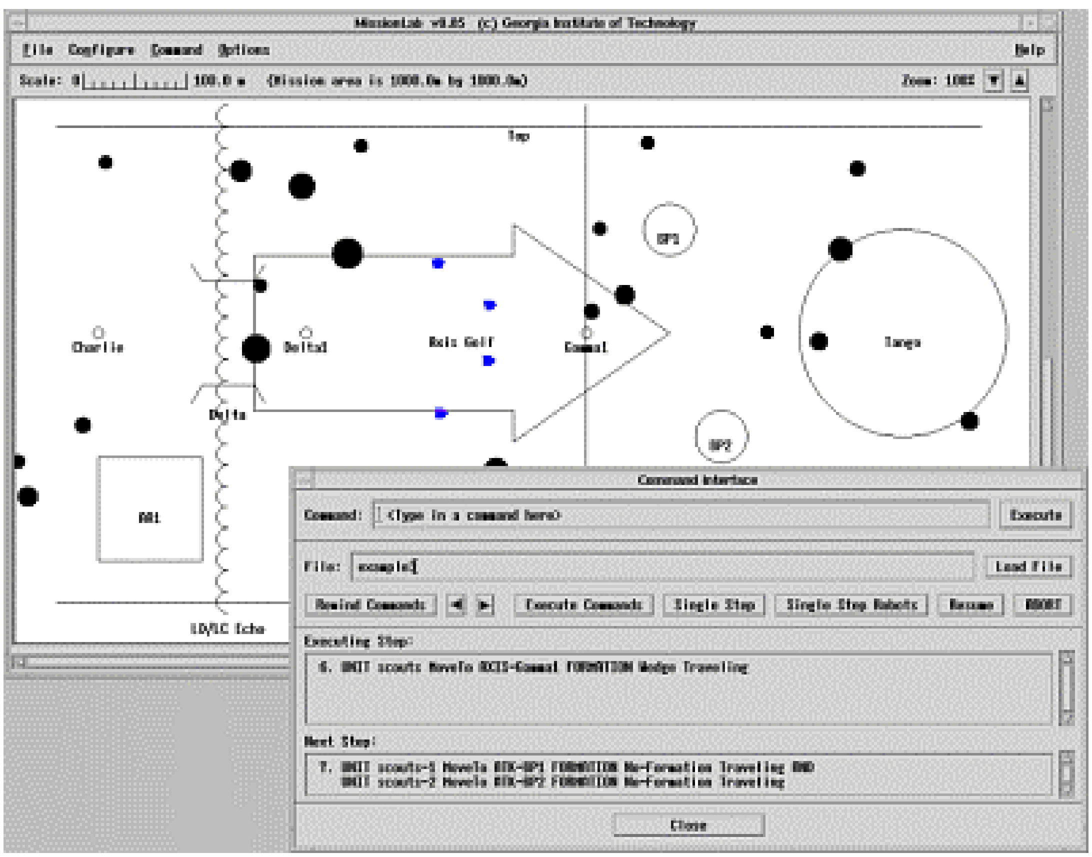

Figure 2: *MissionLab* Console (mlab).

2.1 Executive Subsystem

The executive subsystem consists of the *MissionLab* console, faster-than-real-time simulator, and runtime data logging components.

2.1.1 MissionLab Console

The *MissionLab* console (mlab) (Figure 2) serves as the central interface for the execution of a mission. The mlab program presents results of either simulations or actual robotic missions directly to the operator. It requires the use of the interprocess communications subsystem (IPT), described below, to maintain contact with the robots and other active processes. The *MissionLab* console provides the following capabilities:

- Loads precompiled robot control programs and overlay description files
- Configures the display
  - generating obstacles for simulations
  - altering the scale of the display
  - changing the virtual time for simulations
  - scaling the size of the display (zooming)
- Provides a Command interface that permits interactive step-by-step command issuance by the operator using CMDL, a structured English language
  - has the ability to execute, stop, pause, restart, rewind, single step, and abort missions during execution
  - has the ability to use team teleautonomy by directing robots to particular regions of interest or by altering their societal personality.
- Provides display options
  - leave trails where the robots have been
  - highlight obstacles that affect the robot
  - show instantaneous directional reaction of robot to its environment

The *MissionLab* console also provides a display (Figure 3) that shows either:

1) The output of a simulated robotic mission that is run faster than real-time and can serve to determine whether or not a premission specification has been successfully completed.
2) An operator mission display screen where robots in the field report back their position and relevant mission data that is shown on the mlab display to provide situational awareness and context for higher level decisions regarding aborting, continuing, or biasing the mission in various ways.

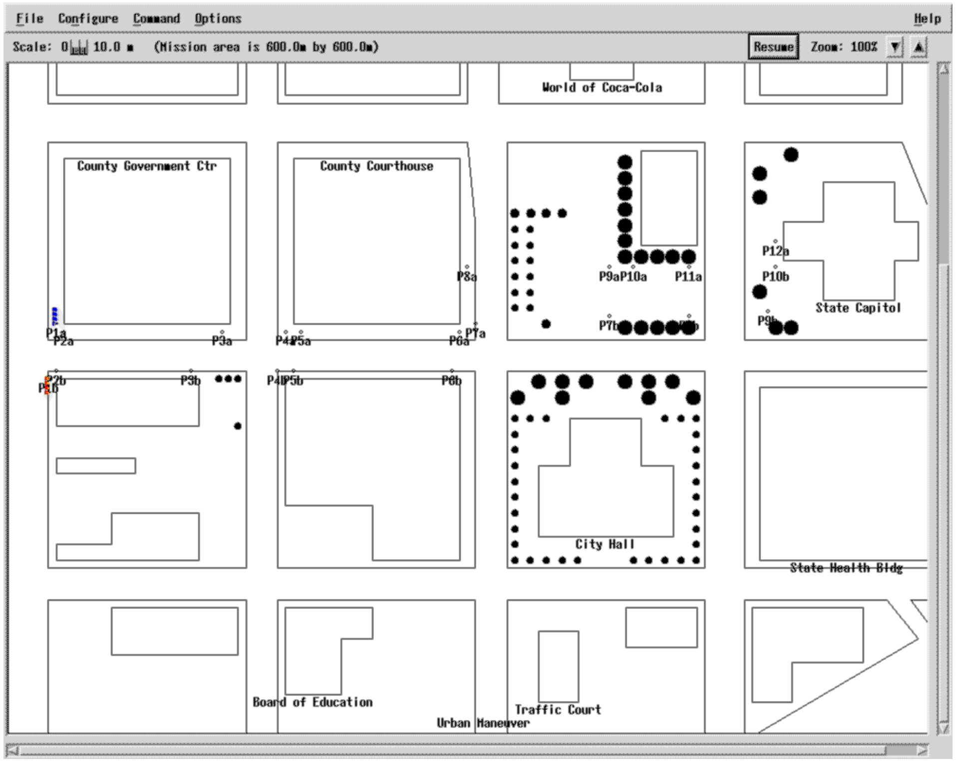

Figure 3: Display during execution of simulated mission (display of actual robot mission is similar).

2.2 *Premission Subsystem*

The premission subsystem involves the specification, creation, and construction of behavior-based robots suitable for specific missions. It provides a user-friendly graphical programming environment and a series of language compilers used to transform the high-level iconic description into executable code suitable for the executive subsystem. In addition, it provides data logging tools that are geared for usability studies leading to the enhancement of the user interface.

2.2.1 Configuration Editor

The configuration editor (*cfgedit*) provides a visual programming entry point into the system (Figure 4). It is geared to average end-users and requires limited training to use. The interactive iconic interface generates configuration description language (CDL) code which, when compiled and bound to a particular architecture and robots, generates a meta-language. In this project this is CNL, the configuration network language, that serves as a precursor to the C++ code that is ultimately generated when the CNL code is compiled. This resulting C++ code forms the executable code for the robot controller itself. Within the executive subsystem, this code is then directed either to the simulation or the actual robots for execution.

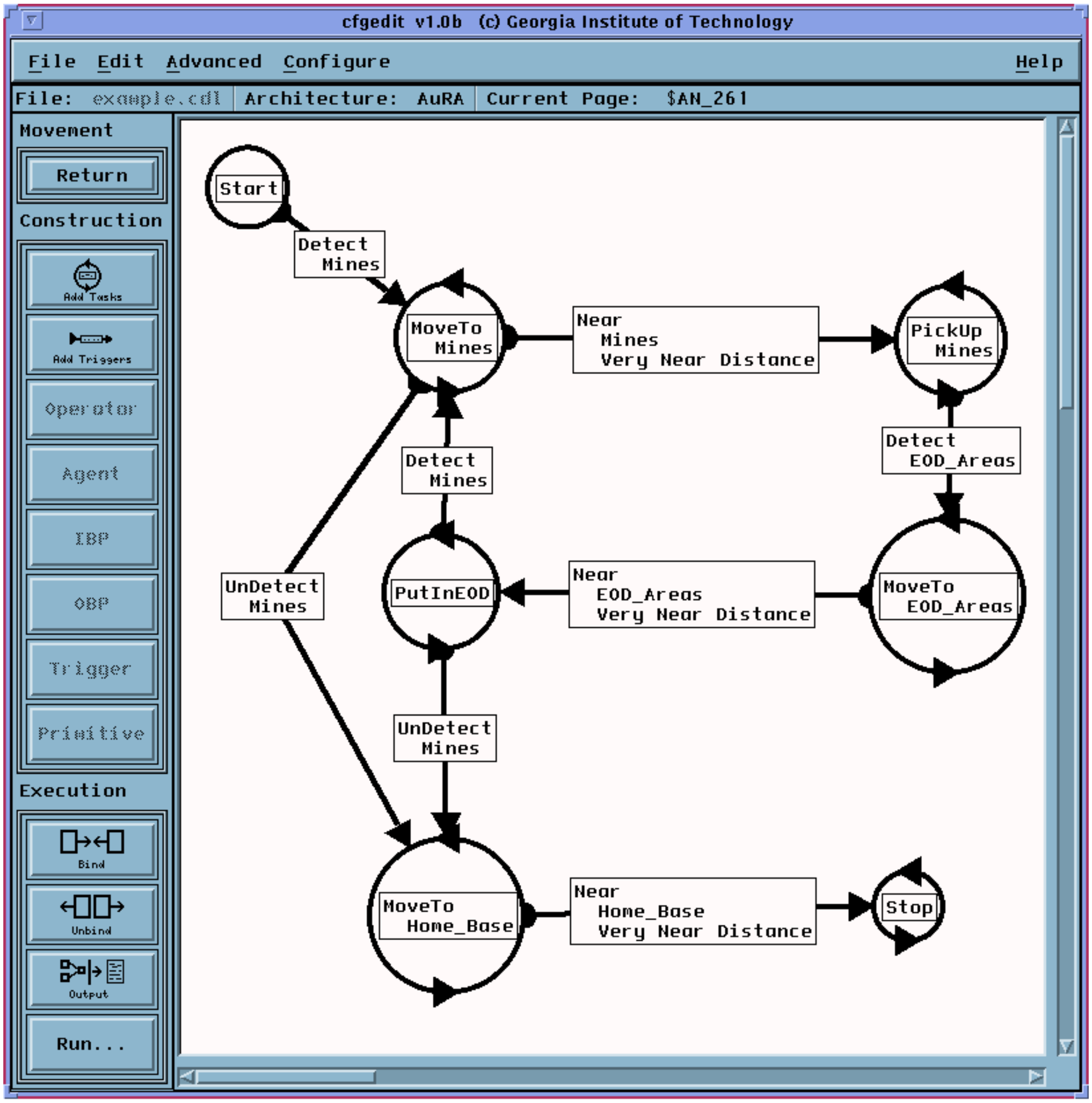

Figure 4: Graphical configuration using *cfgedit.*

2.2.2 Usability Data Logging

Additional software is used to record user actions during premission planning. This includes data such as the number and type of keystrokes and mouse clicks, time to create certain objects, and other relevant data. These data are then used to interpret the skill by which a user is capable of achieving within the system, and after subsequent usability analysis, is used to refine the design interface itself. It is a support tool geared for formal usability studies (

Figure 5).

Figure 5: Usability Laboratory.

2.3 Runtime Subsystems (1 per robot)

The runtime control code created by the premission subsystem and then tested in simulation within the executive subsystem is then sent to the actual robotic systems for execution. Thus there is one runtime subsystem located on each robot required for the mission. IPT provides interprocess communication between the robots and the mlab console.

The runtime system consists of a set of reactive behaviors and sensor strategies to interpret and react to the world; hardware drivers customized to interface designated robots to the *MissionLab* system; low-level robot control code generally provided by the robot manufacturer; and the actual robotic and sensor hardware.

2.3.1 Reactive Behaviors

A collection of reactive behaviors is compiled and downloaded to each robot for execution of the mission. These reactive behaviors embody the mission specification designed within *cfgedit*. They process sensor data as rapidly as possible and issue commands to the lower level software for timely execution on the robot. These behaviors include activities such as obstacle avoidance, waypoint following, moving towards goals, avoiding enemies, and seeking hiding places, all cast into mission-specific reusable assemblages. Action-oriented perceptual code supports both Newton Labs Cognachrome real-time color vision systems, laser rangefinders, infrared proximity sensors, DGPS, and ultrasonic data. Team behaviors, such as team teleautonomy, formation maintenance, and bounding overwatch are also bundled for execution as necessary. The output of these behaviors is sent to the groundstation for monitoring purposes as well as to the robot for execution.

2.3.2 Hardware Drivers

In order for *MissionLab* to be able to build an executable program to run on a given robot, it requires an ensemble of routines to set up, control, and receive feedback from the actual (or simulated) robot. Some variation in capabilities occurs among the various robots that are supported, but the typical routines for the TMR platforms (Pioneer AT and DARPA Urban Robot) include movement commands, range measurement commands, position feedback commands, system monitoring commands, and initialization/termination commands.

Additional drivers are required for sensors which are not tightly integrated into the onboard robot control system (see PSOS and ARC below). These include such vision-related capabilities as specifying the characteristics of a target and requesting target tracking status (and position, if available).

2.3.3 Low-level Software

Low-level software includes embedded software and firmware that is typically provided by the vendors of robots and sensors in order to access the basic capabilities of those devices. For this project, this classification includes PSOS (running on the Pioneer AT robot controller), Mobility and rFlex (running on the Urban Robot controller), and ARC (running on the vision system).

The onboard microcontroller of the Pioneer robot is equipped with the Pioneer Server Operating System (PSOS) software. PSOS serves the serial communication port provided for the receipt of commands and the return of status information. As such, most of the functions listed in the previous section for the robot driver result in the transmission of a message to PSOS, which in turn handles the request.

The Cognachrome vision system behaves similarly, with its serial port served by an embedded operating system called ARC. This multitasking system allows the vision tracking parameters to be changed and issues tracking results at specified intervals. ARC provides a C development environment and runtime system for the generation and support of vision programs that exceed the basic capabilities provided with the Cognachrome system.

The onboard controller of the Urban Robot is a PC-compatible computer running the Linux operating system. It runs a CORBA server which handles requests for hardware operations, including both sensing and locomotion. These requests can originate from other processes running on the same controller or through a networked connection. Both wired and wireless Ethernet connections are possible.

3. SUMMARY OF DEMONSTRATION RESULTS

In addition to numerous experiments performed on a regular basis, and a few onsite demonstrations for TMR personnel, two major demonstrations were performed. One of these was at Fort Sam Houston in 2000, and the other was at the Montgomery County Public Safety Training Academy in 2001. Both demonstrations required at least one earlier site visit for familiarization and experimentation.

3.1 Fort Sam Houston

The primary thrust of our experiments at Ft. Sam Houston was to assess the status and reliability of our intermediate demonstrations that will eventually evolve into an end-to-end demonstration of the hospital assessment scenario. These experiments were divided into three parts, corresponding to the three phases of the demonstration:

Building approach – assess the Pioneer and DGPS as suitable technologies in conjunction with the *MissionLab* system as the waypoint planner and behavior scheduler.

Stair climbing – we expected not to have any experiments in this area, having only received the Urban Robot platform from the TMR pool a few weeks earlier. But since we had already developed a basic *MissionLab* interface, we were able to at least experiment with the reliability of the "Urbie" comm links in a simple mission controlled by *MissionLab*.

Indoor assessment – assess the reliability of visual servoing and the Pioneer hardware platform (sonar and locomotion, especially) in the context of a *MissionLab*-controlled demonstration of room-to-room assessment.

Another area of interest was the assessment of our readiness to port phases 1 and 3 to the "Urbie" platform, since it would clearly be closer to our final demonstration goal.

The results of the experiments in each phase follow. A video of experimental runs can be found at http://www.cc.gatech.edu/ai/robot-lab/tmr/ftsamdemo.mpg.

3.1.1 Building Approach

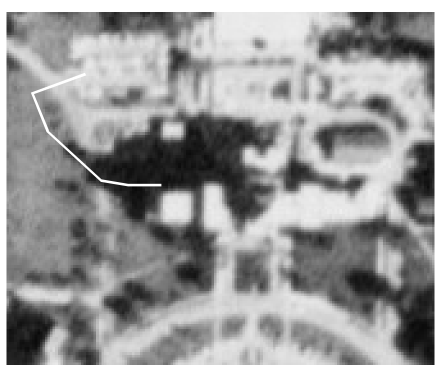

Figure 6: Satellite photograph (1.56 m resolution) with overlaid path shown (white line). Dark area is primarily the building shadow.

Although the DGPS survey conducted by SWRI appears to be quite accurate in a relative sense, it did not correlate with the absolute coordinates of the hospital site, being off by about 6 miles. It was our original intention to set up our DGPS base station at a surveyed location and take advantage of any survey data, but we instead opted to set up our own reference point. We chose a base antenna location whose geographical coordinates could be determined relative to a known National Geodetic Survey marker (accurate to within a few meters). The satellite imagery we had for the site (see Figure 6) can be used as an underlay, but the level of detail is of little use, so this was deferred and may still be revisited. Time permitting, we would like to address the easier use of latitude/longitude data in *MissionLab* prior to our next demonstration.

3.1.1.1 DGPS performance

We will not rely upon highly-accurate DGPS data for the successful execution of typical TMR missions, but would like to be able to place the robot within a known "context," i.e., where it is close enough to search for features that are either known a priori or can be designated by a remote operator. For these purposes, standard non-differential encrypted GPS would be more than adequate. But when DGPS is available, the *MissionLab* system allows the triggering of behaviors that can take advantage of the positional knowledge, such as precisely following waypoints on a paved roadway. Our experiments indicated that DGPS performance (with our own base station and broadcast equipment) at Ft. Sam was adequate for these precise behaviors. Over 95% of the time during cross-country traversal, the robot appeared to maintain positional knowledge within +/- 10 cm, as expected with the RT-20 carrier phase kinematic differential GPS equipment. These are estimates – it is not possible to state the positional accuracy with certainty, since the robot behaviors have loose tolerances for successful achievement of waypoints, but it was clear that repeated demonstration runs usually resulted in the robot following its own tracks from previous runs.

The DGPS station (on the second-floor roof) was available 100% of the time, and the datalink to the robot appeared to be 100% reliable, as well. There were isolated instances of satellite signal loss to the robot GPS unit, usually at one particular waypoint near a tree. This was neither unexpected nor undesirable, as we wanted to observe the robot's automatic degradation to odometry-based navigation. (Bear in mind that although the robot continued to receive DGPS correction signals during these periods of satellite loss, it was of no use in navigation.) As expected, the odometry-based navigation starts as a general movement in the right direction that degrades with each instance of turning or slippage. Once satellites are reacquired (normally within 5-10 seconds), a noticeable course correction occurs, and the robot moves toward the current waypoint again.

3.1.1.2 Terrain and locomotion

We found that most of the nearby terrain was traversable with a Pioneer-AT, but some preplanning was required to avoid the crossing of high curbs, especially at an oblique orientation. Most of the traversability issues would vanish with the use of an "Urbie," given that it had some means of knowing when curbs were present. The Pioneer was able to negotiate small curbs (about 2 inches) and shallow puddles, both of which were deliberately incorporated into the chosen path. Still frames from the demonstration video are shown in Figure 7.

Early experiments were conducted at the same default speed normally used for indoor runs. Later, this was increased with no ill effects on mission performance. It is possible that speed may be increased further, but no attempts have yet been made. In the demonstrated configuration the Pioneer's average speed was approximately 0.45 m/sec (approximately 140 meters traveled in about 5 minutes and 15 seconds).

Figure 7: Sequence of images from Building Approach demonstration.

3.1.1.3 Robot behaviors

The indoor run (see Section 3.1.3) concentrated on more elaborate robot behaviors, but we included some obstacle avoidance in the building approach. The sonar sensors are somewhat unreliable in the medium-to-high grass, causing the Pioneer to take an needlessly undulating path. This would be alleviated somewhat by higher sensors, perhaps like those used in our alternate Pioneer sonar configuration, but this was not tested.

3.1.1.4 Miscellaneous data

We learned that we can dissassemble the main console of a Pioneer, replace the controller board, and reassemble it in 15 minutes, as was done 30 minutes before the start of our demonstration. This was not the sort of data we had hoped to collect, but it does help to understand our ability to recover from failures. Ideally, we would like to have at least one spare system available for each demonstration, but we do not have a full complement of duplicate accessories, such as DGPS receivers.

3.1.2 Stair climbing

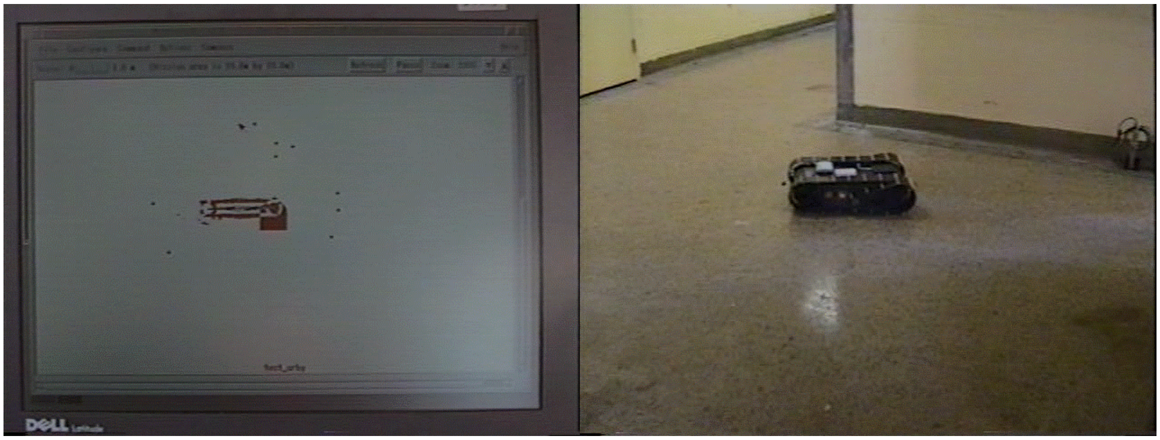

Figure 8: Urban robot under *MissionLab* control. Console is shown at left, where robot has already repeated a simple back-and-forth movement several times.

As noted earlier, we have nothing to report here other than that we were able to transport the "Urbie" to the site and run it under *MissionLab* control (Figure 8). We ran a simple back-and-forth mission and found that the datalink (wireless Ethernet) would be marginal for the distances encountered in the indoor assessment demo described below, but it is possible that it would work if we constrained the area of interest to neighboring rooms (with the wireless access node immediately adjacent). The datalink would probably be suitable for the building approach and an outdoor stair-climbing demo, but only if the wireless access node were in an optimal outdoor location.

3.1.3 Indoor assessment

We have conducted our indoor experiment by setting up the hardware and software of our robot to be able to carry out a mission which can be applied to the "Phase 1: Task B (Contamination Assessment)" scenario specified in *Tactical Mobile Robotics Demonstration Plan Background Scenarios (as of: 10/20/98).*

3.1.3.1 Hardware Setup

For this particular task, we used a modified Pioneer-AT robot produced by ActivMedia with a Sony EVI-D31 pan/tilt/zoom camera and a Newton Cognachrome vision system. The modifications to this platform were the reconfiguration of the sonar sensors and the addition of an onboard laptop. For the sonar sensors, we disabled the default configuration shipped by ActivMedia as it did not provide an adequate spread to do sufficient obstacle detection. Our modification involved adding new sonars to the robot's exterior that provide an even 360 degree sonar spread, capable of tracking obstacles in any direction relative to the robot. We also added a laptop aboard the Pioneer to serve as the control for the robot. The executable program on the laptop maintains serial communications with the robot for gathering sensory data and for issuing move commands, serial communication with the camera, and serial communication with the *MissionLab* console for reporting position information and any other desired data. Wireless communication is achieved through the use of two FreeWave wireless data transceivers, one aboard the robot and the other at the *MissionLab* console. Prior to execution, a PPP link is initiated between the console and the robot, so as to make transparent the actual communication means between the two. To speed the download of the robot executable to the on board laptop while the robot is "docked", a regular ethernet connection is used in lieu of the slower PPP connection. While the *MissionLab* console and the "docked" robots share a local network, this network is completely standalone and requires no external connectivity whatsoever.

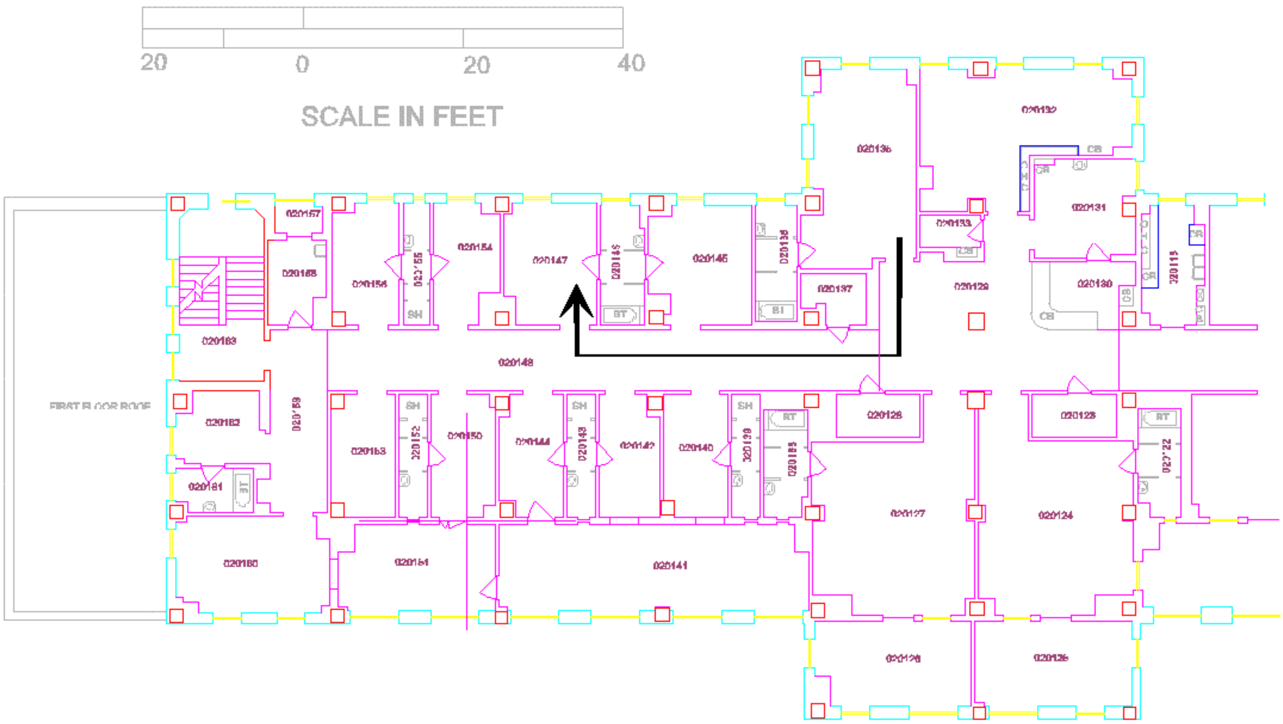

Figure 9: West wing of second floor, showing nominal path of robot.

3.1.3.2 Remote-Room-Inspection Task Construction

At the site, we have created a mission for the robot to inspect one of the rooms on the second floor in the west wing of the hospital from another room, approximately 50 ft away from the starting point near the operator console (Figure 9). We utilized *CfgEdit* (the Configuration Editor), one of our *MissionLab* tools, to generate the mission which performed:

1) departing a room,
2) finding a hallway,
3) navigating the hallway with obstacle avoidance,
4) finding a doorway for the 2nd room at the right hand side,
5) entering the room, and
6) detecting a colored object.

The mission was composed with a set of 10 finite states and 10 triggers (5 types of states and 6 types of triggers) that had already been coded before our arrival to the site. The information from the onboard ultrasonic sensors was used to find obstacles, the hallway, and the doorway, while the information from the vision camera was used to identify color objects.

The robot executable was created very rapidly. Compilation took 17 seconds, and downloading the program to the onboard laptop computer via Ethernet link was a matter of a second.

3.1.3.3 Execution

We chose eight runs for our analysis, in which the robot either completed its mission, thought it did, or was caught in a situation it could not rectify. A typical mission is shown in the sequence of still frames in Figure 10. Aberrations due to interference or improper configuration were discarded. Of these eight trials, the robot successfully completed its mission six times, for a 75% success rate. In the first unsuccessful run, the robot did not detect the second doorway and had no recourse for recovery, so it simply quit. This could be completely resolved had we more time to develop more elaborate missions and allow for alternate action. In the other failure, the robot simply did not detect the goal object, probably due to lighting conditions.

Figure 10: Sequence of images from indoor assessment demonstration.

Our mean execution time for a successful run was approximately 112 seconds with the mode at 123 seconds. This highly volatile statistic is useful only in the sense that it establishes an approximate upper bound on mission execution time. This robot ran at about 0.3 m/sec, and future missions can and will be executed faster, provided that sensors are able to produce reliable data at increased speeds.

Object detection was relatively reliable during our test runs. Inconsistencies in lighting conditions and slow robot reactivity were common reasons for a robot missing a visual cue. We have little control over the former, and we are investigating solutions for the latter. Nonetheless, in the eight trial runs, each consisting of two visual cues, the robot successfully detected the object on the first pass only 20% of the time but found the object on the second pass nearly 80% of the time. In all but one case the robot eventually found the object. Better vision algorithms and faster (more efficient) sensory processing should remedy this.

Our analysis of experimental runs uncovered many key areas that adversely affected the setup times for our experimental runs. These deficits were mainly in the areas of robot-to-console communication and the ability to simulate our desired runs. The lack of this functionality has little impact on the ability to perform the task itself, but does have the effect of requiring more initial "pre-runs" to see that the prescribed behavior was appropriate for a particular task. Due to this, the setup time for the mission that we ran was much higher than normal. However, with improved robustness and further experimental analysis, we should reduce this to an acceptable level. Overall, we have successfully carried out the mission and shown that an indoor assessment such as the "Phase 1: Task B" scenario can be accomplished with the *MissionLab* system.

Figure 11: Urban robot following hallway inside burn building at MCPSTA, searching for biohazard indication.

3.2 Montgomery County Public Safety Training Academy

At the Montgomery County Public Safety Training Academy (MCPSTA) in 2001, two missions were performed that were outgrowths of the 2000 Ft. Sam demonstrations. The indoor Situtational Awareness (SA) mission evolved to use the Urban Robot and some custom integrated sensors, while the DGPS waypoint mission utilized an improved user interface and tighter system integration of DGPS support.

3.2.1 Indoor Situational Awareness Mission

Experiments at Georgia Tech had confirmed the need to develop better obstacle detection capability on the Urban Robot. Even on the Pioneer AT, the ultrasonic sensors were insufficient for simple obstacle avoidance, and on the Urban Robot the problems were compounded by the limited maneuverability of the platform and the physical placement of the sensors themselves. Furthermore, by this time we had developed behaviors to follow corridors and look for door openings, and these required enough information to construct local representations of wall fragments.

Consequently, we integrated a SICK laser scanner into the Urban Robot platform, along with the pan/tilt platform, camera, and vision system used previously as a "placeholder sensor" to detect biohazard visually. This enhanced platform proved to be sufficient for the assessment mission, which required traversal of a hallway, simultaneous search for biohazard indications (sign on wall), detection and entry of doorway, and final search for biohazard (labeled bucket).

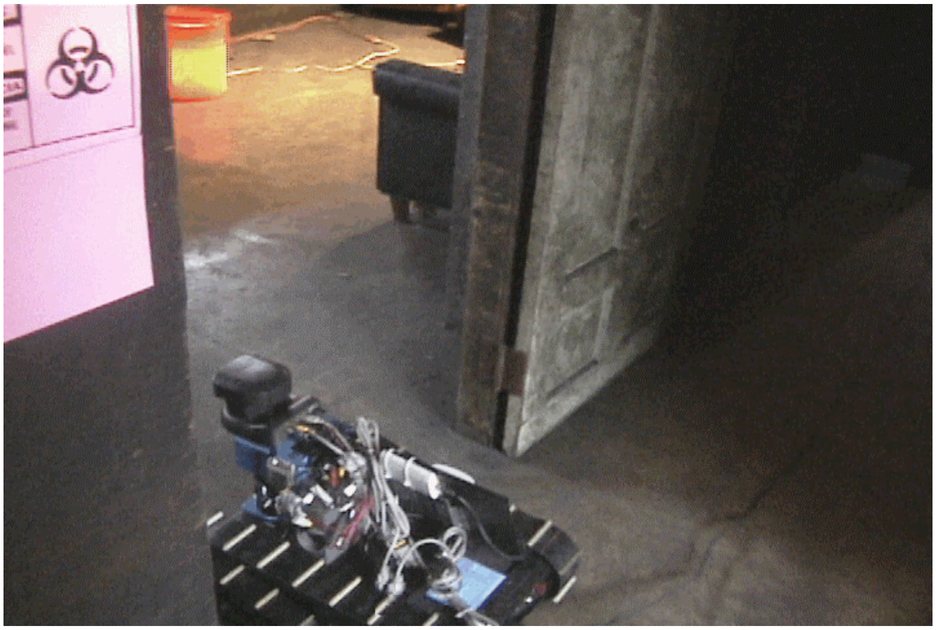

Figure 12: Urban Robot entering room in burn building where biohazard is located.

At MCPSTA, our initial experiments concentrated on adapting to the lighting conditions, which were very dim. The improved range sensing (using the SICK) minimized the number of experiments needed for hall and doorway navigation. Once mission parameters were defined, we immediately achieved success in 8 of 10 consecutive runs (see Figure 11 and Figure 12). The failures were attributed to minor ranging problems. The experiments were cut short on the third evening, and access was not allowed on the following day, so that completed the experimentation phase.

Upon our return to MCPSTA for the final TMR demonstrations, we were able to pick up where we left off and complete the SA demonstration on cue each time it was required.

3.2.2 Outdoor DGPS Approach Mission

For the DGPS Approach mission our initial MCPSTA experiments were totally related to replicating the mission at a new geographic location. We had already successfully integrated the DGPS data stream into the regular communication between the operator console and the robot, and we had incorporated a mission overlay showing the MCPSTA demonstration site.

It was determined that a suitable mission would be to start the robot near the burn buildingg, navigate a series of waypoints, and stop beneath the observation tower in a surveillance position. Once the mission parameters were defined, the mission succeeded in 3 of 3 consecutive runs.

Lack of access to the building prevented continuation of this mission as well, since the DGPS base station was removed on the third evening to accommodate training activities.

Figure 13: Outdoor approach mission, showing Pioneer AT navigating waypoints toward tower.

Upon our return to MCPSTA for the final TMR demonstrations, the DGPS mission was not incorporated into the overall scenario, but was demonstrated individually and as part of the OCU demonstration from the mobile Hummer groundstation (see Figure 13 and Figure 14).

Figure 14: Mobile groundstation used for DGPS approach demonstration.

3.2.3 Additional Results and Lessons Learned

At the Ft. Sam demonstration, 900 MHz FreeWave wireless serial modems were used for SA mission. Although these have good range, there was still occasional dropout, and the process of automatically restoring a PPP connection over a serial link presents an additional demonstration risk. Also, there were some interference issues. Just as JPL's FreeWaves acted as a source of emissions that interfered with analog video in the 900 MHz band, we too contributed to that problem.

At MCPSTA, we switched to the Urban Robot platform with its 2.4 GHz BreezeCom, eliminating the need for the FreeWaves. This WLAN implementation had less range, but showed better overall performance in the more benign setting of the burn building. Some brief experiments at Ft. Sam had shown that the Urban Robot and the BreezeCom were inadequate for the hospital building with its higher degree of shielding.

The BreezeCom also eliminated the need to establish PPP links, which simplified the setup and conduct of the demonstrations.

At MCPSTA, a FreeWave was still used as DGPS base station transmitter, sending packets to the mobile groundstation/OCU, where they were incorporated into data/control packets sent to the robot over a Nokia 802.11 wireless LAN. Just as we had found previously at Ft. Sam, the FreeWave was ideal for the outdoor DGPS application, and was reliable over entire outdoor MCPSTA area.

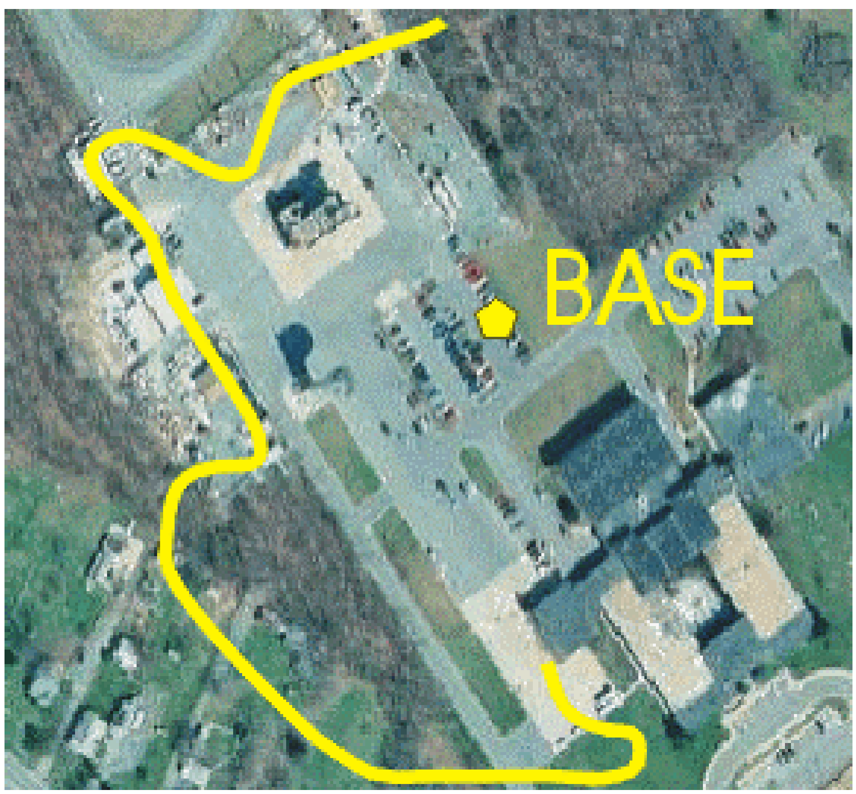

Figure 15: Coverage area as determined from brief site survey. Some directions were not explored due to lack of time.

The 2.4 GHz Nokia 802.11 used for the OCU/Robot link is equivalent to the Samsung 2 Mbit/sec product. A casual site survey was performed, and the results are shown here in Figure 15. There was significant dropout beyond the yellow line, but this was well outside the area needed for the DGPS demonstration. Had it been required to enter the burn building, the signal strength inside was only slightly lower than the corresponding outdoor area.

Significantly, there were no interference complaints during experiments related to our activities, and we experienced no interference from other sources.

A concerted effort was made to reduce the amount of data traffic between the OCU and the robot in both missions. Both the SA and DGPS missions required only a pair of operator commands: "Start" (go to Standby) and "Proceed" (continue). The need for a Standby state was a lesson learned at Ft. Sam, since it enabled the critical startup and test of the motors to take place prior to the actual initiation of the mission.

No operator commands are required after the start of mission until its completion, unless an abort is required. Once underway, the OCU screen is updated with data sent from the robot, as long as the datalink is maintained, but this is not necessary for mission completion. Displayed data included obstacles (as range readings) and robot position.

The data rate was automatically lowered to accommodate network bandwidth considerations. The DGPS correction packets are sent from the OCU at rates as high as once per second, but this affected the DGPS mission only. Absence of DGPS correction data degrades position but does not affect autonomy.

4. SKILLS IMPACT STUDY FOR TACTICAL MOBILE ROBOT OPERATIONAL UNITS

This section provides a detailed study of the design of feasible human-robot interfaces for near-term deployment in a "robot unit," defined as a tightly coupled group of humans using a multiplicity of robots as tactical tools. There is a strong relationship between three phases of fielding man-machine systems of this type: system design, operator selection, and operator training (Figure 16). Here we consider all of these dimensions, developing an understanding of

- the tradeoffs between highly-trained operators versus novice operators,
- the importance of specific cognitive and intellectual reasoning abilities of potential operators, and
- the impact of system design on all of this.

Clearly, a sophisticated, well-designed system will require less training and enable a larger set of people to interact with it. The purpose of this study is to span this space of potential design and human factors issues and identify the inherent wins, losses, and trade-offs given the goal of rapidly fielding such a system.

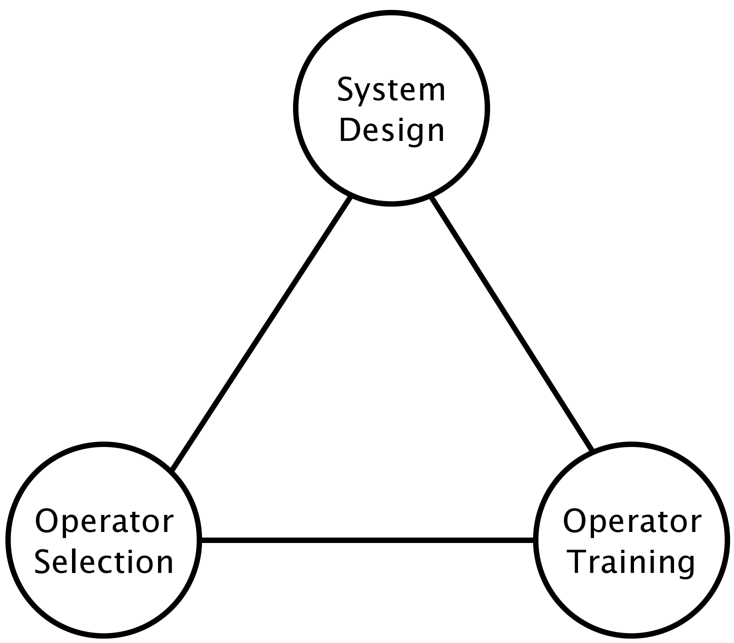

Figure 16: The implementation of a usable man-machine system requires a synergistic approach that takes into account both the hardware and the operator.

To accomplish this, we look heavily towards existing literature and studies. Thus we attempt to synthesize information from a wide range of disparate sources including published papers, military documents, and commercial sources. Visits have been taken to sites that are promising nuclei of relevant information, including:

- Oak Ridge National Laboratory (telepresence concepts, teleoperation techniques, and human factors),
- NASA Ames (human factors techniques), and
- Ft. Benning.

A guiding influence of this work is the report of the TMR Concept Development Group, "Concept Development Report For The Tactical Mobile Robotics (TMR) Program (Extract of 03/24/1999 Revision)," which will be referred to often [TMR 99]. Often, the CDG recommendations serve to constrain the problem and focus this study, and in many cases we cite evidence of the validity of the CDG opinions. In a few cases, we identify areas where some promising technologies may have escaped the attention of the CDG.

4.1 *Human-Robot Interface design*

This section is intended to serve military decision makers as a guide to existing technologies for human-robot interfaces that are practical for field deployment. In this context, "practical" means that the technology has been demonstrated to be reliable, somewhat ruggedized, and ideally available as commercial off-the-shelf (COTS).

The "system" being considered is the combined system of a human, one or more robots, and appropriate interface hardware and software. All robots have readily-identifiable weaknesses, as do humans. Therefore, a major point of this report is to assess the strengths and weaknesses of a human augmented with the remote resources of a robot. In order to justify the use of robots, is not sufficient to merely to note that a robot can have specialized "non-human" sensors or locomotive capabilities. It must be shown that there are reasonable methods to allow a human operator to have access through these capabilities through available technology while still maintaining awareness of local surroundings.

While interfaces for teleoperated and teleautonomous control are getting more attention and becoming increasingly more sophisticated, the primary emphasis of existing systems is concentrated on non-man-portable systems, such as multi-operator control stations for high-value UAVs and elaborate mission control centers for space robotics. The field is considerably narrowed when dealing with the targeted application of an single dismounted soldier controlling multiple platforms.

4.1.1 Wearable Computing and Augmented Reality

A complete robot OCU suitable for field deployment in tactical situations has much in common with what is generally called a "wearable computer." To emphasize just how closely the model of wearable computing fits the TMR requirement, consider the criteria given by Mann as a basic definition of the subject [Mann 97]. Here he states that a wearable computer is:

"1. **eudaemonic:** the apparatus is subsumed into the 'eudaemonic space' of the wearer (e.g. it may be worn, or otherwise situated in a manner that makes it part of what the user considers 'himself' or 'herself,' and in a manner that others also regard it as part of the user . . .). It is sufficient that the interface be eudaemonic (e.g. some of the compute power can be remote);

"2. **existential:** the apparatus is controlled by the wearer. This control need not require conscious thought, but the locus of control must be such that it is entirely within the wearer's domain

. . . . Furthermore, the apparatus provides the wearer with the ability to make its operation completely private and secure when desired. In addition to the obvious privacy afforded by its eudaemonic nature (e.g. securely attached to the body so that it might be less likely to be stolen when working in close quarters with adversaries), the output can be made private when desired by, for example, using a screen that cannot be read by others looking over the wearer's shoulder;

"3. **constant:** (constancy of both operation and interaction):

- Operational constancy: it is always active while worn. . . .
- Interactional constancy: one or more output channels (e.g. screen/viewfinder) are known (e.g. visible) to the user at all times, not just when the computer is being interacted with in a deliberate manner. In this way, context switching time to mentally engage with the apparatus is near zero."

While Mann generally considers the above criteria in the context of a civilian user, enhancing the security and freedom of the individual, the applicability to a military user is clear. In agreement with the principles described in Section 6.2 of the TMR CDG [TMR 99] ("Human Robot Interface"), Mann also states [Mann 98] that essential qualities of a wearable computer include that it be

1. **unmonopolizing** of the user's attention,
2. **unrestrictive** to the user,
3. **observable** by the user: "It can get your attention continuously if you want it to,"
4. **controllable** by the user: ("Responsive"),
5. **attentive** to the environment, and
6. **communicative** to others.

The single greatest difference between a generic wearable computer and a TMR OCU is that the OCU is specialized to act as a remote teleoperation "console," and as such may require specialized input devices for robot control and specialized output devices for robot sensor visualization. In a word, a TMR OCU requires some degree of *teleimmersion* or *telexistence*, a computer user's experience of being part of a remote environment. Wearable computers developed to date sometimes include some capabilities related to either teleimmersion or ordinary *immersion* (a virtual environment rather than a remote environment), but this is essentially an application-dependent characteristic.

We must be careful to define our concept of teleimmersion in the OCU context, since immersion (and similarly, teleimmersion) can imply a monopolizing user interface. At the extreme end of the teleimmersion scale is *virtual reality*, a poor model for what a TMR operator should experience, since by definition it is overwhelmingly distractive. But it can be useful for an operator to **at will** step in and out of an environment that embodies some of the qualities of *augmented reality* and *mediated reality*. (Later we discuss some of the reasons for this, including improved ability to perform remote driving and manipulation operations.)

Augmented reality refers to the enhancement of the actual perceived environment with information that has been obtained by other means. A heads-up display in an aircraft or other vehicle is a common example, where graphical and textual information about location, altitude, and vehicle status are made available while still allowing the pilot to see the local surroundings. Any soldier carrying wireless voice communications equipment is essentially experiencing a basic form of audio-augmented reality, enhancing the visual experiences of the local environment with useful information from other military personnel (and generally augmenting **their** "reality" with return communication, as well).

Mediated reality acts as a filter on the perceived environment, blocking extraneous information and focusing user attention on important stimuli. In the TMR OCU scenario, we can imagine multiple operators in close proximity to each other and a support HMMWV, all potentially exposed to enemy fire. So an approach based on mediated reality would attempt to block out some of the activity of the other operators and support personnel while focusing operator attention on the following important information:

- status of the robots under the operator's control,
- warnings and other pertinent information from sentries providing protective support for the robot unit,
- high-level status of robot teams under control of other operators, and
- operator's own perceptions of local threats (sniper fire, aircraft activity, etc.).

This is a key point: mediated reality should be **better** than reality. Instead of concerning ourselves with how an OCU may impair the operator's ability to deal with other "non-robot-related" activities, we must turn the problem back on itself and strive make the operator's situational awareness **better** than it would be **without** the OCU.

Wearable computing is often considered to be a subset of *ubiquitous computing*, the notion of having computers literally everywhere, in even the simplest devices. Curiously, some consider ubiquitous computing to be the opposite of virtual reality, by virtue of the fact that placing computers in a user's world is the opposite of placing the user in a computer's world. But clearly that is a limited viewpoint – the worlds can mix in almost any proportion, and a TMR OCU represents such a mix.

Most existing COTS wearable technology does not address the teleoperation issues, instead focusing primarily on data entry and database access applications including inventory, maintenance, inspection, medical treatment, cartography, and journalism (Figure 17). Some of these applications are described at the web site of a leading vendor of wearable computers, Xybernaut (www.xybernaut.com).

Figure 17: Emerging applications of COTS wearable computers, including (left to right) cartography, journalism, and inspection/maintenance. (© Copyright 1999 Xybernaut Corporation and subject to use restrictions at http://www.xybernaut.com.)

Of slightly greater interest are applications related to "location-aware" access of data, such as those projects pursued by the Nexus group at the University of Stuttgart (http://inf.informatik.uni-stuttgart.de/ipvr/vs/projekte/nexus/), the Future Computing Environments and Wearables groups at Georgia Tech (http://www.cc.gatech.edu/gvu/fce/index.html, http://wearables.gatech.edu), the Wearable Computing and Vision and Modeling groups at MIT (http://www-white.media.mit.edu/vismod), http://wearables.www.media.mit.edu/projects/wearables), the Wearable Computing Systems group at Carnegie Mellon (http://www.cs.cmu.edu/afs/cs/project/vuman/www/frontpage.html), and others. Location awareness can be on a large scale, as in aids for a tourist exploring an unknown city with the aid of a wearable computer that displays information relative to GPS position (Figure 18a), or on a local scale, as in the use of a *pose estimation* sensor (e.g., a head tracker) to determine where a user is looking so that his view may be annotated (Figure 18b). Both of these are examples of augmented reality, and both may be relevant to a TMR OCU.

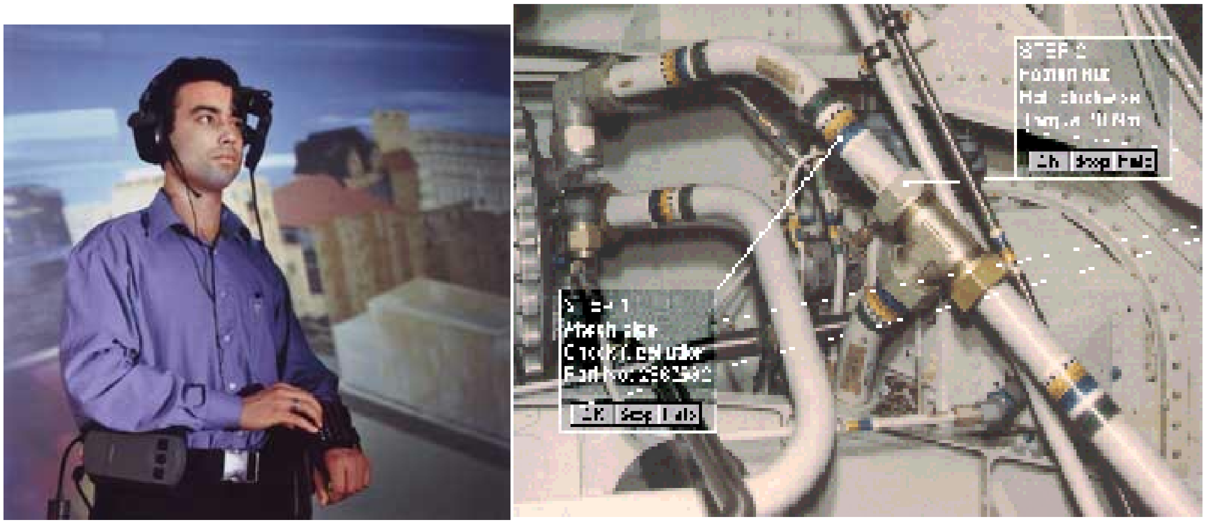

Figure 18: Applications of location awareness for wearable computers. a) A tourist accessing location dependent data in an unknown city, and b) Machinery annotated with information relative to the user's view. (© Copyright 1999 Xybernaut Corporation and subject to use restrictions at http://www.xybernaut.com.)

Ideally, the core elements of a TMR OCU would be interchangeable with any standard-issue wearable computer which is ultimately developed for military use. Such concepts typically include a computer, power supply, voice radio, GPS, display, and input devices. As will be shown, the major differences are likely to be in the display and input devices.

In some of the more relevant research involving wearable computers, Barfield [Barfield98] considered the effectiveness of augmented reality (AR) displays in aiding an operator in the performance of a manufacturing assembly task. The researchers compared four methods of conveying the assembly instructions to the operator:

- printed instructions,
- conventional computer-aided instructions,
- information graphics on an opaque AR display, and
- information graphics on a transparent AR display.

In the Barfield study, the test subjects were given the task of assembling a computer motherboard, admittedly a significant extrapolation of a typical TMR task. They were given training on the insertion process for various components prior to undergoing trials in which the metrics measured were 1) time of assembly and 2) number of errors. This was followed by a questionnaire to assess user preferences. The final results showed lowest execution times for the transparent AR display, followed by the opaque AR display, computer-aided instructions, and printed instructions. Errors were lower with AR displays in general. Certainly this supports the notion of using AR technology to facilitate the operation of a TMR OCU, but it does not address the effectiveness of wearable technology for teleoperation. Another Barfield study briefly described in the same report supported the use of force feedback in the understanding of statics and dynamics.

The usefulness of AR as an effective model for providing information to the warfighter has not been unnoticed by the military. As noted in COTS Journal [Ciufo 00]:

“. . . the trouble with immersive HMDs is that they block out the real world and prevent the operator from reacting to real events while immersed in the virtual world. Whereas this downside can be overcome by piping in real-world video on top of the virtual environment, information overload sets in, and the operator can quickly become disoriented. A better approach is augmented reality (AR) technologies that allow viewing the real world with superimposed virtual objects.

“The U.S. military is using AR in a big way. HMDs are used by pilots to supplement the traditional heads-up display (HUD) in platforms ranging from the F-15 and F/A-18 to the new Joint Strike Fighter and Comanche helicopter. Armored vehicle drivers and commanders will use HMDs with "head-out" views of the real world while still viewing vehicle instruments and weapons systems. Battlefield soldiers have a digital view of the battlefield, the locations of ‘friendlies’ and opposing forces (OPFOR), and remote viewing capabilities around corners or in anti-laser ‘eye-safe’ mode. And both medics and mechanics can call up on-the-spot documentation for ready access to on-site documentation.”

A key issue in the near-term deployment of robot units is the ruggedness of available equipment. This report deals primarily with COTS equipment and some devices that are only slightly past the proof-of-concept stage. In that respect, ruggedness is evaluated in terms of the potential for ruggedization. This results in three possible classifications for a component or system: 1) ruggedized (suitable for military use as is), 2) ruggedizable (a clear path for ruggedization exists, using mature technology at reasonable cost), or 3) questionable (fragility exists, and there is no obvious solution at this time). “Questionable” technologies will not be utilized in the proposed robot units.

It is probable that TMR operators will often perform their supervisory tasks within close proximity to a support vehicle. In such cases, it is still important that the operator remain unencumbered and able to react to the local situation, but it opens up possibilities for non-wearable devices that can remain resident on the support vehicle. These devices will be considered here, with appropriate notation of their limitations for man-portable applications.

4.1.2 Input Device Technologies

This section describes a wide range of input device technologies in the context of a TMR OCU. The evaluation of these devices with regard to wearable computers, teleoperation, or teleimmersion has resulted mainly from the experiences at major centers of advanced users.

4.1.2.1 Pose Estimation Sensors

Pose estimation sensors are devices that measure some relationship of one or more of an operator’s appendages to the operator or a reference frame. Typically, this relates to the operators head, hands, or fingers, but in some of the more immersive versions it may include virtually the entire body. In general, the pose estimation sensors used for research in immersive environments are too cumbersome to be practical for a wearable TMR OCU. But some feasible alternatives exist, including head position sensors and gloves, which will be described in the following sections.

Pose estimation sensors tend to be analog in their response characteristics, providing some degree of continuous control. In most of the available literature on robotic teleoperation, there is little mention of using discrete "cursor-key" type control. The MPRS program demonstrated some effective operation of teleoperated (not teleautonomous) robots with keys on a pendant device [Laird 00], but it requires the dedicated use of both hands. This sort of operation, including the adjustment of speed with a rotary potentiometer, can be suitable for dedicated control of a single machine, but is less desirable for TMR.

4.1.2.1.1 Gloves

While human operators are adaptable to a variety of devices using different types of muscular action, the need for continuous control appears to be obvious. The CDG advocates the use of gloves for sending commands. In this context, it is possible to consider discrete commands (through the recognition of specific gestures) or continuous control (through the recognition of degrees of finger extension, for example). In the survey of hardware included here, no consideration is given to gloves which are part of large suits or systems which are clearly impractical for TMR, nor to "toy" devices that are not comparable in performance and durability.

Pioneering virtual reality research was performed with the DataGlove from VPL Research, whose technology has since been purchased by Sun Microsystems. The fiber optic sensors used in these gloves were reported to be fragile and subject to calibration problems, and they are no longer available. Sun is apparently more interested in the virtual reality software developed by VPL Research than their hardware, and none of the original VPL devices are in production. But back in 1987 when they first produced the DataGlove, VPL Research licensed Nissho Electronics as their sole distributor and technical partner in Japan. Nissho apparently still produces their version, the SuperGlove (http://www.tradepia.or.jp/nevc/advanced/vr/vr5-1e.htm), but there is little reported research activity with this device. Supposedly, some of the calibration problems were addressed by including a quick 3-step calibration process in hardware, but unfortunately this requires a bulky control box, adding to the difficulties in using a glove that is not especially flexible and therefore a bit cumbersome. The SuperGlove has a total of ten sensors and provides an RS-232 interface, but requires the control box for the interface.

Figure 19: SuperGlove from Nissho Electronics.

The glove that is generally acknowledged as superior by researchers in the field is the CyberGlove® from Virtual Technologies (http://www.virtex.com/products/hw_products/cyberglove.html). It is available as an 18-sensor model or a 22-sensor model, with

- two bend sensors on each finger (including thumb),
- four abduction (side-to-side finger motion) sensors,
- sensors measuring thumb crossover, palm arch, wrist flexion and wrist abduction, and
- sensors to measure the flexion of the distal joints on the four fingers (22-sensor model only).

The CyberGlove is lightweight and flexible, and should be satisfactory for TMR applications from the standpoint of allowing the operator's hand(s) to still be usable for handling a weapon, radio, etc. The standard interface is an RS-232 serial connection, which is suitable for a variety of potential OCU controllers. The COTS version requires an external enclosure for the interface electronics.

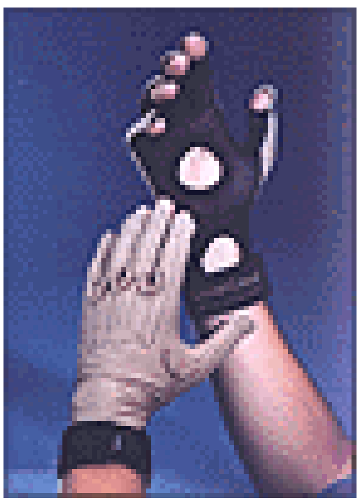

Figure 20: CyberGlove from Virtual Technologies.

A less expensive glove, the Fifth Dimension Technologies (http://www.5dt.com) DataGlove, is available in 5-sensor and 14-sensor configurations, but is bulkier. It is an instrumented glove for finger flexion and extension measurement, and it includes a 3DOF sensor for hand orientation (see below). Earlier versions included a flexor strip for elbow or knee flexion measurement, which may a potentially useful feature. Like the CyberGlove, the DataGlove uses an RS-232 serial interface.

Figure 21: Fifth Dimension Technologies DataGlove with integral orientation sensor.

For the simple detection of finger-to-finger contact, the FakeSpace PINCH^{TM} glove is available (http://www.fakespacelabs.com/products/pinch.html). The PINCH system uses cloth gloves with electrical sensors in each fingertip. It is able to sense contact between any combination of two or more digits by detecting a completed conductive path. As with the other devices that are more commonly used in a virtual reality setting, no effort has yet been made to miniaturize the interface electronics, which are housed in a separate control box.


Figure 22: PINCH system from FakeSpace.

One additional glove is described below in section 4.1.2.5 in the context of muscular motion detection, and gloves for output feedback are described in section 4.1.3.3.1.

Most research with gloves is related to either virtual reality or gesture recognition. It is relatively clear that an "alphabet" of gestures can be trained for a given user and that the system will perform adequately well for the input of some ensemble of discrete commands. This is possible using COTS software that comes with the CyberGlove, for example, and this functionality can be useful in a TMR OCU for menu navigation, discrete command generation, etc. It is also apparent that gloves are useful in virtual reality environments. Bug it is less obvious how well they can be used for continuous control (e.g., teleoperated driving and telemanipulation). Not surprisingly, the relevant research has focused on telemanipulation, mimicking the motion of the hand with a robotic gripper. At the Dextrous Manipulator Laboratory of Stanford (http://www-cdr.stanford.edu/telemanip/) the CyberGlove has been used to control a two-fingered robotic hand that provides force feedback, under a US Navy SBIR program. In this capacity, it has been a success for manipulating objects, but the force feedback mechanism (CyberGrasp^{TM}, discussed below) is impractical for consideration when operating a TMR effector-bot.

Telemanipulation of a more dexterous hand, the UTAH/MIT hand, was done with a more awkward device that has evolved into the commercial Dexterous HandMaster (Exos, Inc.). Like it's predecessor, it is essentially an exoskeleton for the hand and is not practical for field use.

It is apparent that continuous control of a vehicle in a driving mode with glove technology (COTS or otherwise) is an unknown entity and is therefore a risk area. TMR experimentation results from Raytheon are almost certainly the best available information on the use of a glove in controlling a mobile robot. Later, there is some discussion on the use of gestures for controlling a mobile robot, which could possibly be extrapolated to consider gloves as the source of the gesture information.

4.1.2.1.2 Orientation Trackers

Another commonly-used device in virtual reality are orientation trackers that estimate the roll, pitch, and yaw of an operator appendage, usually the head or hand/wrist. In TMR applications, this probably has more value in the context the head motion, since it is best not to constrain the hand orientation as a means of input.

The CyberTrack II (Figure 23) is similar to the the pitch/roll sensor found on the DataGlove and is also produced by Fifth Dimension Technologies, except that it incorporates a magnetic compass for yaw output as well. It is inexpensive and provides stated accuracies of +/- 2 degrees, although this must surely be degraded for the magnetic compass under most circumstances.

Figure 23: CyberTrack II.

Ascension (http://www.ascension-tech.com/) also manufactures an orientation sensor, the 3D-BIRD, shown in Figure 24. It has no external electronics unit and plugs directly into an RS-232 port. Like the CyberTrack, it is targeted for for head-tracking applications in which one needs to look around virtual environments and simulated worlds. 3D-BIRD makes up to 160 measurements per second with a latency of about 15 msec, so it is suitable for real-time tracking. Angular accuracy is given as 2.5 degrees static and 4 degrees dynamic. Its dimensions are 1.34" x 1.08" x 1.20" (3.4cm x 2.74cm x 3.05cm), and it weighs only 1.2 oz.

Figure 24: 3D-BIRD orientation tracker.

4.1.2.1.3 Direct-contact devices

The CDG argues against using any input device that requires the dedicated use of the operator's hands, since they should be free to use a weapon, radio, or other device that may be needed to deal with other situations as they arise. In the strictest interpretation, this would preclude the use of what we here call *direct-contact devices* (of the general "joystick" class). But for obvious reasons related to ease of use, most interfaces for the direct control of manipulators or mobile robots in a visual servoing mode include some means of physically directing the machine with intuitive motions. This is usually implemented with devices such as 3D mice, joysticks, styli, steering wheels, and custom devices [Hong 99, Fong 00, Kawabata 99]. And while visual servoing by a human operator is an undesirable mode of operation from the standpoint of a single operator maintaining control of several robots simultaneously, it must still be accepted as a necessary evil in isolated (hopefully) circumstances.

Consequently, it is incumbent on the OCU designer to consider if there is some way to take advantage of this more natural means of teleoperating a robot without impairing the operator's ability to **immediately** have both hands free as the situation requires. We propose here that there are, in fact, methods for achieving this. The key elements of this approach to using direct-contact devices in TMR applications include:

- Availability of small, low-profile devices,
- Body ("sewn-on") mounting of the device in an unobtrusive, yet accessible, location,
- Incorporation of a dead-man switch on the device to provide immediate context switching to autonomous operation when the operator must interrupt teleoperation, and
- Behavioral software support for the dead-man switch.

The last two elements (related to the dead-man switch) are actually desirable for any means of teleoperating a TMR robot, not just the proposed direct-contact approach. For example, even if it were possible to teleoperate a robot by brain waves only, there must still be some consideration given to detecting when the operator is unable to continue this mode of operation because of distracting influences.

A widely used device in virtual reality research and CAD is the Spaceball, currently produced by Labtec, which in fact claims that it is the “most widely used 3D motion controller in the automotive, aeronautic, and consumer design industries worldwide.” It allows intuitive interaction with small forces and limited motion of a ball suspended over a base platorm, as shown in Figure 25. Although this particular implementation is larger than desired for TMR usage, there are no significant difficulties in producing a smaller version. It supposedly is driftless, which eliminates the need for periodic calibration to zero out biases that may be interpreted as robot commands.

Figure 25: SpaceBall 3003 FLX from Labtec.

Logitech manufactures a line of similar devices, including the SpaceMouse XT (Figure 26a) and CyberPuck (Figure 26b). These devices (http://www.logicad3d.com/products/products.html) provide motion control in up to six degrees of freedom simultaneously using a disc-shaped device, with a lower profile than that of the SpaceBall. The sensitivity is adjustable, with up to 600 levels. The CyberPuck lacks the user-programmable buttons of the SpaceMouse, which could be useful as part of a minimalist user interface, but may be difficult to package in a wearable configuration. No calibration is necessary for these devices, and they support either RS-232 or USB connections. They also require no separate power input, drawing power instead from the data connection.

Figure 26: a) Magellan/SPACE MOUSE "Plus XT" (188 x 120 x 44 mm and 720 grams) and b) Cyberpuck (140 x 140 x 45 mm and 510 grams).

A significantly different approach is taken by Digital Image Design, Inc. with their Cricket (http://www.didi.com/www/areas/products/cricket/). The Cricket (Figure 27) is a 3D input device, specifically tuned to work in non-immersive desktop Virtual Reality environments. It provides 6DOF spatial input along with two conveniently located buttons for user-defined functions. The buttons are pressure sensitive, and the thumb button (on the upper surface of the handle) acts as a “flat joystick,” sensing motion in three dimensions. Perhaps most interesting is the incorporation of vibration output as a means of providing tactile feedback through changes in amplitude, frequency, and waveform. Problems with the Cricket include availability (Digital Image Design appears to only recently have begun considering production of the concept), and tracking technology (it was designed to work in a virtual environment laboratory with external support). Nevertheless, it is interesting conceptually and provides a bridge to the next section, which considers tracking systems.

Figure 27: Cricket.

4.1.2.1.4 External observation/tracking systems

At first glance, it would seem impractical to consider the field deployment of systems that have been developed for the recognition of body position and gestures in controlled environments by observing the user with external cameras or other sensors. But it may be reasonable to mount support equipment in the rear opening of a HMMWV or other vehicle. Such devices have been shown to be useful for gesture recognition in remote environments [Chien 98].

The Polhemus FASTRAK system (http://www.polhemus.com/ftrakds.htm) is based on the creation of magnetic fields by a stationary transmitter, which are in turn sensed by a receiver mounted on the user, with both the receiver and transmitter connected to a control unit by cable. At distances as large as 30 feet, it accurately computes the position and orientation the receiver as it moves through space in real time with only 4 msec latency. It can be used with multiple receivers, sacrificing only the position report rate. The computer interface is high-speed RS-232 interface (up to 115.2K baud) or an optional IEEE-488 interface at up to 100K bytes/sec. It is not necessary to maintain line of sight.

Figure 28: Polhemus FASTRAK system.

The Flock of Birds system from Ascension (http://www.ascension-tech.com/products/flockofbirds/flockofbirds.htm) is similar (Figure 29), and was originally developed for military applications. Each Flock receiver makes up to 144 position measurements each second, with latency of approximately 15 msec. The DC field technology is supposedly more robust in harsh environments. A single transmitter/controller can work with up to four units, as in the case of four robot operators each equipped with tracker mounted on their head or hand, all operating in the vicinity (approximately 10 ft.) of a single support vehicle. The host computer interface is RS-232, with selectable baud rates up to 115 kBaud. Static position accuracy is given as 0.07" (1.8mm) RMS, and static orientation accuracy is given as 0.5° RMS. The receiver is less than 1 cubic inch.

Figure 29: Ascension Technology Flock of Birds system.

Systems such as these would likely be used best to convey gestures. The use of gestures for mobile robot operation has been investigated with visually-detected gestures, which is a more difficult recognition problem, but conceptually similar. Fong et al. found that such gestures could be used to teleoperate a mobile robot (Figure 30), but it was not as easy as would be expected based upon human experience with following such gestures [Fong 00]. They concluded that it would probably be necessary to add other inputs to disambiguate visual gestures.

Figure 30: The virtual joystick mode of the *GestureDriver*, showing right, left, forward reverse, and stop commands [Fong 00].

4.1.2.2 Keyboards

Any keyboard device is a severe compromise to the hands-free requirement of TMR. During operation of the OCU with robots, input of textual and numeric data must be avoided, and this should be a key concept behind the development of the software that implements the user interface. During breaks from active robotic control, it would be advantageous to have the capability of annotating logged data within the OCU, and perhaps performing other functions that would be much easier with a full keyboard.

One possibility would simply to support the connection of a standard PC keyboard when the user is at a command post or some other location where equipment is available. If possible, it would be preferable to have built-in capability for those instances where the operator cannot return to such a facility between periods of robot operation. A novel approach is a flexible keyboard within the operator's uniform, such as the embroidered approach shown in [Pentland00] (Figure 31). COTS possibilities include "chord keyboards" like the Twiddler (Figure 32), handheld touch-typing keyboards like the AlphaGrip (Figure 33), and small "normal" keyboards like those from Electrone (Figure 34).

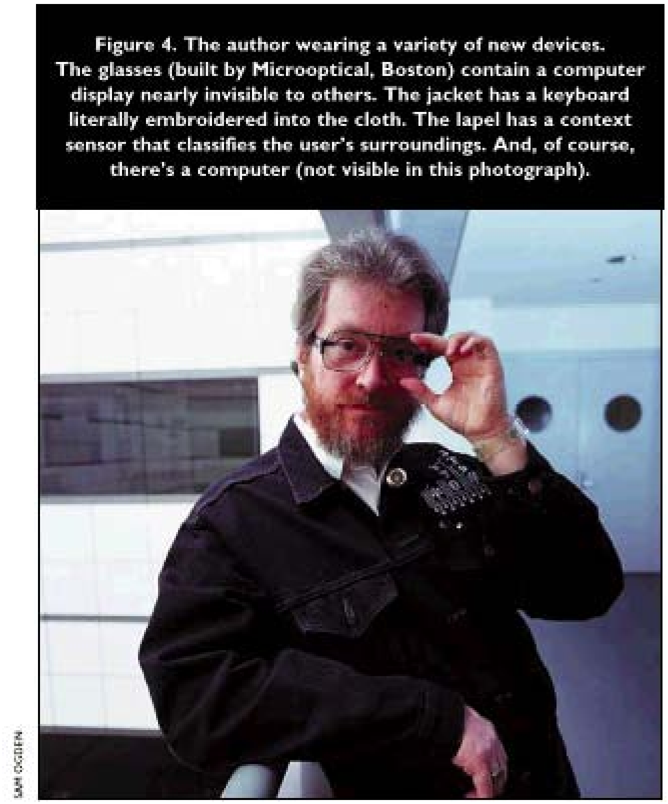

Figure 31: Embroidered keyboard concept (and Microoptical display), from [Pent-

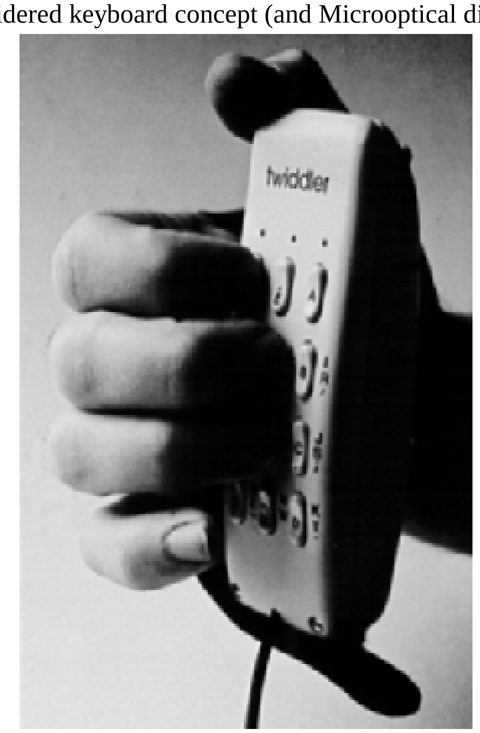

Figure 32: The Twiddler one-hand keyboard.

Figure 33: AlphaGrip

Figure 34: Electrone Model 9001 (10.25 inches wide, about 60% of a standard keyboard).

4.1.2.3 Speech Recognition

Speech recognition input is undesirable in a TMR OCU because of background noise, changes in voice characteristics under stress, and the general problems associated with recognition technology. One such problem is that there is a tradeoff between recognition reliability and the degree of speaker independence. And without speaker independence, there is the problem of training the voice recognition software in the field for a specific user. This is unfortunate, because there is evidence that voice control is superior to manual control of devices such as pan/tilt camera platforms [Draper 87], but speech recognition is still not a hurdle that is worthwhile for TMR to take on.

Motorola has added a voice control system as a technology upgrade to a variant of the Land Warrior system, the Force XXI Land Warrior (http://www.mot.com/GSS/SSTG/ISD/ws/vcs.html). In this concept, voice is used for hands-free control of radios and the display. Although targeted at high-noise background environments, there is still valid concern this sort of technology is not yet suitable for a TMR OCU. A "wait-and-see" stance is probably the most appropriate course to take – by using some Land Warrior components (computer and radios), TMR could leverage development in those areas and have the optional use of the voice control system, if it proves to be reliable, without becoming dependent on the technology.

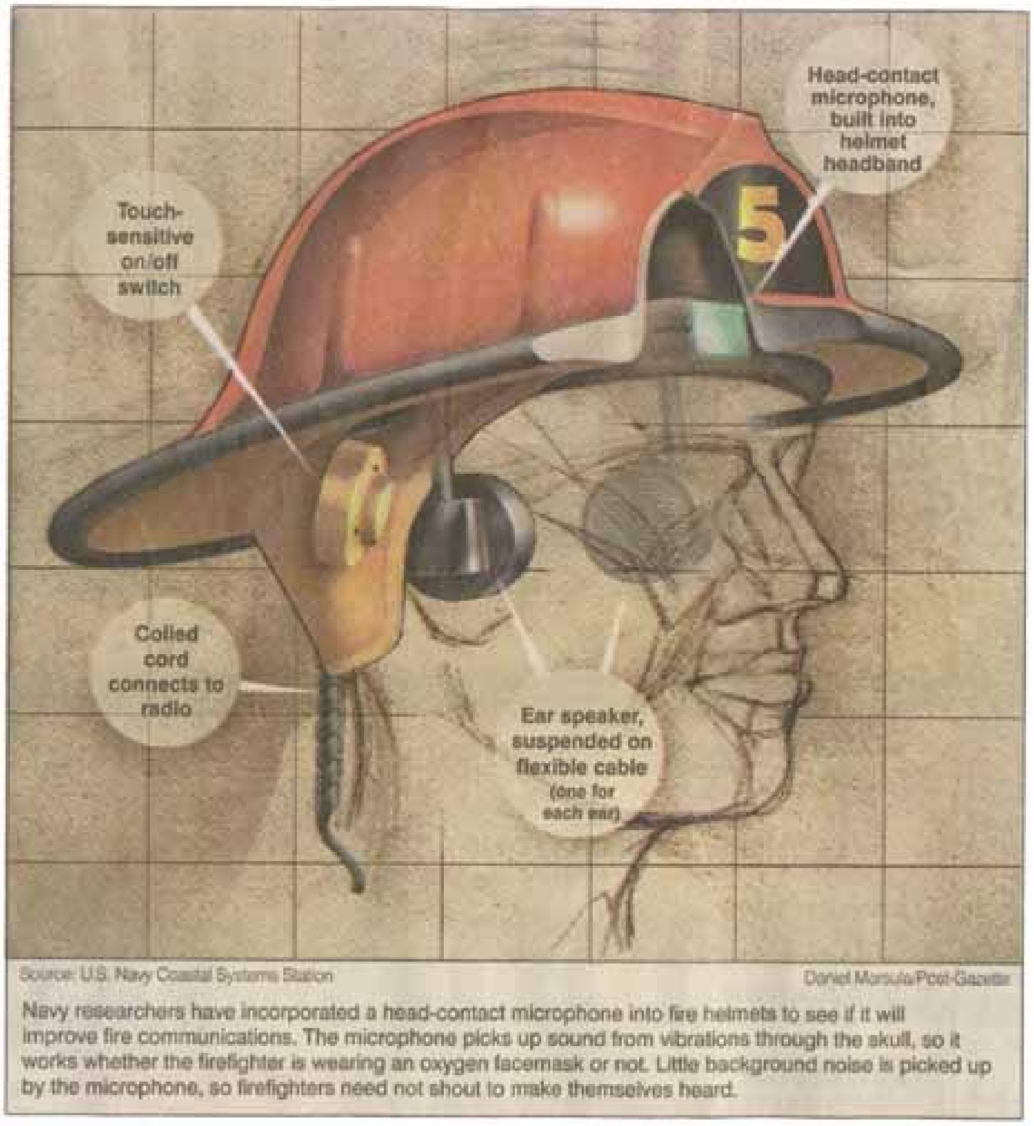

Figure 35: Head-contact microphone modified for firefighter helmet use.

Independently of whether or not speech is used for direct operator input, it may be advantageous for the OCU to include a complete audio system that can be used either with the computer or with wireless communications equipment, multiplexing the two channels and providing the best possible performance in a noisy environment. The output speakers of such a system will be addressed later. A candidate input technology (http://www.mtac.pitt.edu/WWW/html/pg_article.html, http://www.stac.ufl.edu/flc/Head%20Microphone.html, developed originally for Navy SEALS at the Coastal Systems Station of the Naval Surface Warfare Center, utilizes direct conduction of sound from the operator to the microphone through the skull, thus eliminating the need for holding a microphone in a particular place and simultaneously reducing background noise considerably. This technology is being commercialized by Sensory Devices, Inc. for use in firefighter helmets (Figure 35).

4.1.2.4 Eye Trackers

Discussions at Oak Ridge National Laboratory have identified the importance of assessing the operator’s attention state. Eye trackers are one possible means of achieving this, and they also provide the additional capability of acting as pointing devices for the user. But the physical size of devices such as the EyeGaze (LC Technologies, Inc.) and the helmet mounted iView (SensoMotoric Instruments) makes them impractical at this time, given the limited benefit of having them as part of the TMR OCU, as shown in Figure 36. Experimental platforms like the visor used at the University of Pennsylvania‘s Head-Mounted Eyetracking Lab (http://www.cis.upenn.edu/~ircs/Trueswellabs/HeadmountedET.html) do not address the portability factor, either.

Figure 36: The portable version of the EyeGaze system (left) and the iView helmet mounted system (right) are not suitable for a mobile warfighter.

4.1.2.5 Other

Ultimately, an effective means of controlling a robot may be the use of brainwaves, muscular electric signals (myography) or small, subtle movements of muscles such as those in the face. Efforts in this area include those of MindTel and Sandia Laboratories.

At MindTel, under the direction of David Warner, a series of TNG transducers (Figure 37) have been developed to flexibly interface a variety of devices to computers, with a primary emphasis on aids for the disabled. TNG-1 was the first of these, and was targeted at direct input of EMG (electromyographic) signals from facial or other muscles (http://www.pulsar.org/2k/technology/coretech.html). Perhaps because of limited success with EMG sensing, subsequent TNGs have relied on more standard sensors (e.g., resistive) that are mounted in some fashion where the user can manipulate them, even with only limited muscular control.

The Sandia research [Amai 00] has attempted to actually control a small mobile robot (a Mini-RATLER™) using a commercially-available device, the CyberLink™ MindMouse. While the Sandia team was able to construct a reasonable mapping of detectable signals to robot control functions, there are clear obstacles to using this approach in the foreseeable future. Brain waves, in particular, are extremely difficult to control under stress or even in the face of minor distractions. Facial muscular movements and the resulting signals are easier to control, but difficult to distinguish enough for any fine level of control. Without improved technology in this area, robot control is likely to consist primarily of overt (almost discrete) commands generated by general muscular motion within a fairly large region of the face (e.g., movement almost anywhere in the jaw/neck region could be interpreted as a single discrete command). This corresponds in many respects with commanding a robot with cursor keys, and as noted earlier, discrete "cursor-key" approaches to robot control are not particularly promising.

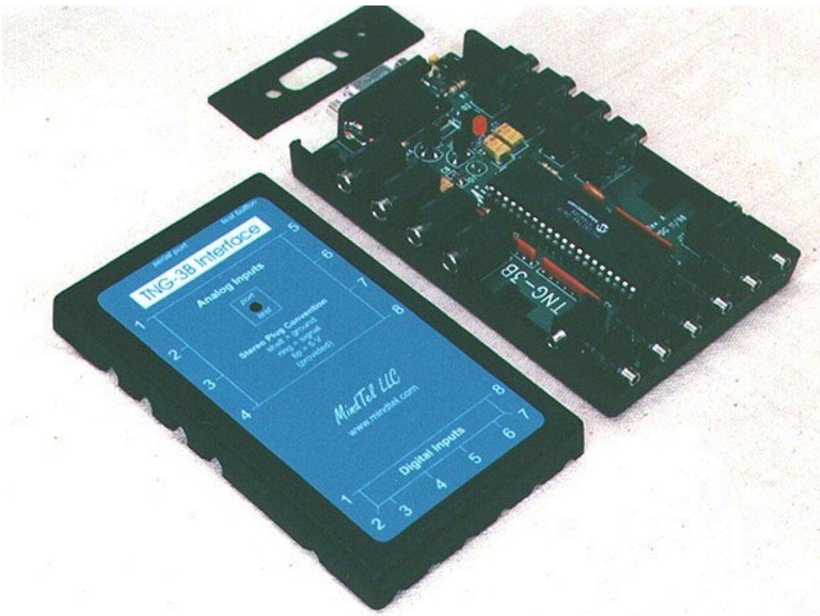

Figure 37: TNG-3B, the most recent sensor interface from MindTel.

[Robinson 98] also describes some of the limitations of electromyography as a means of robotic teleoperation. Although a potential site on the lower arm is identified as to provide a range of specified control signals, they also recognize practical difficulties with EMG control.

Given that a TMR OCU may want to input from various muscles and would probably take the more reliable course of detecting movement directly rather than by means of EMG, it may be useful to consider resistive touch sensors such as those from Infusion Systems (http://www.Infusionsystems.com/). These devices are targeted at musicians for the control of instruments, lighting, and effects during performance. The basic Touch Sensor is a 1.7"x1.7" touch pad, with a 1-2 msec response time and capable of sensing pressure over a range of 100 grams to 10 kg. With identical specifications, mini- and micro- versions are available as 0.5" and 0.2" diameter circles, respectively. A 24" x 0.5" strip, trimmable to user requirements, is also available.

Six of these touch sensors are included in the Infusion Systems TouchGlove, designed as a controller for drum machines. One sensor is mounted in each fingertip, and one is mounted in the palm. Since the TMR operators hands are already in demand, it may be more appropriate to consider the use touch/pressure sensors elsewhere, such as in the shoes where they can be activated by toe movements.

Finally, we note that relative to operator attention and perhaps to operator stress level, it may be useful to assess certain physiological conditions, such as heart rate, breathing rate, and galvanic skin response. This is a lower priority with respect to initial deployment and will not be considered in detail at this time. Emerging technologies such as the "Smart Shirt" (http://vishwa.tfe.gatech.edu/gtwm/gtwm.html) provide possibilities for nonobtrusive monitoring of vital signs, utilizing optical and conductive fibers woven inside the garment.

4.1.3 Output Device Technologies

There is tendency to rely primarily upon visual output to convey information to any remote operator of autonomous or teleoperated systems, mainly because of the high information bandwidth of visual displays. The importance of non-visual feedback is stated in the context of UAVs in AFRL research [Draper 00], in which it is noted that detecting turbulence visually is probably too slow or too unreliable for effective and safe control. This is not to say that non-visual feedback cannot be conveyed by visual means, and the AFRL recommendations in fact include the display of other data (e.g., orientation and attitude) by HUD techniques. The following sections first consider the available technologies for non-distracting visual displays and then other means of providing operator feedback.

4.1.3.1 Displays

Prior efforts have shown that real-time video is the single mechanism most relied upon for feedback when it is necessary to take control of a robot, either one designed for dedicated teleoperation [Draper 95, Hainsworth 00, Wettergreen 97, Ballou 00, Laird 00, Power 00] or for teleautonomous (telereflexive) operation [Bares 97, Fong 00, Gilbreath 00]. For this application alone, if nothing else, it is necessary to survey and evaluate displays that may be feasible for field operation in TMR scenarios. Based on this, and in conjunction with other TMR requirements, we can formulate three principles that can guide the survey of video display technology:

1. It is necessary, at least in isolated instances, to display full video frames (camera views, maps, etc.),
2. It is desirable, MOST of the time, to display augmented reality data in the least obtrusive manner possible (still allowing the operator to "see through" the data), and
3. At some intermediate level of frequency, it MAY be necessary to display GUI interfaces, such as menus and dialog boxes.

The need to satisfy these constraints with a heads-up display, minimizing the inconvenience of managing two separate visual inputs at once, has been noted by various researchers, including [Starner 95].

One example of an impractical and distracting display is the early Land Warrior prototype shown in Figure 38. Although it can be swung out of the way (which may be suitable for intermittent use by soldiers in general), this is not desirable for a soldier interacting almost constantly with a group of robots while still maintaining awareness of his surroundings. And while one could argue that such a display is transparent in the sense that one eye still can see beyond it, experience indicates that this is difficult in practice.

Figure 38: Early Land Warrior helmet mounted display that clearly exhibits some of the features to be avoided.

Newer developments in wearable display technology are less cumbersome and provide some degree of transparency (and admittedly are less ruggedized). But even casual observers can see the problem. At a gathering of wearable computer enthusiasts and vendors, CNN reporter Ann Kellan observes “One eye on the monitor, one eye on the real world, may be natural for these techies, but it takes getting used to,” noting that it takes a conscious effort to pay attention to reality.

4.1.3.1.1 Head Mounted Displays

Head mounted displays have been used in military applications for many years already, but suffer from criticisms of awkwardness, visual discomfort, fragility, and vision obstruction. As long ago as 1995, however, Starner et al. [Starner 95] argued that such displays are victims of several misconceptions. First, they note that focus depth is not a problem, since many units have adjustable focus depth, and this can be set to provide a level of comfort exceeding typical fixed display monitors. There is an implicit assumption here, arguably not valid for TMR, that the user will have a somewhat constant focus depth in the real world. Supposedly this assumption holds true for many everyday situations, such as walking down the street, sitting in a meeting, etc.

Second, Starner et al. note that these displays do not act as an “eye patch,” with the display image possibly overriding the real world, and instead allow most users to easily merge the images from both eyes. They do acknowledge, however, that the greater the degree of difference between display content and real-world content, the more difficult this may be. And finally, they argue that there is no significant adaptation period when taking these displays on and off.

Improvements in head mounted displays (HMDs) have resulted in those such as the Land Warrior HMD, developed by Kaiser Electronics, as shown in Figure 39. Devices such as this are rugged enough for military use, and they attempt to avoid the distraction issue by allowing them to be moved aside completely or at least out of the direct line of sight, as in Figure 39(b). Comprised of an 800 x 600 pixel resolution LCD, the unit provides a 40-degree FOV.

Initial experiences with these displays in warfighting experiments are encouraging. Also, the use of an HMD in the MPRS (Man Portable Robotic System) seemed to cause no difficulties during exercises in which robots were teleoperated in tunnels, aside from the reported desire of secondary operators to also see the video and some difficulties in bright sunlight [Laird 00, Bruch 00].

Figure 39: Land Warrior HMD developed by Kaiser Electronics. (a) side profile (b) in use while aiming a weapon.

Alternatives to the rugged Land Warrior HMD exist providing other attractive characteristics. TekGear (www.tekgear.ca) is producing the M2, a high end portable viewing device targeted at mission critical display. The integral LCD provides 800 x 600 resolution in full color. The base model shown in Figure 40 is intended to be a universal form factor and can be modified to OEM configurations (e.g., helmet-mounted).

Figure 40: TekGear M2. a) complete headset version, and b) details of LCD display.

TekGear M2 Specifications	
Field of View	22° Horizontal, 16.6° Vertical
Optics	High Efficiency, See Through
Video Resolution	480,000 pixels (800 x 600)
Pixel Pitch	12 Microns
Input Signal	24 bit Digital RGB GVIF interface
Video Refresh Rate	60Hz
Contrast	50:1
Operating Temperature	0 to 50 degC
Storage Temperature	-10 to +80 degC
Shock and Vibration	Industrial Environment
Total Weight	210g
Controls	Brightness, Image Flip
Power Consumption	Under 2.0W
Input Voltage	5V DC

MicroOptical Corporation (http://www.microopticalcorp.com/) has developed an "Invisible Monitor" technology that can be clipped on as in Figure 41(a) or integrated into eyeglasses as in Figure 41(b). The C-1 clip-on field test kit contains one Invisible Monitor Clip-on information display with "see-around" display optics, articulating mounting arm, and VGA and NTSC conversion electronics. The housing of the conversion electronics is separated from the display by a 4-foot cable. The Integrated EyeGlasses contain simlar optics, cabling, and conversion electronics.

Figure 41: MicroOptical C-1 Clip-On display (a) and integrated eyeglasses (b).

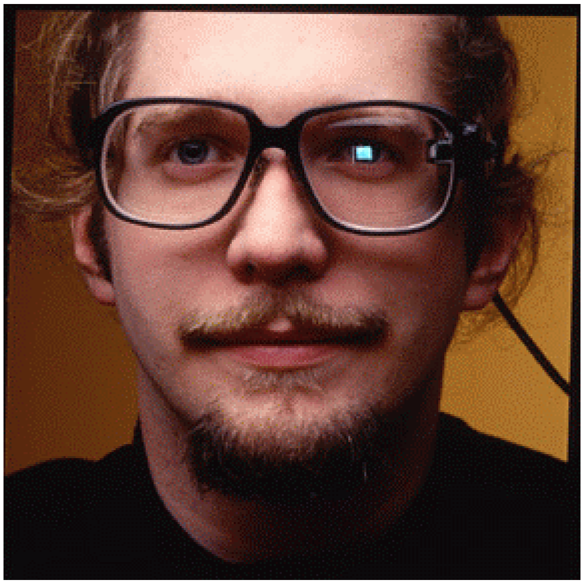

Figure 42: Thad Starner from Georgia Tech wearing the MicroOptical glasses.

MicroOptical Specifications	
Display Format	320 x 240, 16-Bit Color (640x480 under development)
Refresh Rate	60 Hz
Field of View	Approximately 11 degrees horizontal
Optics	Left eye version is available now, right eye versions by special order
Focus Range	Pre-set to 1 meter (other distances available upon request)
Eyeglass Frame Size	Clip-on fits most wire frame glasses. Plano glasses supplied
Video Input	Standard VGA, female DB-15 connector and standard NTSC, RCA plug
Power Requirements	9 V, 100 mW (display and backlight). 9 V, 2.9 W (VGA interface). 9 V, 1.9 W (NTSC interface) 4.5 V, 300mW (RS170).
Operating Temperature	32 degrees to 104 degrees F (0 degrees to 40 degrees C)
Storage Temperature	-4 degrees to 104 degrees F (-20 degrees to 40 degrees C)
Head-Supported Weight	Clip-on: 33 grams Integrated EyeGlasses: 62 grams

4.1.3.1.2 Retinal Displays

Even the best HMD implementations have several problems, including limited field of view (without sacrificing real field of view), size, weight, resolution, brightness, lack of true transparency, and power consumption. A promising approach to solving these problems of traditional HMDs is the virtual retinal display (VRD). Invented at the HIT lab of the University of Washington (http://www.hitl.washington.edu/research/vrd/) in 1991, VRDs do not require the size and energy associated with actually forming an image on a screen, instead directly scanning the image onto the retina in the most efficient way possible. The technology is being commercialized by Microvision (http://www.mvis.com/) as the Retinal Scanning Display (RSD). In keeping with the intent herein of providing an interface more akin to augmented reality, the RSD is targeted at applications in which it is necessary to display an image that is overlaid and does not block a user's view. Initially, this is monochrome, but with technology improvements it will be possible to provide full-color displays. According to a recent trade publication article, "adding green and blue is only a matter of time, especially since funding from the commercial and military industries is ample, and the Army, Navy and Air Force are all investigating the RSD for use in next-generation AR HMD systems" [Ciufo 00].

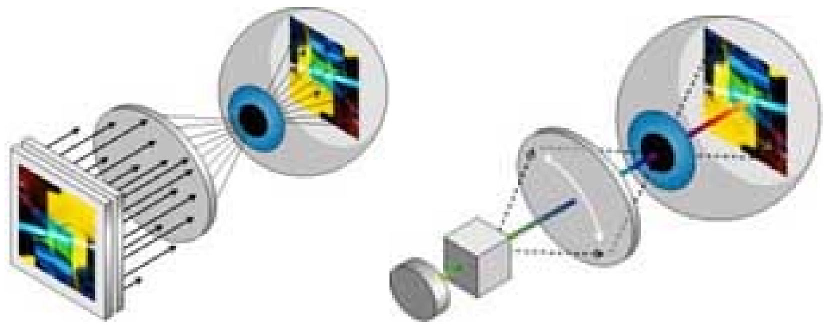

Figure 43: Viewing a planar image (a) vs. the Retinal Scanning Display approach (b).

RSD relies upon low-intensity lasers and microelectromechanical (MEM) devices to scan an image directly onto the retina of the eye, as shown in Figure 43. This completely eliminates the need for an image display such as an LCD, as well as the optics required to allow the user to focus on the close device. Since the image characteristics can be controlled directly by a host computer, it is possible to vary the size or apparent distance as needed. Although initial versions, like that shown in Figure 44, rival other HMDs in physical size, it should be possible to immediately reap the benefits of a sharp, clear, transparent display.

Figure 44: Nomad prototype RSD headgear from Microvision.

Retinal Scanning Display Specifications	
Resolution	VGA (640 X 400 pixels) SVGA (800 X 600 pixels*)
Luminance	1-480 FL at the eye (500+ FL*)
Grayscale	32 user discernable gray shades
Dimming Ratio	1000:1
Field of View:	30 degrees horizontal, 22 degrees vertical, approximately equivalent to a 19" Monitor
Display Color:	Monochrome red (635 nm)
Refresh rate	60 Hertz
Interface	SVGA*, VGA, NTSC*, PAL*
HMD weight	< 1.5 lb. (657g)
Power	12 VDC
	* in development, available mid 2001

For all of its promise, RSD technology is not without its risks. In addition to the fact that commercial deliveries have not begun, and some of the specifications pertain to upcoming improvements, other possible problems include difficulty in maintaining proper alignment of the exit pupil with the eye, cost reduction, and ruggedization.

4.1.3.1.3 Omnidirectional camera imagery

TMR has accepted the value of omnidirectional (actually, *panospheric* is probably a better description) camera imagery for typical missions. Development of the OmniCam at Columbia University (http://www.cs.columbia.edu/CAVE/omnicam/) resulted in the licensing of the technology to RemoteReality (http://www.remotereality.com), formerly CycloVision Technologies. Although other omnidirectional approaches had been implemented, this was the first to provide a *single effective viewpoint* [Baker98]. Such a viewpoint preserves perspective in all directions, and thus makes it possible to choose a direction to look at any time and see it from exactly the same point in space. In robotic applications, prior work with NASA's Nomad [Wettergreen 97] and the Ames Marsokhod Rover [Christian 97] had established the usefulness of this data for a variety of applications including teleoperation, exploration, reconnaissance, or searching.

From the standpoint of OCU design, the important issue is the presentation and use of omnidirectional imagery. Ongoing research at the University of Pennsylvania has addressed this within the context of TMR and similar applications (http://www.cis.upenn.edu/~kostas/omnigrasp.html). Some of the most relevant work on utilization of omnidirectional images for teleoperation has been done at Lehigh University (http://www.eecs.lehigh.edu/~tboult/remote-reality.html). Vehicles, including the one shown in Figure 45, have been teleoperated by presenting users with interfaces combining multiple unwarped images [Power 00]. Usability studies have indicated some disorientation problems, and not surprisingly the forward view is most suitable for normal driving [Boult 00].

Figure 45: A vehicle built at Lehigh for teleoperation with omnidirectional imagery.

4.1.3.2 Audio

The operator must remain in voice contact with other military personnel, and it is straight-forward to allow any OCU audio outputs to reach the operator through a shared output device. Intuitively, it illogical to use an earphone or headphone, since this would mask local sounds that may be important cues of impending danger to the operator. Consequently, direct auditory conduction through facial bones appears to be a more appealing prospect. But although studies have shown that bone-conduction speech recognition thresholds are similar to normal air-channel thresholds [Edgerton 77], and even though noise-masking characteristics are also similar in the two mechanisms [Robinson 82], there are few COTS products that directly use conduction, aside from hearing aids. According to the Military Audiology Association, research continues in this area (http://www.militaryaudiology.org/newsletter02/aac.html), but little published data is available.

4.1.3.3 Tactile and Haptic devices

One of the most widely adopted technologies for tactile/force feedback is the TouchSense technology available from Immersion (http://www.immersion.com). This has been incorporated into a variety of entertainment products (mostly joysticks, steering wheels, or variants thereof) and several medical products. Medical applications include training, such as the simulation of the sensation of insertion of a needle, catheter, endoscope, or other medical device into a human subject (HT Medical). Analogous sensations for a robot operator could include the "skin resistance" as the robot attempts to penetrate a door or other opening, the "pierce-and-relax" sensation as the robot succeeds, and the "steady drag" as the robot moves down a hall or other close-quarters situation.

SPAWAR researchers have uses a vibrating pager-like device inside a pendant controller to directly provide velocity feedback [Gilbreath 00]. Hong, et al. demonstrated force feedback to teleoperate a mobile robot with a joystick over both level ground and stairs [Hong1999]. The reflected force corresponded to the potential field of nearby obstacles in the level ground case and to the impulse force of climbing when on stairs.

Fong et al. [Fong 00] have used the Delta Haptic Device (Figure 46),device developed at the Ecole Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology) to provide feedback during teleoperation of a small Koala Robot (Figure 47). The robot is equipped with short-range proximity sensors, and the *HapticDriver* interface transmits to the operator a force proportional to the closeness of detected obstacles. Trials with test subjects (complete novices at a trade show) showed that the force feedback often made the difference in being able to drive through a maze without collisions. It was determined to be an "effective interface for navigating cluttered environments and for performing docking maneuvers." Unfortunately, the Delta Haptic Device is impractical for field deployment, and it is not obvious how a portable device could be constructed to convey that degree of force information.

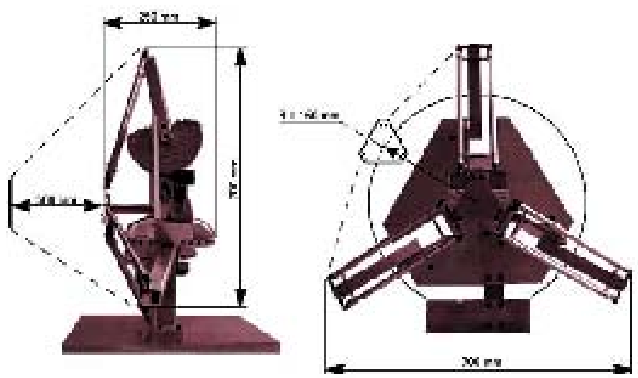

Figure 46: The Delta Haptic Device.

The *HapticDriver* currently uses only 2D force information, but the developers are considering the possibility of mapping wheel torques, 3D orientation, or accelerations into 3D forces, perhaps allowing operator perception of driving across uneven terrain or through minor obstructions, humps, etc.

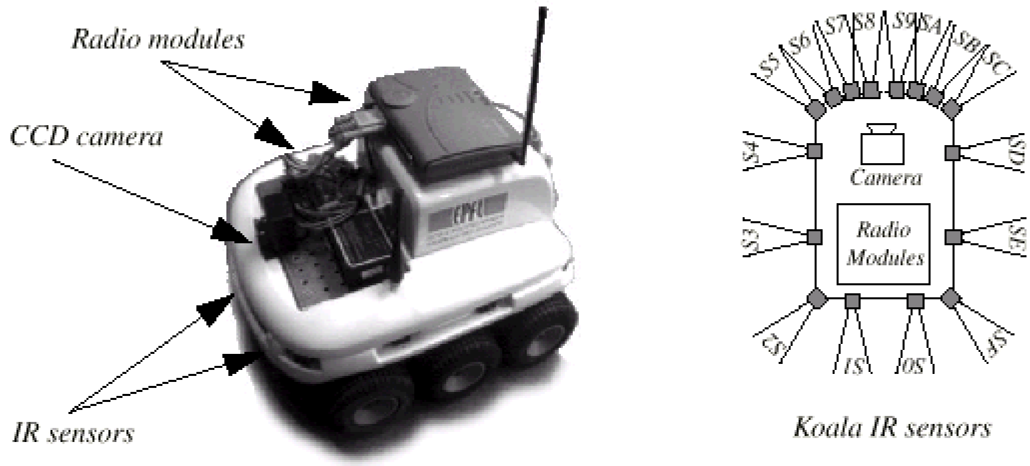

Figure 47: Koala robot used for teleoperation with haptic interface.

4.1.3.3.1 Gloves for Haptic and Tactile Feedback

True haptic feedback is not an option for a man-portable configuration at this time. Devices like the Delta Haptic Device described above are far too cumbersome. The least objectionable implementation is the CyberGrasp, from Virtual Technologies, the maker of the CyberGlove described earlier (http://www.virtex.com). Designed to be used in conjunction with the 22-sensor version of the CyberGlove, the CyberGrasp is a massive cable driven mechanism, clearly not practical for a TMR OCU. Furthermore, it requires a 6DOF sensor like the Flock of Birds or Polhemus systems discussed earlier.

Of greater interest, and also manufactured by Virtual Technologies, is the CyberTouch option for the CyberGlove. This introduces small vibrotactile stimulators into each finger and on the palm of the glove. The stimulators are individually addressable and support both pulsed and sustained vibration. According to Virtual Technologies, it is possible to achieve the perception of touching a solid object, which could of course be useful if using a glove to teleoperate a robot. Even aside from such a capability, the vibrotactile stimulators provide a means of signaling the operator without requiring visual attention. This could be useful both during continuous control of a robot (to convey remote sensory information or robot status) or simply to get the operator's attention as an "interrupt." Specifications of the CyberGlove include a vibrational frequency range of 0-125 Hz, a vibrational amplitude of 1 N peak-to-peak @125 Hz, and a weight of 5 oz.

4.1.4 Support Technologies

4.1.4.1 Cabling and Communication

The larger issues of reliable communication between robots, warfighters, and command posts will not be addressed here, and in fact are the subject of other programs with much wider scope than robotics. For the purposes of near-term demonstrations, the working assumption must be that wireless communication between agents (robotic or human) will be much as it has been in the 2000 TMR demonstration, a mixture of wireless point-to-point modems and standard WLAN (wireless local area network) technology with add-on equipment to improve performance. To address early deployment of robotic units and the need for improved LPI/LPD performance, this will have to be replaced with emerging military radio technology, possibly from the Land Warrior program or a new "lightweight warrior" ATD (advanced technology demonstration) that could begin in 2000-2001 [Erwin 00].

Of greater interest for the design of a near-term OCU is the interconnection of the devices that are proposed for an individual warfighter. Most of the devices can be interconnected with cables that pass through sewn loops on the uniform, minimizing the possibility of snagging. Wireless Bluetooth technology for peripherals, where available, is certainly a possibility to minimize the use of cables. Because of its short range, it is less of a risk for a deployed system, but should still be used only with caution and after prior testing. Infrared peripherals, using protocols such as IRDA, are generally not desirable because of their requirement that line of sight be strictly maintained.

But since it is necessary to provide cables to supply power to wireless peripherals, it is arguable whether any significant advantage is gained by not using the same cable route to convey signal information. This is especially true of some of the RS-232 serial devices which can be self-powered off of the wired data interface.

4.1.4.2 CPUs

As noted earlier, wearable computing technology is the logical source to ultimately provide COTS components for the heart of the OCU. In the short term, for the sake of ruggedness, there are distinct advantages in considering the Computer/Radio Subsystem (C/RS) of the Land Warrior program, developed by Motorola (http://www.mot.com/GSS/SSTG/ISD/ws/warriorcrs.html). Although more bulky than the sleekest units currently available from vendors like Xybernaut and VIA, the C/RS is still only 3.2 pounds (with radio, frame grabber, and GPS) and provides a variety of interfaces, including

- VGA or RS-170 for Helmet or Hand Held Display with Touch Screen
- Thermal Weapons Sight or Video Camera video input
- Radio Interfaces, 2 internal, 1 external
- 4 Channel Laser Detector
- PCI and ISA Bus for future expansion
- Keyboard/mouse
- 2 ea. RS-232

- Ethernet
- USB

Physical size is 10.6 x 7.0 x 1.7 in. for the computer and 4.5 x 3.0 x 1.5 in for the radio, and is designed to be carried within a backpack frame.

4.1.5 Operator Interface Design and Integrated Augmented Reality

The importance of an augmented reality (AR) model to describe the conveyance of remote information in a TMR OCU has already been discussed. In this section, we elaborate on some notional concepts for the actual implementation of the operator interface and the incorporation of AR techniques. This is necessary to develop a complete concept of a recommended hardware implementation in the next section.

The nature of the robot status information being displayed in prior efforts to develop OCUs tends to depend on the criticality of the robot (its intrinsic value, relative to the risk in which it is placed) in conjunction with the "cost" of displaying such information. In cases where robots are sent into dangerous situations, such as advance exploration of mines [Hainsworth 00] or space applications [Lane 00a, Wettergreen 97, Christian 97, Nguyen 00] and where multiple large format displays are available, informational displays become very extensive. Since such situations normally fit the "Mission Control Station" model of an OCU, often with multiple operators available to monitor mission status, it is quite understandable to build displays that provide all information that may possibly be useful.

NASA Ames has developed the Virtual Environment Vehicle Interface (http://img.arc.nasa.gov/VEVI/index.html) for the purpose of remotely teleoperating robotic vehicles such as Nomad [Wettergreen 97] and the Ames Marsokhod Rover [Christian 97]. This approach, however, takes the extreme position of immersing the operator in a complex representation of the robot's environment in order to maximize the probability of successful operation, since the robot is extremely valuable, latency is high, and the environment is typically not well known. But given the available bandwidth for display of data, visual or otherwise, sacrifices must inevitably be made in the status information provided by a TMR OCU. It cannot be "designed by committee" to accommodate the wishes of all designers and potential users, as difficult as the decisions may be to defend later with the benefit of hindsight.

Even if the adverse effects (primarily distraction) of a teleimmersive environment could be tolerated, it is interesting to note that some research suggests that it may not even be that effective of an approach for many tasks. In applications involving remote driving and operation of heavy equipment, researchers at the Helsinki University of Technology [Halme 00] discovered that the use of a head tracker with a pointable camera was sometimes helpful in choosing direction in unfamiliar terrain, but not as useful when moving in a specific direction, as when being constrained by walls or tunnels. The use of a HMD in any of these applications was found to be stressful and could cause nausea.

In the context of the MPRS program, SPAWAR researchers also note the taxing nature of teleoperation through onboard video, often accentuated by problems with contrast and lighting [Laird 00]. The results of MPRS tests with military users at Fort Leonard Wood are somewhat limited in their applicability to the primarily autonomous nature of TMR, since most users were uncomfortable with any degree of autonomy in the MPRS systems.

After experiments with Dante II [Bares 97], the following guidelines emerged with respect to the interface design:

> *"Consistent appearance and interaction:* Similar or identical design throughout the interface allows operators to focus on robot actions rather than the mechanics of using the interface.
>
> *"Functional organization:* It is appropriate to embed the functional layout within the interface to avoid operator confusion. The use of operational control contexts pro-vides a unifying and simplifying perspective on human-machine interaction. This approach enabled us to concisely organize the interface so that commands appropriate for a particular type of function are grouped together.
>
> *"Uncluttered layout:* Clean graphical design with qualitative or simple quantitative representations of sensor and state information allows quick assessment of current conditions. Numeric data provides precision and should support graphical features unobtrusively.
>
> *"Simple command generation:* Clear, easy-to-use controls allow efficient, rapid command sequences. Easily modified values and reusable commands are important for reducing operator workload during teleoperation.
>
> *"Visual indication of safeguards:* Different command safeguards are appropriate depending upon the situation and the types of commands being applied. Indicators that clearly reflect active safeguards reduce operator misconceptions and error." [Bares 97]

Mobile robot operator interfaces, whether for teleoperation or supervisory control, and regardless of the operational domain (air, ground, underwater, space) historically have several major modes. While there are differences in nomenclature and in implementation, it is only a minor oversimplification to say that most prior work advocates the use of at least four primary modes:

- Sensor/status mode,
- Command mode,
- Robot perspective mode, and
- Map mode.

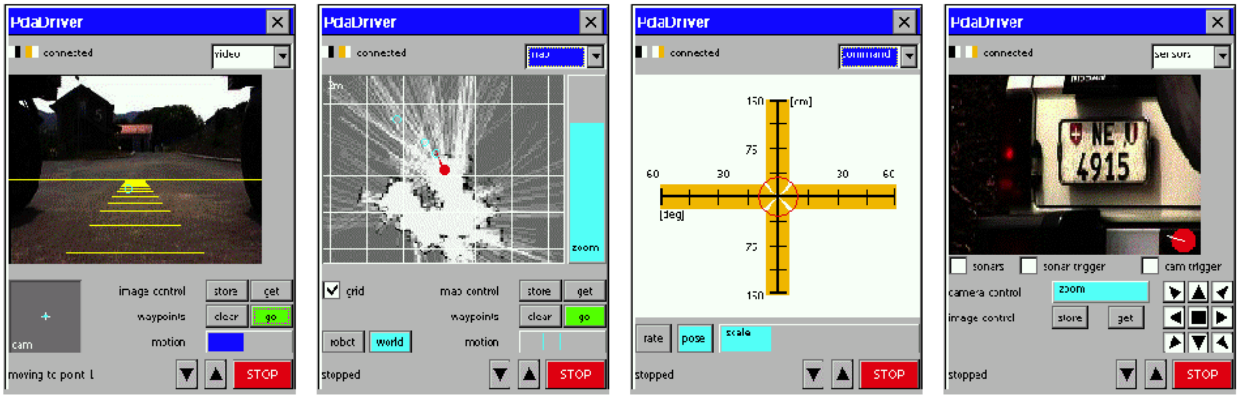

Figure 48: Multimodal display of the PdaDriver, showing their "video," "map," "command," and "sensor" modes [Fong 00].

Archetypal examples of multimodal interfaces for teleoperation of mobile robots include the Virtual Dashboard of the NASA Nomad [Wettergreen 97], the PdaDriver [Fong 00], and TMR concepts [Bay 00]. Depending on display constraints, some were implemented as multiple panels on a large display, and some were implemented as alternate user displays. Also, lessons learned from the Dante II mission to an Alaskan volcano [Bares 97] included the importance of graphical displays of telemetry in a multi-page format. There is also demonstrated value in the use of attitude and heading reference displays similar to those used in heads-up displays of aircraft [Hainsworth 00]. Definitions of the four modes for the purposes of this discussion follow:

Sensor/status mode provides all critical information about the robot's internal state and its external sensors. It may also be called *telemetry* mode, especially in the case of machines with little or no autonomous capability. It is the mode typically used to assess the operational state of the robot and its ability to proceed.

Command mode provides an interface tailored to issue commands to the robot, perhaps allowing the user to drive it with a virtual joystick or with cursor keys, to actuate mission-specific devices, to change default speeds, gains, and sensitivities, etc.

Robot perspective mode is usually dominated by one or more camera views from the robot's current position, but may include any environmental perceptions that enhance the general impression of telepresence. Remote driving is often conducted from this display, since it is intuitively the most comfortable for typical operators.

Map mode provides a top-down perspective of the robot's local environment, placing it in context with known (or hypothesized) environmental features, geographical coordinates, other robots, etc. Often, multiple levels of zooming are provided. This mode is often required for global navigation.

In the best implementations, there is modal overlap, and it is therefore possible to make use of some of the same functionality in different modes, but the rationale for the different modes usually includes a) there is insufficient space in the display to provide all interfaces at once and b) even if there were enough space, it would be overwhelming to the operator.

In a TMR OCU, it is especially desirable not to present too much information, so the multimodal model is appropriate, and the typical modal interface will generally be even less information-rich than full-fledged GUI interfaces. With creative use of some of the alternate input devices (other than visual displays), it becomes possible to convey some additional data, including that of modes other than the active mode. And if the primary visual display is effectively transparent, some of the modal information can be displayed as non-distractive AR data.

Several opportunities exist for the effective use of AR displays. During manual teleoperation, for example, the effect of autonomous behaviors (e.g., obstacle avoidance) can be masked from the actual motor control, but displayed as arrows on the "driving mode" display (e.g., as arrows away from obstacles). Similarly attractive forces can be shown as well, as in the pheromone robotics displays of Payton [Payton 00]. Also, research at the University of Maryland has shown that there is great value in showing the predicted effect of operator commands, especially when there is high latency in communication [Lane 00b].

With respect to the design of the OCU interface, much can be learned from the efforts at Carnegie Mellon in the area of *collaborative control*, their description of joint human-robot operation, in which the robot may function autonomously and make requests of the human operator [Fong 99]. The Georgia Tech *MissionLab* system supports the notion of *teleautonomous control*, in which human control can be superimposed upon robotic behaviors, and several interface concepts have been developed to support this modality.

4.1.6 OCU System Design

From the standpoint of hypothesizing an integrated system design that would be appropriate for TMR applications, it is proposed that a multimodal interface (as discussed in the previous section) be implemented on a hardware suite consisting of the following major items:

- Wearable computer,
- See-through heads-up display,
- Gesture-sensitive glove on dominant hand,
- Fingertip contact-sensitive glove on secondary hand,
- Direct-contact "joystick-type" device sewn into uniform at mid-thigh,
- Helmet-integrated microphone and audio feedback.

Key points to this approach include:

- Microphone is used for person-to-person communication only, not voice recognition,
- Attention-getting "operator interrupts" provided simultaneously by audio alarms and flashing visual indicators,
- Navigation of multimodal visual screens, video feeds, etc., strictly by fingertip commands of secondary hand,
- Use of dominant hand only as required for critical positioning and gesturing, including glove commands or joystick control (by dropping hand to thigh, either sitting or standing).

Much of the rationale for this approach has been provided earlier in the discussions of the various devices and previous user interfaces. Central to the design philosophy is the fact that the operator of the proposed system can perform a variety of control operations without requiring use of his dominant hand or losing sight of the immediate surroundings.

Specifically, a reasonable approach would be to allow the operator to select between four different operational modes by “double-tapping” his thumb against one of the four fingers on the same (non-dominant) hand. The operational modes correspond to those described earlier, and many variations are possible, but for example:

- Index finger – command mode
- Middle finger – sensor display mode
- Ring finger – map mode
- Little finger – immersive robot view mode

This particular choice of displays might be designed to be increasingly immersive, where the command mode and sensor display mode simply superimpose a few gauges and indicators over the operator’s normal visual field, while allowing minimal screen navigation and user input with “single-taps” of the thumb against the four fingers.

The dominant hand could be dropped to the thigh-mounted “joystick” for finer control of user input in these screens, but this feature would primarily be used for driving in the map mode (which takes up a bit more of the visual field), and the immersive “robot’s-eye” view mode (which ideally is seldom used). Similarly, the gesture recognition glove on the dominant hand could be used for additional input functions in these modes, under the same assumption that the operator would not have entered these modes unless he temporarily had use of both hands for robot operation.

Figure 49: Key devices for the implementation of the proposed approach, including the contact sensitive PinchGlove, the gesture sensing DataGlove, the low-profile CyberPuck for mounting on the thigh as a joystick, and the virtual retinal display.

The actual hardware used to implement (Figure 49) this could consist of

- any of a variety of wearable computers, including a subset of the Land Warrior system,
- a PinchGlove for the non-dominant hand,
- a DataGlove for the dominant hand,
- a CyberPuck for attachment to the uniform at the front of the thigh, and
- the Virtual Retinal display.

Backups to all of these devices are commercially available, but the largest risk is probably in the display. Both the MicroOptical and TekGear displays are viable alternative to virtual retina technology. All of these devices require ruggedization, but all are suitable for experimentation in their current form. As noted earlier, comms gear being developed for Land Warrior and other programs should be integrated where possible.

4.2 <u>Human Factors and TMR</u>

4.2.1 Human Factors Introduction

In designing a TMR system capable military use, we first revisit the principles of teleoperation and study how this has evolved into telepresence. We can learn from the history of this area about human factors issues that affect design, operator selection and training.

[Draper 95] defines a teleoperator as a "general-purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments." He cites several human factors challenges in teleoperation which are likely germane to TMR:

- Human role: what level of control is chosen (supervisory, shared, traded, etc.)
- Design of feedback systems (viewing, force)
- Pace of control (user, machine, or non-real-time);
- Role of feedforward
- Measuring performance.

An interesting quote appears in [Draper 93]:

> *In teleoperation, the [human-machine] interaction ... is more than merely an exchange of information - energetic interactions are as least as important.*

One of this things this report focuses on is how to achieve more than just information exchange and to be able to tap into the user's perceptual, cognitive, and motor channels more effectively than with mere information presentation.

4.2.1.1 <u>Organization of Control</u>

Sheridan's work is considered central to telerobotics research. Figure 50 denotes the many different aspects of control feasible, ranging from manual to supervisory to fully automatic (autonomous) control.

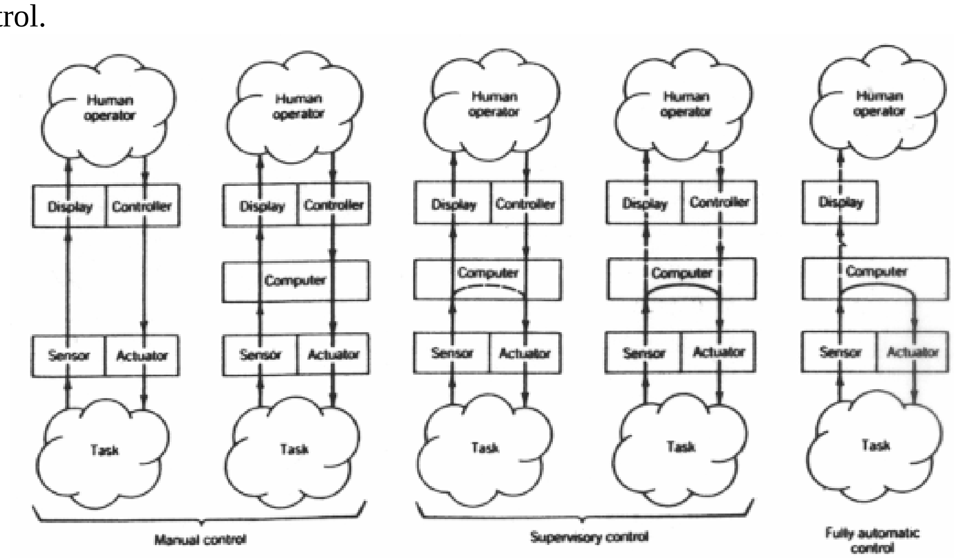

Figure 50: Levels of Control for Teleoperation through Autonomy (from [Sheridan92])

4.2.1.2 Telepresence and Cognition

[Draper et al 1998] cite studies that show that the shape of the robot controller is not important during teleoperation but spatial correspondence is. The artifact must be easy to use and predictable. Other studies have shown that displaying force information via audio can produce better results than with haptic displays. They use the definition of telepresence as "a mental state in which a user feels physically present within the computer mediated environment.". Sheridan refers to telepresence as the loss of awareness of the actual user's surroundings. Table 1 shows the many different definitions and performance factors associated with telepresence, while Table 2 lists several psychological models developed for telepresence.

Approach	Nature of Telepresence	Causes	Relationship to Performance
Akin et al. (1983)	A feeling of actual presence at the work site	1. Manipulator dexterity 2. Feedback scope and fidelity	Telepresence improves performance
Sheridan (1992 a, b; 1996)	User feels physically present at the remote site; compelling illusion; subjective sensation	1. Sensory fidelity 2. Sensory control 3. Manipulability	Telepresence improves performance
Steuer (1992)	The sense of being in an environment; the experience of presence in an environment by means of a communication medium	1. Vividness 2. Interactivity	Telepresence improves performance
Zeltzer (1992)	Sense of being in and of the world	1. Autonomy 2. Interaction 3. Presence	Telepresence may improve performance, but may make tasks more difficult and fatiguing
Slater and Usoh (1993, 1994)	The (suspension of dis-) belief that they are in a world other than where their real bodies are located	1. External factors 2. Internal factors	Telepresence improves performance
Witmer and Singer (1994)	subjective experience of being in one place when physically in another; subjective sensation, much like 'mental workload'; a mental manifestation	1. Control factors 2. sensory factors 3. distraction factors 4. realism factors	No clear relationship
Schloerb (1995)	The person perceives that he or she is physically present in a computer-mediated environment	1. Information flow 2. Ability to manipulate computer-mediated environment	Performance must reach some minimum level before telepresence can occur; relationship not established beyond that
Mühlbach, Böcker, and Prussog (1995)	Sense of sharing space with distant interlocutors	1. Spatial presence 2. Communicative presence	Performance improves telepresence

Table 1: Performance factors in telepresence (from [Draper et al 98])

Approach	Nature of Telepresence	Causes	Impact on Performance
Behavioral Cybernetics	Relationship between feedback and feed-forward (not experiential)	Degraded by temporal, spatial, and filtering perturbations	Performance improves with cybernetic telepresence
Flow	Concentration on an activity to exclusion of distracting stimuli	Focus on task; match between task requirements and user abilities	None
Distal Attribution	a compelling impression of being at the location occupied by the slave device	Relationship between sensory inputs and nervous system commands necessary to respond; moderated by quality of afference-efference linkages	Performance improves with telepresence
Situation Awareness	Maximization of SA in the computer-mediated environment accompanied by the loss of SA for the local environment	Focusing attention on the computer-mediated environment	Depends on importance of local SA

Table 2: Psychological Approaches to Telepresence (from [Draper et al 98])

Tele-existence appears to be synonymous with telepresence and is defined by [Halme and Suomela 2000] as "the situation where the main senses of operator, like sight and hearing, are transferred to the remote place by telecommunication means so that he/she have the 'feeling' of presence". They conducted experiments using an ATV with an operator in a stereo-head mounted display, with head tracking audio capabilities. Five scenarios were tested: driving in a corridor, in unknown terrain, for loading, maneuvering, and fast driving. A small subject pool (5 men) was used. Principal results included the facts that training improved performance, and that loading was the most difficult task. System differences in display made little difference after training on a repeatable task. In a different experiment it was noted that servo cameras controlled by head movements were rejected as very bad by all drivers, both subjectively and objectively. This may have been due to the position of the cameras that were located where a driver normally sits, instead of along the centerline of the vehicle. Camera placement appears to be a very important factor for telepresence systems. Stereovision did help in the loading task. The head mounted display was also uncomfortable and induced nausea in the drivers. The conclusion was that a monitor was better than the technology they introduced.

Another study in telepresence [Ballou 2000] looked at remotely operated submersible vehicles. Again a very small data set was used that is inadequate to draw conclusions. Observations suggest however that here as well, operators performed better with a panel display than a head mounted one, although the reasons for this are unclear. It was also noted that novice users tend to lock their head in position when active coupling of head position to the camera is present.

[Simsarian 2000] studied user interfaces for teleautonomous control in the context of virtual reality, i.e., where a well-defined model exists for the environment in which the robot operates. While this is an interesting premise, unfortunately it holds little utility in battlefield scenarios as a priori models of the world are generally not available at the level of detail required nor do they necessarily correlate with the realities of the moment.

It is worth observing that some recognize the importance of trying to quantity the notion of presence in systems such as these. [Prothero et al] describes *vection* which refers to a "sense of self-motion induced by visual cues". They provide insights into how metrics for certain classes of vection can be measured. Presence is less well defined here, but they advocate a measure referred to as *simulation fidelity* in terms of "the ability of a virtual environment to induce a change in perception of gravity-referenced eye level. The latest references refer to the beginning of experiments to determine the usefulness of metrics such as these.

4.2.2 Sensory Feedback

This section surveys the impact various sensor modalities have in teleoperation from a human factors perspective; i.e., what works and what doesn't, especially as related to TMR issues.

4.2.2.1 Sensory Characteristics of Humans

[Corliss and Johnsen 1968] present in Tables 3-5 a summary of the sensory channels, and their limits, by which a human operator can be engaged with a teleoperator. No doubt gaps in these tables can be closed and refinements made due to human studies since their compilation, but they do provide useful information that can be applied to interface design.

Sense	Intensity Range		Intensity Discrimination	
	Smallest Detectable	Highest Practical	Relative	Absolute
Vision	2.2 to 5.7 x 10^{-10}	Roughly, the brightness of snow in the midday sun, or about 10^9 times the threshold intensity	With white light, there are about 570 discriminable intensity differences in a practical range.	With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 millilamberts.
Audition	1 x 10^{-9} ergs/cm^2	Roughly, the intensity of the sound produced by a jet plane with afterburner or about 10^{14} times the threshold intensity	At a frequency of 2,000 cps, there are approximately 325 discriminable intensity differences.	With pure tones about 3 to 5 identifiable steps.
Mechanical vibration	For a small stimulator on the fingertip, average amplitudes of 0.00025 mm can be detected.	Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold	In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.5 mm provides 15 discriminable amplitudes	3 to 5 steps
Touch pressure	Varies considerably with body areas stimulated and the type of stimulator. Some representative values: Ball of thumb—0.026 ergs Fingertips 0.037 to 1.090 ergs Arm—0.032 to 0.113 ergs	Pain threshold	Varies enormously for area measured, duration of stimulus contact and interval between presentation of standard and comparison stimuli	Unknown
Kinesthesis	Joint movements of 0.2 degree to 0.7 degree at a rate of 10 deg/min can be detected. Generally, the larger joints are the most sensitive	Unknown	No data available	No data available
Angular acceleration	Dependent on the type of indicator used 1. Skin and muscle senses 1 deg/sec^2 2. Nystagmic eye movements 1 deg/sec^2 3. Oculogyral illusion 0.12 deg/sec^2	Unconsciousness or "black-out" occurs for positive "g" forces of 50 to 8 g lasting 1 second or more Negative forces of 3 to 4.5 g cause mental confusion, "red-vision" and extreme headaches lasting sometimes for hours following stimulation	No data available	No data available
Linear acceleration	In aircraft—0.02 g for accelerative forces and 0.08 g for decelerative forces	For forces acting in the direction of the long axis of the body, the same limitations as for angular acceleration apply.	No data available	No data available

*Adapted from Ref. 55.

Table 3. Human Sensory channels (from [Corliss et al 68])

Sense	Wavelength or Frequency Range		Wavelength or Frequency Discrimination	
	Lowest	Highest	Relative	Absolute
Vision (hue)	300 mμ	1,500 mμ	At medium intensities there are about 128 discriminable hues in the spectrum	12 to 13 hues
Interrupted white light	Unlimited	At moderate intensities and with a duty cycle of 0.5, white light fuses at about 50 interruptions per second	At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 375 separate rates of interruption in the range of 1 to 45 interruptions per second	No greater than 5 or 6 interruption rates can be positively identified on an absolute basis.
Audition (pure tones)	20 cps	20,000 cps	Between 20 cps and 20,000 cps at 60 db loudness, there are approximately 1,800 discriminable steps	4 to 5 tones
Interrupted white noise	Unlimited	At moderate intensities and with a duty cycle of 0.5, interrupted white noise fuses at about 2,000 interruptions per second.	At moderate intensities and with a duty cycle of 0.5, it is possible to distinguish 460 separate interruption rates in the range of 1 to 45 interruptions per second.	Unknown
Mechanical vibration	Unlimited	Unknown, but reported to be as high as 10,000 cps with high intensity stimulation.	Between 1 and 320 cps, there are 180 discriminable frequency steps.	Unknown

Table 4: Discriminatory capabilities of Human Senses (from [Corliss et al 68])

Parameter	Vision	Audition	Touch	Vestibular
Sufficient stimulus	Light-radiated electromagnetic energy in the wavelengths from 400 to 700 mμ (violet to red)	Sound-vibratory energy, usually airborne	Tissue displacement by physical means	Accelerative forces
Spectral range	120 to 160 steps in wavelength (hue) varying from 1 to 20 mμ.	20 cps to 20,000 cps	>0 to <400 pulses per second	Linear and rotational accelerations
		~3 cps (20 to 1000 cps) 0.3 percent (above 1000 cps)	$\frac{\Delta pps}{pps} \simeq 0.10$	
Dynamic range	~90 db (useful range) for rods = 0.00001 mL to 0.004 mL; cones = 0.004 mL to 10,000 mL	140 db (0 db = 0.0002 dyne/cm^2)	~30 db, 0.01 mm to 10 mm	Absolute threshold $\simeq 0.2^\circ$/sec/sec
Amplitude resolution $\left[\frac{\Delta I}{I}\right]$	contrast = $\frac{\Delta I}{I} = 0.015$	0.5 db (1000 cps at 20 db or above)	0.15	~0.10 change in acceleration
Acuity	10 arcminutes	Temporal acuity (clicks) $\simeq$0.001 sec	Two-point acuity = 0.1 mm (tongue) to 50 mm (back)	
Response for rate for successive stimuli	~0.1 sec	~0.01 sec (tone bursts)	Touches sensed as discrete to 20/sec	~1 to 2 sec nystagmus may persist to 2 min after rapid changes in rotation
Reaction time for simple muscular movement	~0.22 sec	~0.19 sec	~0.15 sec (for finger motion, if finger is the one stimulated)	
Best operating range	500 to 600 μ (green-yellow) 10 to 200 foot-candles	300 to 6000 cps 40 to 80 db		1 g acceleration directed head to foot
Indications for use	1. Spatial orientation required. 2. Spatial scanning or search required. 3. Simultaneous comparisons required. 4. Multidimensional material presented. 5. High ambient noise levels.	1. Warning or emergency signals. 2. Interruption of attention required. 3. Small temporal relations important. 4. Poor ambient lighting. 5. High vibration or g forces present.	1. Conditions unfavorable for both vision and audition. 2. Visual and auditory senses.	1. Gross sensing of acceleration information.

*Adapted from Ref. 55.

Table 5: Human sensory characteristics (from [Corliss et al 68])

4.2.2.2 Vibratory Feedback

Kontarinis and Howe at Harvard University investigated how effectively vibration can convey information in teleoperation environments. They categorize relevant tasks in three categories:

1) Where detection of vibrations is the fundamental goal (i.e., detecting a vibration on a door)
2) Where performance can be enhanced by indicating the mechanical state of the hand-object system (e.g., indicating when contact has occurred as in grasping a doorknob).
3) Tasks where vibration information regarding the environment in not important, but vibration increases the subjective feel of the environment to the user.

They used a teleoperated hand system to conduct experiments for ball bearing inspection, puncturing, and a peg-in-slot task. Results indicated:

- Force and vibration are complementary modalities, and vibration in conjunction with force is most useful.
- The importance of high-frequency feedback is task related.
- Display design is low cost, using a simple loudspeaker. More expensive tactile feedback units can be provided with pins to operator's fingertips.

[Desombre et al 95] physically shook operators using a vibratory platform and evaluated the consequences on their ability to perform simple decision-making tasks. The relevance of this study to TMR is for operators who may be doing mission specification or run-time control while on the move in a vehicle. This is a form of stress testing. Bar graphs seemed better perceived than polygonal visualizations under these conditions in certain cases. Overestimation of graphic shapes tended to occur which was not found in bar graphs when vibration was present. Oddly subjects time to perceive bar graphs when shaken decreased over stable states.

4.2.2.3 Haptic/Tactile Feedback

Hoffman at the University of Washington observed that most VR systems do not provide force or tactile feedback. He used a mixed reality feedback system, with both VR and actual physical components, which indicated that the subjects performed more effectively in this environment than in pure VR without tactile feedback. This is not surprising but does document these results. This same group expanded this work further, showing that tasting virtual objects enhanced the realism of these virtual experiences as well. Again not a surprise, but it does formally document this aspect. The experiment involved touching and tasting a candy bar when the same object was seen within a virtual environment. It is unclear how this could be practically implemented, but it is of note that it would be of value in enriching the overall immersive experience to the subject.

[Burdea 96] studied haptic (force and touch) feedback for VR applications. In his book, he provides data on spatiotemporal resolution of various body regions (Table 6). He also discusses the various classes of skin mechanoreceptors (Merkel disks, Ruffini Corpuscles, Meissner corpuscles, and Pacinian corpuscles) as well as thermoreceptors and nocireceptors (pain). This was translated into a figure depicting human finger sensing and control bandwidth suitable for hand feedback (Figure 51). This all translates into a set of interface requirements shown in Figure 52.

TABLE 2.1 Average Pressure JND as a Function of Contact Area

Body site	Contact Area (cm^2)		
	1.27	5.06	20.27
	Pressure JND		
Elbow (Volar)	0.167	0.062	0.040
Elbow (Dorsal)	0.113	0.052	0.033
Wrist (Dorsal)	0.188	0.044	—
Overall Average JND	0.156	0.053	0.037

Adapted from Tan et al. [1994]

Table 6: Spatiotemporal resolution of various body locations (from [Burdea 96])

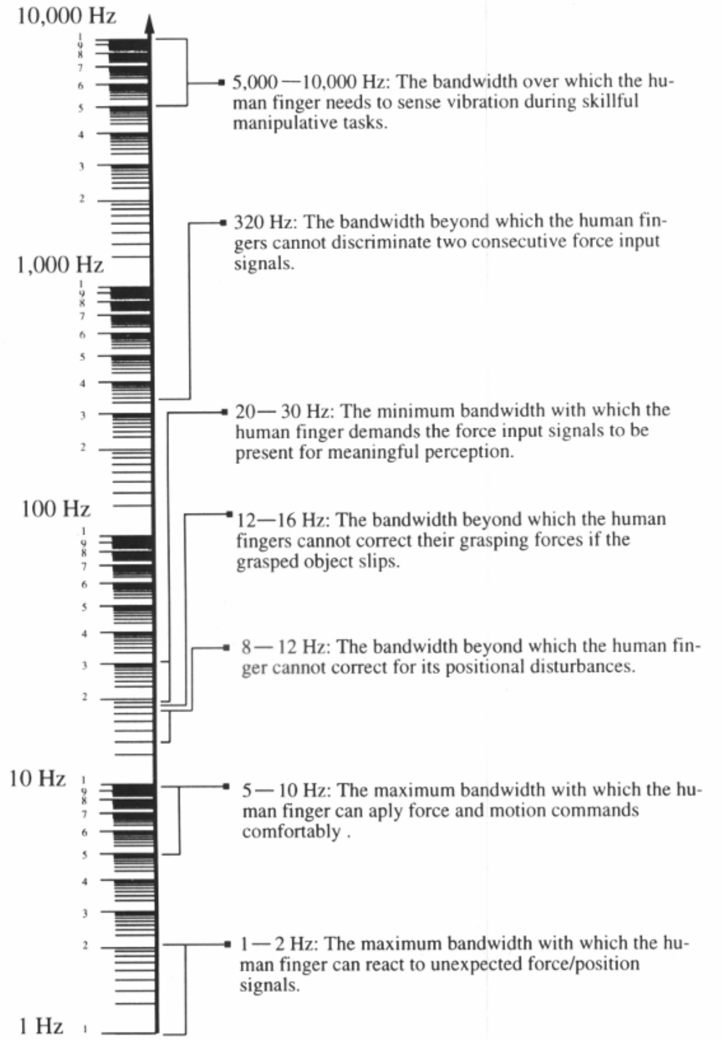

Figure 2.14 Human finger sensing and control bandwidth. Adapted from Shimoga [1992]. © Éditions Hermès. Reprinted by permission.

Figure 51: Human finger sensing response (from [Burdea 96])

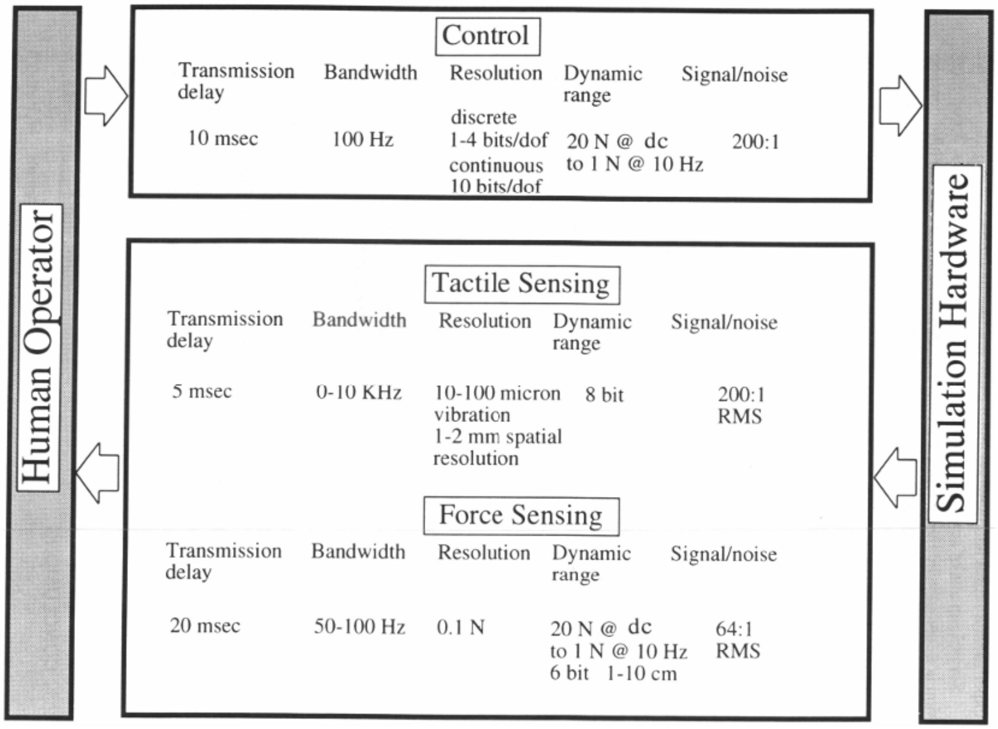

Figure 52: Tactile Interface Requirements (From [Burdea 96])

4.2.2.4 Auditory feedback

The [National Research council Report 1998] provides guidelines when to use auditory presentation over visual presentation for soldiers (Table 7). Table 8 further shows the advantages and disadvantages of variants of auditory displays of information to the soldier.

Use auditory presentation if:	Use visual presentation if:
1. The message is simple.	1. The message is complex.
2. The message is short.	2. The message is long.
3. The message will not be referred to later.	3. The message will be referred to later.
4. The message deals with events in time.	4. The message deals with location in space.
5. The message calls for immediate action.	5. The message does not call for immediate action.
6. The visual system of the person is overburdened.	6. The auditory system of the person is overburdened.
7. The receiving location is too bright or dark adaptation integrity is necessary.	7. The receiving location is too noisy.
8. The person's job requires him or her to move about continually.	8. The person's job allows him or her to remain in one position.

Source: Deatherage (1972: Table 4-1).

Table 7: Auditory versus visual presentation (From [NRC 98])

	Advantage	Disadvantage
Monaural	Inexpensive Single earphone	Sounds can not be localized Reduced signal detection Reduced speech intelligibility
Biaural	Small increase in signal detection	Headphones required
Stereo	Increased signal detection Increased speech intelligibility Minimal increase in complexity	Headphone required
3DAD	Improved signal detection Improved speech intelligibility Signals localizable Multiple channels monitoring Waypoint navigation	Increased complexity Headphones required

Table 8: Relative Merits of Auditory Feedback Modalities (From [NRC 98])

[Hollier et al 99] discuss a range of presentation methods and technologies using 3-D spatial sound to the end-user, but unfortunately they do not include any formal user analysis of its efficacy.

4.2.2.5 Visual imagery

Work by [Prothero and Hoffman 95] at the University of Washington confirmed what appears to be the obvious, that a wider field of view does indeed increase the feeling of presence in a human subject in immersive environments. 38 subjects were used to confirm this hypothesis. Goggles were also shown to be better (foreground occlusion) than a background occlusion (projection onto paper).

[Sayers et al 95] at the University of Washington studied visual feedback for undersea remote teleoperation. A heavily constrained communications channel required the use of automatic windowing and subsampling of the image. This study, however, focused on the technical design of the system with seeming little regard for operator capabilities.

4.2.2.6 Improper Feedback: Motion Sickness

Research at the University of Washington's Human Interface Technology Laboratory studied the effects of motion sickness in virtual environments. Clearly TMR does not want to induce this phenomenon in its users. This group has constructed a means and metrics by which motion sickness can be evaluated. It appears that it is primarily due to visual-inertial sensory conflict. A solution appears to be maintaining an independent visual background for the immersive environment that is consistent with the subject's inertial cues. Thus if a TMR operator is driving while operating, feedback from the driven vehicle should be coupled to the immersive environment for background projection.

Preliminary research has attested to the feasibility of this approach using a head-mounted display. Observations include:

1) That a simple stationary background grid in the sky portion is insufficient to reduce motion sickness.
2) The induced motion of the background grid did not appear in peripheral vision.
3) A simple foreground grid did assist in reducing motion sickness.

4.2.3 Operator Performance

Sheridan states [Sheridan and Ferrell 1974] two relevant tenets: when working at capacity one can increase speed only at the expense of accuracy, and conversely; some parallel processing can be carried out, but to do several tasks will require switching among them.

In reference [Sheridan and Ferrell 1974] to an earlier study by Merkel, response times are increased when:

1. The stimulus is unexpected
2. There are many possible stimulus-response pairs
3. The stimulus or responses are unfamiliar
4. It is difficult to discriminate between stimuli or when searching or scanning is required for detection
5. The response is related to stimulus in complex manner
6. The response in difficult to perform.
7. Visual stimuli responses are longer than auditory which are longer than for tactile

These trends can serve as targets for TMR interface and training design.

4.2.3.1 Metrics

It is interesting to note that in the early work in teleoperation system design [Corliss and Johnsen, 1968, Johnsen and Corliss, 1967] virtually no effort was dedicated to human factors evaluation, as evidenced in statements such as "Assertions regarding the relative effectiveness of different teleoperators often imply that considerable experimental data exist, but no thorough studies have been made" [Johnsen and Corliss, 1967]. Unfortunately, the situation appears only slightly better today, with more lip service than actual experimental studies having been conducted. Most human factors studies have not focused on direct measurements of human control of robots, but rather involve other forms of control (e.g., air traffic controllers) from which we must extrapolate.

There are exceptions however. In discussions with John Draper at Oak Ridge National Laboratories, one of the main users of teleoperators over the past several decades, he alone is involved in human factors related work. In a sense it is better that there does exist at least one individual within DOE to design and conduct these studies, but it is a sad commentary still regarding how engineering typically regards human factors issues.

The most commonly used metric for quantifying performance of teleoperators is task completion time [Book and Love, 1999]. Other measures considered include are typically resolved into total task time, time effectiveness ratio (time relative to if the task was performed directly by the human), and unit task time (related to performance of subtasks of the overall task). Operator fatigue, success ration and subjective user satisfaction are also common measures, although often difficult to evaluate analytically. Task-specific metrics are also created on an ad hoc basis, and may in this context deal with detectability issues.

So-called information-based performance measures relate the rate of information that is transmitted through the system to or from the operator. While the definition of manual control is self-evident, supervisory control refers to a human operator(s) intermittently or continuously programming a robot that itself is operating autonomously. The operator also continuously receives information from the robot. In a fully autonomous system, the human operator is rather an observer than a controller.

4.2.3.2 Operator Characteristics in Supervisory Control

Moray outlines the general characteristics from the human end of supervisory control:

1. Scheduling what to do
2. Sampling a display or other data source
3. Acquiring data through sensing
4. Combining information from past and present sources
5. Decision-making
6. Diagnosing the system state
7. Executing the appropriate action
8. Allocating control between human and computer

The advantages of this approach over pure teleoperation also become apparent:

1. Improved performance over operator alone
2. Once taught, more efficient performance
3. Enables tasks operator may not be able to do due to remoteness (e.g., signal delays)
4. Reduces operator workload
5. Improves operators task planning through predictive displays
6. Help operator to monitor, detect and diagnose system failures
7. Provides failure actions when operator responses would be too slow
8. Makes direct control easier by better display and control aids
9. Reduces costs, saves lives by removing operator from hazardous environment.

Figure 53 shows how control of navigational processes can be affected at multiple levels under supervisory control. Sheridan further indicates that human skills and reasoning proceed at multiple levels as well, referring to Rasmussen's paradigm (Figure 54). Of particular relevance for the robot unit concept is the control of multiple robots concurrently (Figure 55).

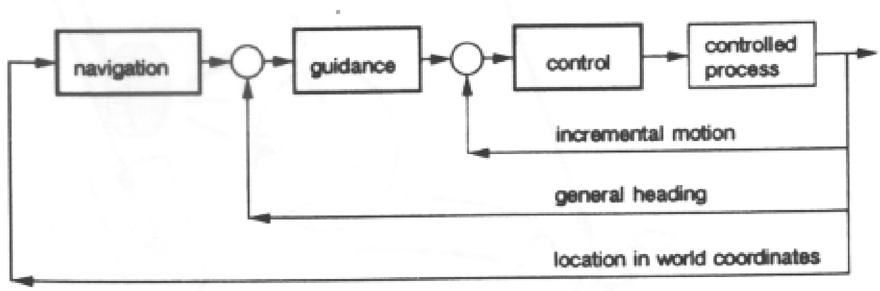

Figure 53: Supervisory Control (from [Sheridan 93])

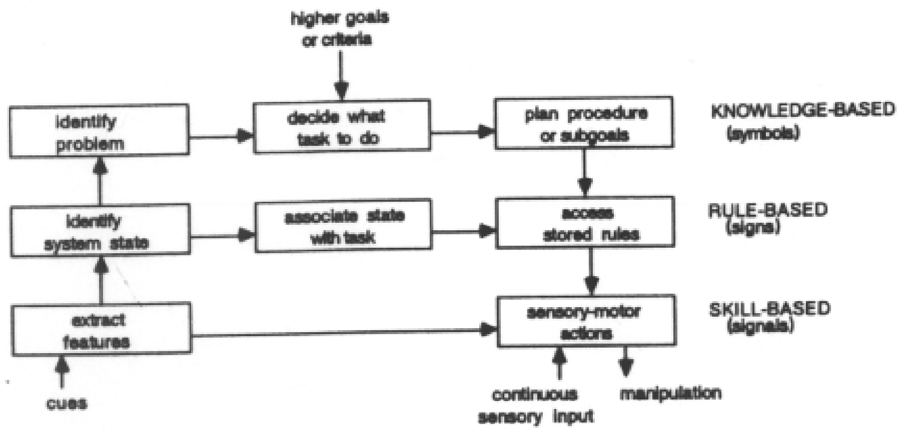

Figure 54: Multiple Levels of Human Reasoning (from [Sheridan 93])

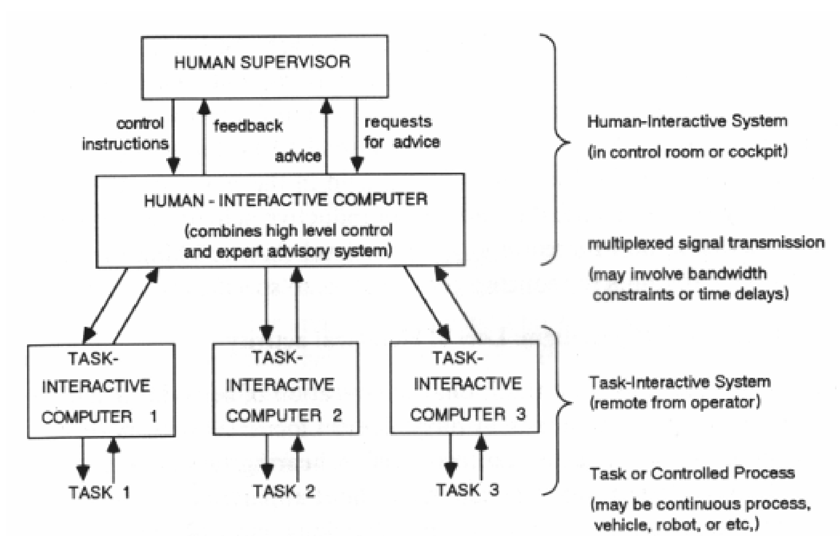

Figure 55: Control of multiple computers/robots concurrently (from [Sheridan 93])

Interestingly, Sheridan's experimental results indicate that human subjects "approached optimal behavior ... both when they had plenty of time to plan and when their workloads were reasonably heavy" in multitask environments [Sheridan 93]. There was an observed time, as workload increased when the subjects switched from planning ahead to putting out fires and shedding tasks. This clearly points to a need for effective workload management on a robot unit operator.

Figure 56 shows the different requirements placed on the operator in shared control: specifically including the abilities to plan, teach, or intervene, and monitor performance. We study human factors affecting performance of these duties throughout this report.

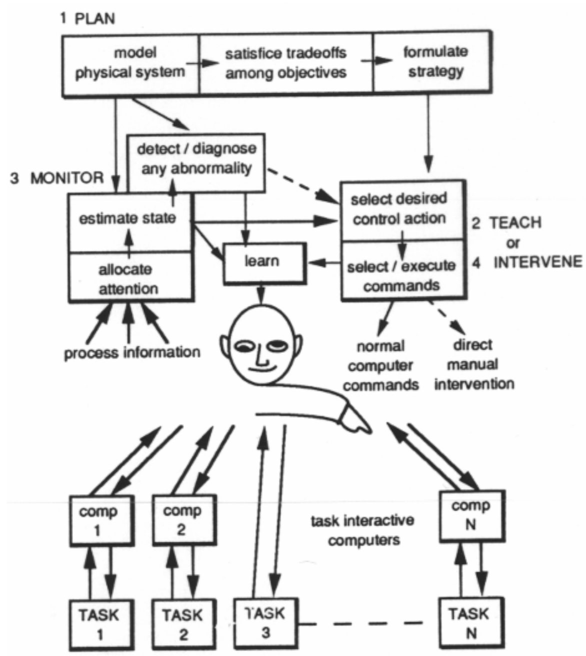

Figure 56: Requirements placed on Operator (from [Sheridan 93])

Sheridan also discusses the importance of human-attention allocation models as a component of supervisory control systems. Figure 57 shows the range of tasks when supervisory control is better than direct teleoperation relative to the time required to provide the capability to the robot.

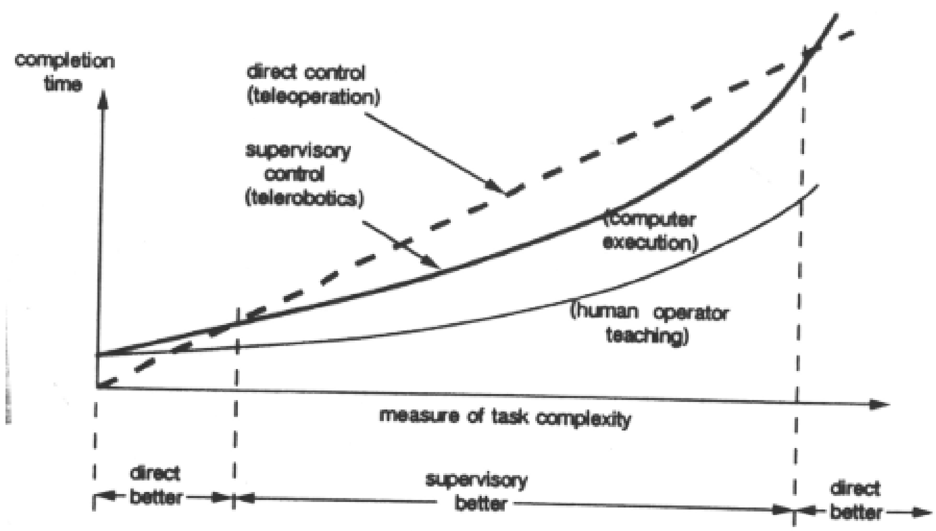

Figure 57: Teleoperation versus Supervised Control (from [Sheridan 93])

4.2.3.3 Monitoring Tasks

[Thurman and Mitchell 95] discuss why monitoring is difficult via operator displays. First it is a boring and passive task, which when under supervisory control does not require active engagement of the operator. Monitoring is also an unstructured, ill-defined task for complex systems. Finally, in general the interfaces operators use are often not designed for monitoring. Sometimes artificial tasks are deliberately added to displays to ensure that the operator remains engaged. The authors advocate a specific design methodology for these displays based on task, operator and information-flow analysis which has been shown to provide better fault detection rates among other things, where this methodology for creating operator displays for highly automated supervisory control systems which is depicted notionally in Figure 58. It starts with the necessary operator functions and proceeds through an analysis to produce the necessary information at the right time in the display. Although it was tested on a NASA satellite ground control system, it has relevance for TMR-related display design and should be considered as a candidate methodology for the design of such a system.

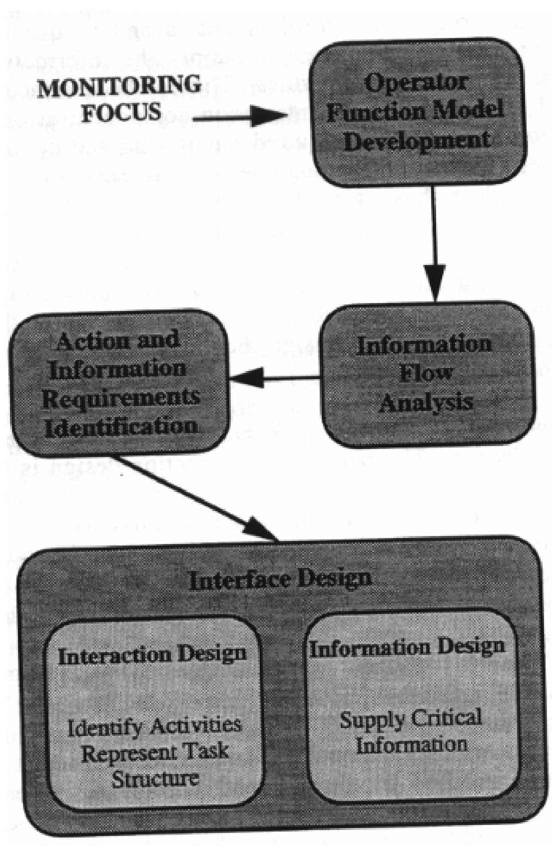

Figure 58: Design Methodology for monitoring/control interfaces
(from [Thurman and Mitchell 95])

4.2.3.4 <u>Driving/Navigation Performance</u>

Specific human factor problem and issues related to driving that may have relevance in a TMR robot unit include:

- Distraction and confusion while driving
- Reading and interpreting maps, text, and symbolic displays
- Increased hand control complexity
- Ignored or too-complex warnings
- Excessive dependence
- False alarms
- Effective heads-up displays
- Situational awareness displays
- Automatic control of speed/braking or steering imposed on human control
- Transients in human to fully automated platoon control
- Variations in operators due to age, education, etc.

Work by [Levison and Baron 1997], studied the impact of task difficulty in driving a remote vehicle. It is possible that these results may potentially extrapolate to multi-vehicle remote driving as needed for TMR Robot unit applications. Table 9 summarizes their results.

Perf	Performance Trends	
	Model	Experiment
Multitask vs single-task driving performance	Multitask worse	Multitask worse
Increasing difficulty of the driving task	More attention to driving task Driving performance degraded	More attention to driving task Driving performance degraded
Increasing relative importance of the auxiliary task	Less attention to driving task Driving performance degraded	No significant influence on attention or driving performance
Driver-controlled attention	Better performance when not attending to road	Better performance when not attending to road
Periodic attention	Better performance when attending to road	

Table 9: Driving Performance (from Levison and Baron 97])

An earlier experiment by Noy summarized in [Levison and Baron 1997] found that:

1. Driving errors were larger for dual-tasks than single task conditions
2. Making driving harder had only modest impact on driving performance, a larger impact on scan behavior, and little impact on secondary task performance
3. Making the difficulty of the auxiliary task harder did not affect the driving and scanning performance significantly, but had large impact on auxiliary task performance.
4. Oddly, driving performance was slightly better when subject when looking at auxiliary task display rather than road.

[Draper et al 99] cite a study for robotic rover navigation tasks conducted in simulation. It was interesting to note that the more immersive the environment was, the faster it took to conduct the navigational task. There was a correlation that showed immersive environments helped for this class of task (which was not always the case for others). It was believed that the ability to direct attention assisted here.

[Peterson et al] at the University of Washington studied the effects of two different interfaces for navigation. One was a joystick controller and the other a sophisticated virtual motion controller that senses the body of the user by having him stand on it (Figure 59). Maneuvering performance was better with a joystick when following a marked route. The ability to form a mental map (survey knowledge) and alternate route planning was better with the body controller and was dependent on how difficult the task environment was (i.e., the more difficult the better the body controller was). It was postulated that the additional kinesthetic and vestibular modalities might have aided sensory integration that people normally expect while wayfinding in unknown areas. Route learning (replicating the same route) was the same for both devices. The subjects used head mounted displays.

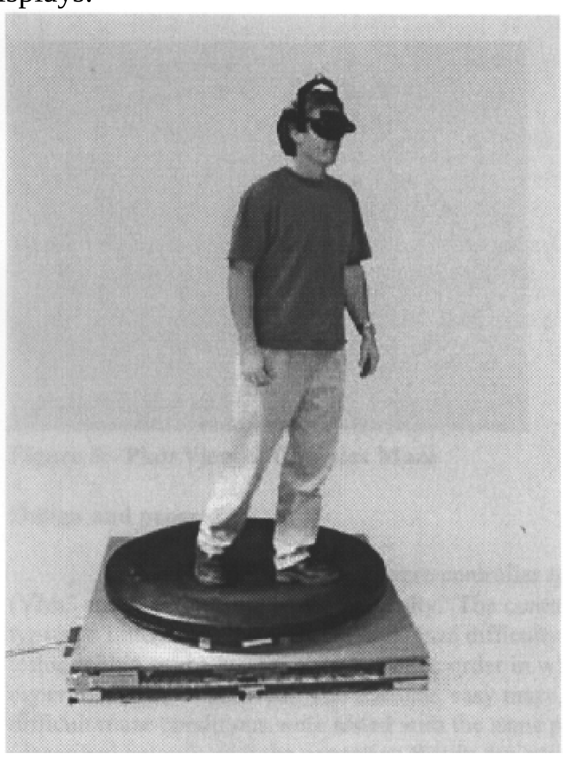

Figure 59: Experimental Setup (From [Peterson et al])

4.2.4 Human Factors and Displays

Problems with displays, in general, include information overload, display inter-correlation and redundancy; and the keyhole problem (if information is not on the screen, how to get it?). This section focuses both on general issues as well as problems and trends associated with specific display types.

4.2.4.1 Helmet Mounted Displays

[Schrage 94] evaluated the state of the art in helmet-mounted displays (HMDs) in terms of human factors for aviation. A vendor inventory assessment was conducted. The human factors study was related to the anthropomorphic physical properties of the display system, than user perceptions, were they were ranked for adjustability, range of head movement and comfort. Additional psychophysical tests were performed on a pool of 4 subjects, for data such as image sharpness, color quality, acuity, and image quality. These were not evaluated, however, in terms of task performance unfortunately. Therefore we cannot draw conclusions from this study as to how well HMDs will or will not work in a TMR-related task environment.

4.2.4.2 Heads-up Displays

Other studies have pointed out difficulties with Heads-up displays (HUDs). In one case [Foyle et al, McCann et al], pilots took 2.5 seconds longer in responding to runway incursions with HUDs than without the technology. It is believed this is a consequence of attentional tunneling leading to inefficient processing of the regular out-of-the-window scene. Thus the use of superimposed symbology in HUDs is not always a blessing. Use of scene-linked symbology, i.e., enhancements of existing features, apparently assists in alleviating this psychological phenomenon. So careful choices should be made on what and how data are represented in heads-up displays. The authors recommend removing the HUD cues that distinguish its information from the natural world, in particular: color (typically saturated green), lack of perspective (planar instead), and differential motion (it does not move with the world).

The National Research Councils Report on Tactical Displays for Soldiers [1998] recommends that if the display occludes the soldiers' view, then hand-held or wrist mounted displays should be considered as an alternative to helmet mounted displays. The loss of local situational awareness may be unacceptable.

4.2.4.3 Other Display considerations

Studies involving displays for air traffic controllers were also considered as relevant, as they are used to improve their situational awareness [Johnston et al], a crucial TMR task. These SADs (situational awareness displays) currently rely heavily on alphanumeric information requiring multiple eye fixations and complex mental transformations to generate the 3D representation of the world. One notion is the use of perspective displays (as advocated for HUDs above). Color was also shown to be better than achromatic displays and was demonstrated to work well for managing attention. Using various spot sizes to represent planes that correlated to altitude also provided useful information regarding altitude versus uniform size spots.

Another potentially related study for teleoperation involved studies in support for pilots on taxiways in conditions of low visibility. We have just seen in the Singapore airlines disaster that such failure can lead to catastrophes. In certain aircraft, heads-up displays provide symbology to the pilot. A recent addition is the electronic moving-map display that, using GPS technology, depicts the aircraft's location in real-time. In some case, route guidance is provided on the display as well, showing where the plane should go as cleared by the tower. Pilots are able to move at greater speeds and make fewer navigation errors when these displays are available, especially when route guidance is provided [McCann et al]. The main problem seems to lie in the coordinate system, which is world-centered instead of egocentric, requiring the pilots to make several cognitive transformations that are "effortful and time-consuming". Work is ongoing in trying to align 3D perspective displays to eliminate these problems. The 3D displays did result in slower taxi speeds despite the pilots' preference for them, evidently due to fewer look ahead cues being available. Variable zoom levels were also presented and the pilots generally preferred the highest zoom. [Foyle et al 96] describe a system engineered to assist pilots based on human factors considerations for this very task, including scene-linked HUD symbology, a perspective moving map display, and 3D audio ground collision and warning system. The audio system actually provided stereo feedback as to the direction of the impending collision.

4.2.5 Mental Workload

Mental workload, according to [Sheridan 93] consists of objective factors such as number of tasks, urgency, and cost of non-completion of task on time or correctly, as well as a range of subjective factors and environmental variables (workstation display geometry, ambient temperature, lighting, etc.) (Figure 60).

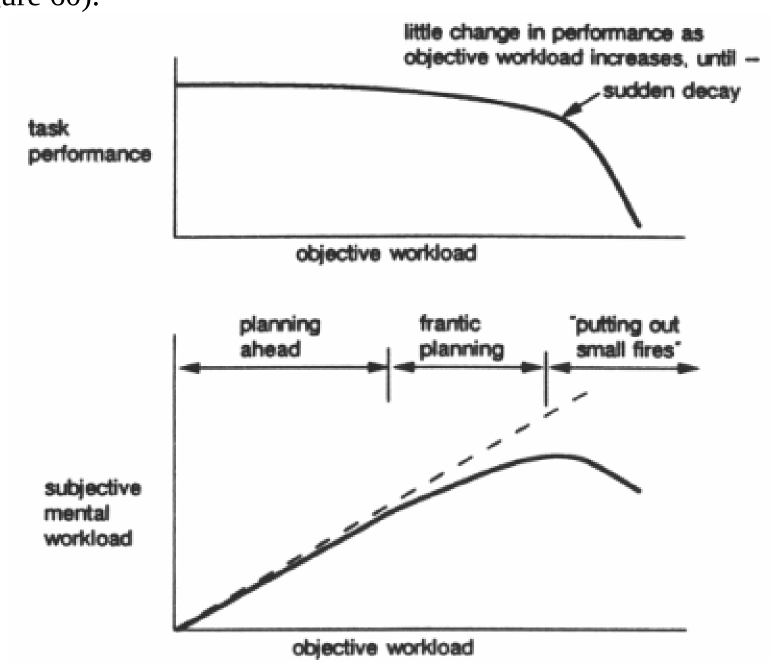

Figure 60: Mental Workload Factors (from [Sheridan 93])

Performance tends to decrease steeply when workload becomes too high, while through the normal range little change is noticed. It is worth noting that if the operator has too little to do, that performance declines as well due to inattention and lack of vigilance for monitoring. This is illustrated in Figure 61. Sheridan provides a rating system for workload measurement (Figure 62) and a decision model associated with it.

Figure 61: Relation of Performance to Workload (from [Sheridan 93])

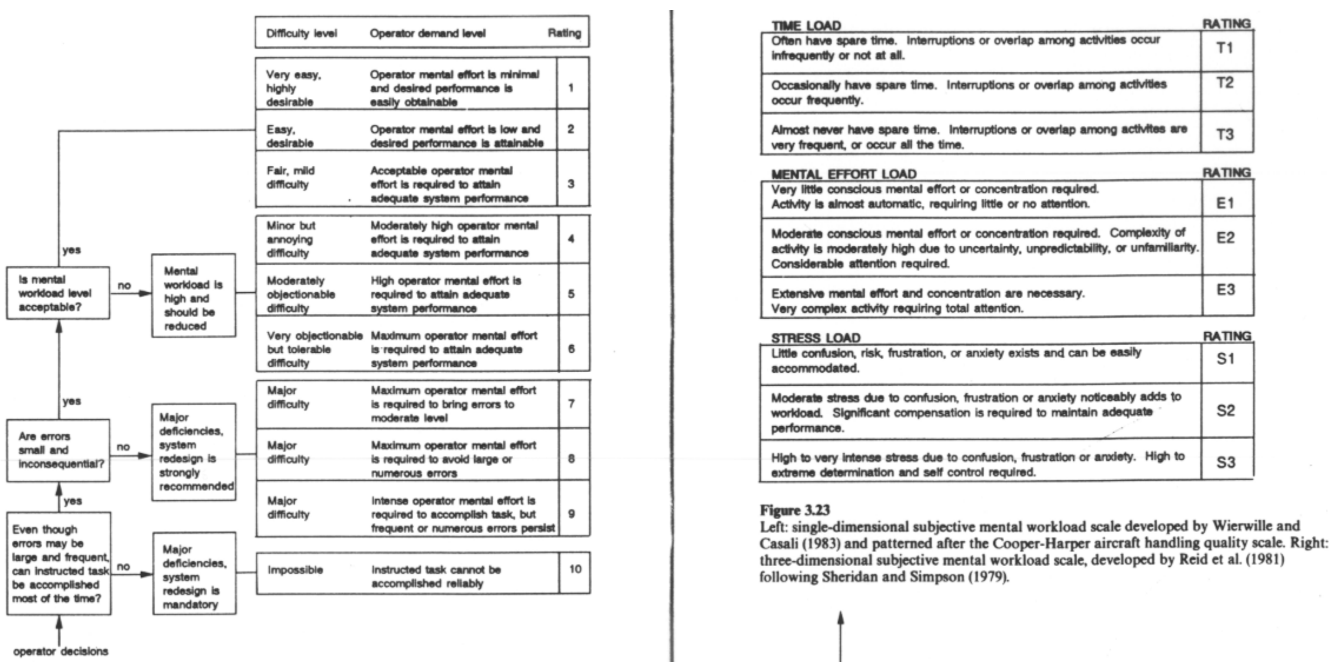

Figure 62: Workload Measurement Rating System (from [Sheridan 93])

Subsequent research by [Draper and Blair 96] studied the role of workload and flow in a similar context. In this study highly trained operators were used. They employed the NASA TLX workload index as a basis for quantifying their measurements (Table 10). The dimensions shown in Table 11 measured flow. Similar metrics could potentially be applied to TMR-related tasks. This led to their development of a cognitive model for teleoperation, which addresses the role of attention (Figure 63). It would be interesting to see how this model stood up to TMR type tasks.

Scale Name	Scale Definition
Mental	How much mental and perceptual activity was required?
Physical	How much physical activity was required?
Temporal	How much time pressure did you feel?
Performance	How successful do you think you were?
Effort	How hard did you have to work (mentally and physically)?
Frustration	How discouraged versus gratified, annoyed versus content did you feel during the task?

Table 10: NASA Study Dimensions (from [Draper and Blair 96])

Flow Dimension	Flow Definition
Goals	Clarity of task-related goals
Attention	Strength of commitment of attentional resources to task performance
Challenge	Degree to which the task was a challenge for the operator
Control	Degree to which the operator felt in control of the situation during task performance
Others	Degree to which operator was concerned about other persons' opinions of his performance.

Table 11: Study Dimensions of Flow (from [Draper and Blair 96])

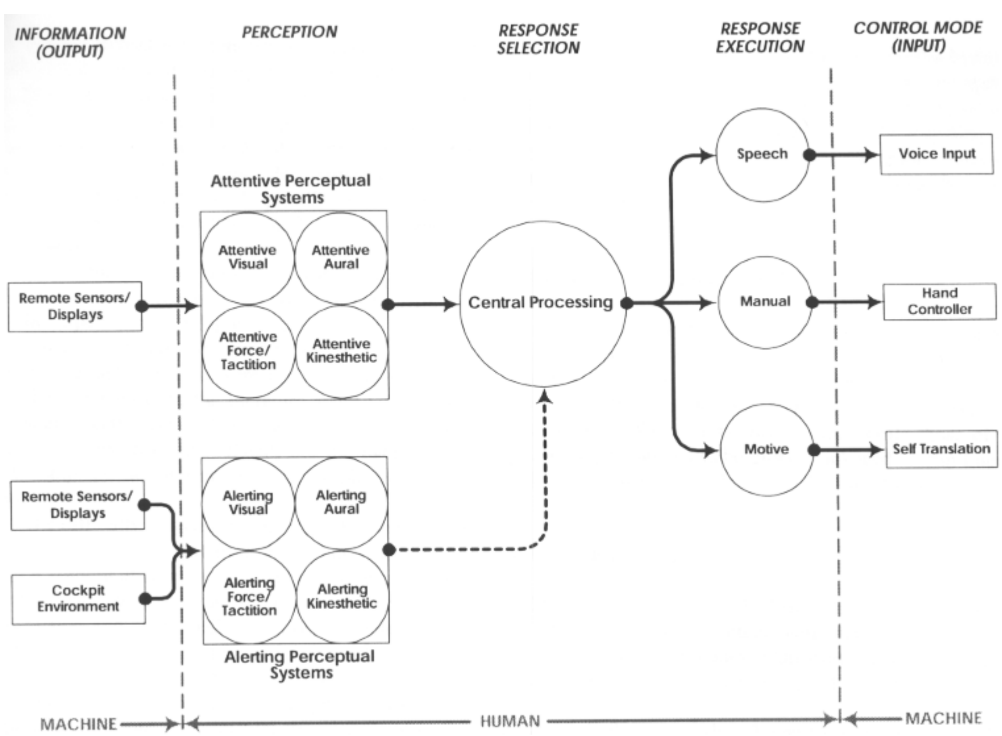

Figure 63: Attention Model for Teleoperation (from [Draper and Blair 96])

[Wei et al 1995] conducted user studies in operator supervision of a system and its relationship to workload. The came to several interesting conclusions:

1. It does not always follow that with more automation that operator performance will improve.
2. Optimal balance between mental load and system performance depends on both task number and task characteristics.

The overall conclusion is that the functions that should be automated in a system depend on both what enhances system performance and reduces operator workload (improves operator performance).

4.2.6 Human error

A major question is when should the operator intervene within autonomous systems. Human errors seem to be most apparent during intervention [Sheridan 93]. Human error is an action that fails to meet some implicit or explicit standard of the actor or of an observer [Sheridan 93]. There exist several taxonomies for this sort of error, most notably the Senders-Moray taxonomy. Errors occur in the:

1. Environmental context: omission, substitution, unnecessary repetition, etc.
2. Cognitive/behavioral: attention, perception, memory, or control
3. Bias: anchoring, overconfidence, confirmation, cognitive lockup, tunnel vision
4. Behavioral complexity: simple sensing, detecting, identifying classifying errors; sequencing from memory; estimation errors in responses; reasoning errors
5. Exogenous (caused by actor) or endogenous (caused by actor's environment)

The main sources of error [Sheridan 93] include:

- Lack of feedback
- Capture (inappropriate conditioned responses)
- Invalid internal models
- Hypothesis verification on the basis of inadequate data
- Stress and perceptual narrowing
- Risk homeostasis (constant level of risk maintained even with safety aids)
- Individual error proneness
- CNS factors (sleep, drugs, emotionality, etc.)

Error factors can be reduced through solid design practices, training incorporating the ability to think about potential errors, and suitable environmental conditions.

Another class of errors that operators are prone to when dealing with complex system are associated with systems that function in various modes. This leads to mode error and ambiguity [Dezani et al 98]. Mode errors occur when a situation is incorrectly recognized, and although the correct action is taken for the perceived situation, it results in an error due to the misperception. Mode ambiguity is a bit different. This occurs when the operator has a different expectation regarding the outcome of the undertaken action in response to the situation. Obviously, neither of theses situations is desirable, and effort must be made to reduce or eliminate the possibility in a TMR-style system. While the authors discuss methods to model these events, unfortunately no general proactive actions are prescribed.

Dual-task interference is another type of error. [Van Selst] notes that this problem occurs even in the absence of the need for a response. It is a consequence of the psychological refractory period effect, which provides a fundamental limit on human parallel task performance. There appears to be a central bottleneck in human information processing associated with the so-called cognitive slack associated with the problem. His study points to the root cause being related to stimulus classification and not action formulation. There is extensive literature on this phenomenon, and in TMR we must be concerned how to eliminate parallel situations to ensure rapid and correct responses.

Another source of human error is when the operator's mental model of the system is not in agreement with the system. [Palmer] studied flight operations for MD-88 and DC-9s and noticed that so-called automation surprise occurred when using the autopilot and autothrottle resulted in altitude deviations. In the case study, the automation worked correctly, but it did not respond as expected by the pilots. The lesson is to develop designs that either eliminate unusual automation modes or provide better displays of normal but unusual modes. Basically a "what you see is what you get display" is needed.

4.2.6.1 Fatigue

Managing fatigue is another important area, especially for combat systems. [Rosekind et al] have studied this problem for NASA. Fatigue is unavoidable as there are circadian rhythms that force us into certain patterns of sleep. Sleepiness has been shown to affect waking performance, vigilance and mood even to the point where an individual is unable to perform at all. There are countermeasures that can be undertaken: minimizing sleep loss, having good sleep habits, providing a comfortable sleep environment, minimize the effects of food, alcohol and exercise, as well as manage circadian clock (chronobiotics). Social interaction, caffeine, bright light and melatonin all can be used to ensure alertness. There is little information on the design of systems to manage this affect, but operator fatigue management should play a role to ensure reliable performance in TMR systems.

4.2.6.2 Trust

[Wickens et al 98] discuss the importance of trust by the operator in the automation they are using. This is clearly essential for acceptance of TMR-related technology as well. They cite 7 main attributes of trust:

1. Reliability
2. Robustness
3. Familiarity
4. Understandability
5. Explication of intention
6. Usefulness
7. Dependence of trusting person upon automation.

If any of these criteria are neglected in the design of a TMR system, it will adversely affect the acceptance by the end-user.

There is a danger as well in overtrust and complacency as well as mistrust when operators rely on complex automation more than they should. A calibration process for trust in the operator is required through the construction of accurate mental models by training and through the participation in automation design by potential operators.

4.2.6.3 Vigilance Decrement

Human performance degrades over time when monitoring systems with low event rates - this is called the vigilance decrement. Providing alerts and cues when significant events occur help reduce this phenomenon. Presenting a video image at that time may be best rather than continuous output. The operator is then challenged to identify what and where the event is. Mobile sensor platforms complicate the job for the operator, as the images are not static when compared to fixed cameras. Redundant reports from multiple overlapping sensors also must be correlated. Work at NOSC [Murray 1995] conducted studies on this problem with focus on multiple moving robotic systems but in indoor simulation only. Of note is the comment:

> *Results of this study provide some guidelines for predicting human-machine performance for systems involving multiple, autonomous sensors. The rapid increase in response time for even the modest levels of manipulations used here is cause for concern especially when newer systems are planned with large numbers of sensors and are designed for operations in cluttered environment.*

Human performance may be rate limiting in deploying multiple TMRs. [Murray 95] contends that traditional supervisory control (a la Sheridan) does not hold here. He advocates information extraction by the individual sensors ("keyholes") into a coordinated picture that could then possibly make the task more tractable. Also adding visual cues to the imagery (overlays) and methods to reduce redundancy from sensor overlap might also help.

4.2.6.4 Stress

The National Research Council Report cites numerous sources of stress for the soldier that can have impact on interpretation of display performance. These include

- Physical Sources
    - Heat and Cold
    - Noise
    - Vibration (see Section 2.1)
    - Extended operations/Time of Day
- Operational Sources
    - Task
    - Information overload or underload
    - Information versus disinformation (trust)
    - Physical work

These factors can result in fatigue or performance failure.
Several specific design guidelines for soldier displays are forwarded.

1. Rely on absolute judgment. Don't make calls on variables such as intensity or color with more than 5-7 levels.
2. Don't violate expectations based on previous experience.
3. Present the same information in multiple formats (voice and visual) - it increases understanding.
4. Make displays represent things realistically.
5. Moving displays should match mental model of users expectations.
6. Ecological design should encourage display to maintain correspondence with the environment it represents.
7. Information gathering cost should be minimized. Reduce eye movements from one location to another.
8. Use multiple sensory resources (sound and sight).
9. Provide predictive aids.
10. Place required information in environment such as checklists.
11. Be consistent across displays and with user habits.
12. Provide graphic displays whenever possible as opposed to textual.
13. Simplify graphics as much as possible reduces workload in high-stress environments.
14. Present salient info in center of display; peripheral information is neglected in high-stress situations.
15. Use redundant audio and visual warnings for threat location.
16. Reduce data entry requirements and menus to bare minimum during engagements
17. Use a small and understandable icon set.

4.2.7 Human Factors in Design

Now we examine how human factors considerations can and should influence the design of complex systems such as a TMR robot unit operator control unit.

4.2.7.1 <u>Design Methodologies</u>

In this early work, [Corliss et al 68], they partition the design task into the following allocations:

- Human assignments: Pattern recognition, target identification, new exploration, long-term memory, trouble shooting and emergency operation, planning, interpreting complex data, inductive thinking, settings goals and priorities while evaluating results
- Machine assignments: Monitoring multichannel inputs, boring repetitious tasks, precise motions and force applications, high speed motions, short-term memory, optimization, deductive analysis, computing, and monitoring

They arrived at this division using an algorithmic systems approach to partitioning the work between man and machine. The following design activities are prescribed in sequence and could be applied to a TMR robot unit as well.

1. Hypothesize the potential basic role of man
2. Hypothesize potential complementary and support role of man
3. Review manned system solution feasibility
4. Develop a preliminary operator concept
5. Analyze personnel support requirements
6. Review potential operator role for acceptance and reliability
7. Synthesize optimal operator role
8. Establish feasibility of man-rated allocation
9. Develop potential man-rated allocations
10. Review allocation potential against psychophysical capacities
11. Review allocation potential against system or function constraints
12. Review allocation potential against human reliability
13. Synthesize man-rated allocations

A related design approach appears in [Johannsen 1997] and is shown in Figure 64:

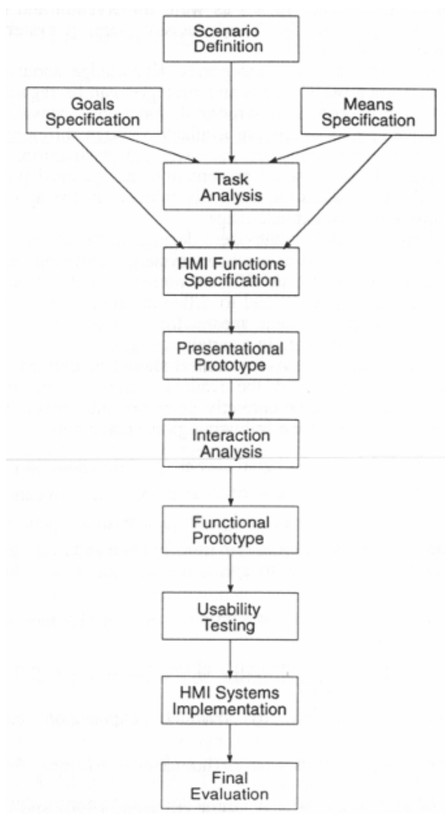

Figure 64. Johannsen's Design Methodology (from [Johannsen 97])

In another study, [Draper 93] cites three different ways to design telemanipulator systems:

1) Minimalist (TV and joystick)
2) More-is better- approach (full spectrum of sensory feedback)

3) Mission-oriented approach: acknowledges design tradeoffs in capability and cost seeking efficient solutions.

He recommends (as do we) the last of these approaches as the basis for design.

[Draper et al 99] further compares user-centered versus telepresence design approaches (Table 12). This helps to separate the hype surrounding immersive environments from the realities.

TABLE 1. COMPARISON AND CONTRAST OF DESIGN APPROACHES

	User-centered	*Immersive/telepresence*
Information	Efficient displays promoting situation awareness; information may be summarized or pre-processed before presentation	Displays that reproduce the sensory milieu at the remote or simulated site and eliminate stimulation from the user's physical environment (all information presented may not be relevant to developing situation awareness for task performance)
Responses	Ergonomical controls accepting inputs from modalities appropriate to stimulus-response paired with displays and tasks	Devices that digitize human actions (e.g., walking) or the results of human actions (e.g., sound, as in speech) in a natural way
Attention	Controls and displays are designed to focus attention on critical parts of a task	Controls and displays are designed to re-create the environment, usually with no attempt to shape attentional processes
Fatigue/ease of use/ workload	Interfaces designed to be minimally fatiguing and for ease of use; workload is an important concern and the task may be modified to maintain acceptable levels throughout the mission	Interfaces designed to be no more fatiguing than if the user was physically present in the SE: ease of use is assumed to be optimal because of naturalness and transparency; workload is not raised as an issue
Training	Some training is usually assumed to be necessary to efficiently operate interfaces	Interfaces are assumed to be so natural as to make training unnecessary; naturalness is also assumed to promote skill transfer from SE to real world if SE is being used as training tool

Table 12: Comparison of Different Design Methods for telepresence (from [Draper et al 99])

Sheridan [Sheridan 92], from an engineering perspective, describes 4 different classes of HMI interface systems (at the left) and their displays (right) as shown in Figure 65.

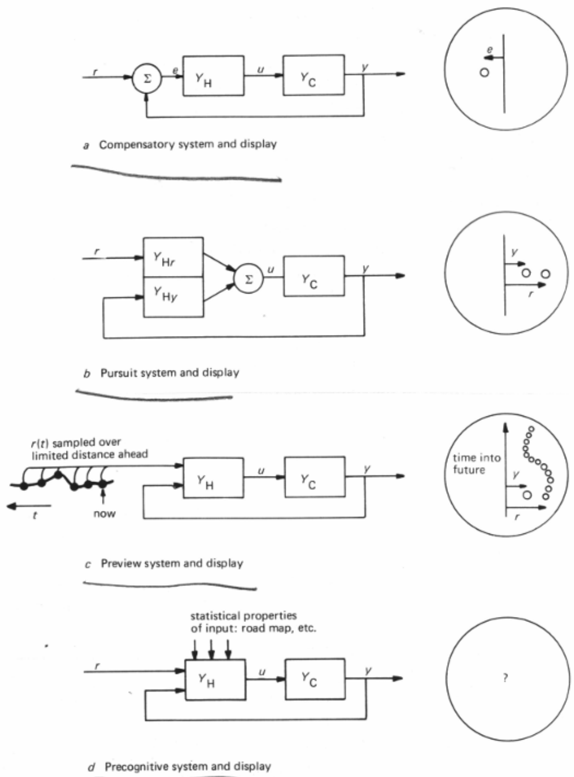

Figure 65: Sheridan's 4 classes of HMI designs (from [Sheridan 92])

4.2.7.2 Display Design Considerations

The National Research Council study on Tactical Displays for Soldiers [97] provides guidelines for display system design of potential use in TMR.

1. Design should minimize itself as a physical barrier to acquiring environmental information such as sight and sound.
2. It should enhance sensory input only when required.
3. It should not distract attention.
4. It should minimize cognitive load on operator by:
   - Providing fused information from multiple sources.
   - Allow for easy input of information.
   - Minimize memory needs.
   - Reduce irrelevant information.
   - Simplify information presentation.
   - Reduce tasks.
   - Present information in properly ordered sequence for task.
   - Provide information in correct format (e.g., maps).
   - Provide suitable cueing and attention directing mechanisms
5. Design should minimize complexity and avoid complex automation.
6. Should provide new capabilities to soldier.

7. Should allow for the easy sharing of information.

[Draper et al 1991] conducted a series of experiments to determine when and if to use stereoscopic television displays for teleoperation. There results showed that is was heavily task dependent in terms of performance improvement. They contend that "it is necessary to use an ecological perspective when considering teleoperator viewing systems", hence it is crucial to understand the task-environment in which the robot(s) resides. So whether or not stereo display systems are suitable for TMR type tasks will require specific task-sensitive studies to be performed.

4.2.7.3 Task Analysis Models for Design

[Draper et al 99] show the use of a task analysis model for the development of a DOD application for the navy (flight deck aircraft servicing). This formal approach assists in the design of an effective system, based on what is needed for what tasks. Summarizing the approach:

1. Identification of tasks and task elements.
2. Initial screening of tasks in terms of their impact on workload, and perceptual, cognitive, and movement requirements.
3. Development of task network models, establishing relationships between tasks.
4. Identification of task requirements for each task.
5. Identification of constraints on operation (physical and operational) to allow for development of alternatives.
6. Identification of subtasks (task decomposition).
7. Identification of replacement and alternatives (where robotics can best fit).
8. Evaluation of gains.

This process is iterative. The study cited above can serve as a potential exemplar for the development of a similar TMR-related study. One of the key outcomes would be a sound justification for the use of robotics technology in certain TMR-related task areas.

4.2.7.4 Alarm Design

[Riera et al 95] discuss the role of alarms in supervisory processes when operators are in a removed supervisory room. This may only extend in some ways to the work in TMR. Two categories of alarms are cited: not-programmed alarms that arise from external events (sensors for intrusion, overheating, etc.) and programmed alarms defined at time of design (threshold exceptions, etc.). These programmed alarms are of 2 types: breakdown (failure of physical components) and process (abnormal condition or behavior). They provide an inductive method from dependability science as a basis for alarm design, which involves a functional analysis of the system.

[Kuchar and Hansman 95] describe methods for evaluating the performance of these alerting systems. Figure 66 shows how alerting systems relate to both the operator and environment. This approach incorporates a human response model in its design.

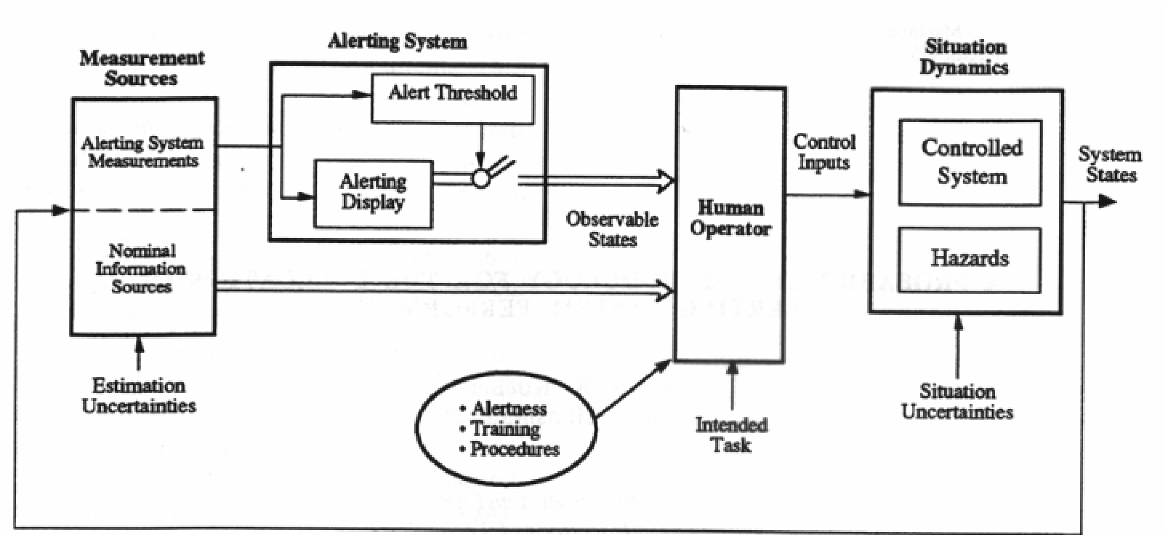

Figure 66: Alerting System Model (from [Kuchar and Hansman 95])

4.2.7.5 Teleoperator interface design

Research at SPAWAR [Gilbreath et al 2000] used several techniques to reduce cognitive load on the user of a teleoperated Mobile Robot (Robart II). Human-centered mapping is one such strategy where a human guides map building and exploration. The operator guides the robot into an area, using natural commands (e.g., follow the wall on the left"). This disambiguates sensor data, as the robot can use the human input for labeling purposes. This is also one of the very few systems that document weapon control (non-lethal) for a mobile robot. Unfortunately no user studies were conducted to validate the hypothesis that these techniques are of direct benefit to the end-users.

Additional SPAWAR work studied teleoperation in sewers and tunnels [Laird et al 2000], which clearly are TMR relevant tasks. In this instance, user studies were conducted on a reflexive teleoperated interface. It was said that the interface provided more sophistication than required by the soldier, the soldiers preferring a purely teleoperated strategy, interestingly. More automation is clearly not always better. A heads-up display was useful within the tunnels but not outside due to glare. Another complaint was the inability to view the video by more than one soldier at a time. Lack of a zoom feature on the camera was also a complaint. A second generation OCU was created but has not yet been field-tested. In any case, the soldiers preferred slow and steady exploration rather than faster semi-autonomous operation for this task.

[Murphy and Rogers 96] describe TeleSFX/TeleVIA, a system that provides a method for semi-autonomous control of robots that incorporates user modeling. They introduce the notion of tele-assistance where the operator only provides support for the robot, not control. Here an intervening computational agent between the human and the operator facilitates the communication and control between them. The system uses focus of attention and hypotheses panels to help direct the operator's attention and goals. The examples presented are more for error detection and diagnosis rather than for navigation, helping the operator to determine what to do in the light of sensory malfunction. Having the intervening agent, between robot and operator, digest and process the information prior to requiring operator intervention minimizes communication. The extension of this work to a broader class of failure diagnosis is clear and could make a useful support agent for this single aspect of TMR mission conduct (sensor management).

4.2.8 Operator Selection

Regarding operator selection, [Johnsen and Corliss 1967] state that "The operators [for telerobotics] should be selected with the same care as for jet pilots." In traditional teleoperation domains, they refer to the following essential capabilities (p. 65):

- Excellent depth perception
- Superior eye-hand coordination
- Display stability and resourcefulness in hostile environments
- Good physical condition

This assessment culminates in the statement that "Good manipulator operators are hard to find". Clearly TMR then should pay attention to the types of personnel dedicated to these tasks.

4.2.8.1 Individual Differences

Ackerman (currently at Georgia Tech) has addressed the question of identifying individual differences between operators for air-traffic control and other complex skill acquisition tasks. This can aid in determining who may qualify as the best TMR operators. In one study, he addresses ability testing methods for general, reasoning, spatial, perceptual speed, and perceptual/psychomotor abilities for assessing terminal radar approach tasks. He has developed a theory of ability determinants (Figure 67) that relates skill acquisition to different people. It is broken into three phases: cognitive, psychomotor, and autonomous. While beyond the scope of this report to discuss the underlying theoretical implications, it is of note that this theory can be used to design tests that can be applied to tasks to differentiate who might be the best operators for multi-robot control tasks. Some generic conclusions on the air traffic controller test that were gender based, include that men perform better on spatial ability tasks, while women outperform men on perceptual speed tasks [Ackerman 92]. The key for TMR is understanding what tasks are involved. The analysis, if desired could be extended to other subject dimensions as well: education, age, etc.

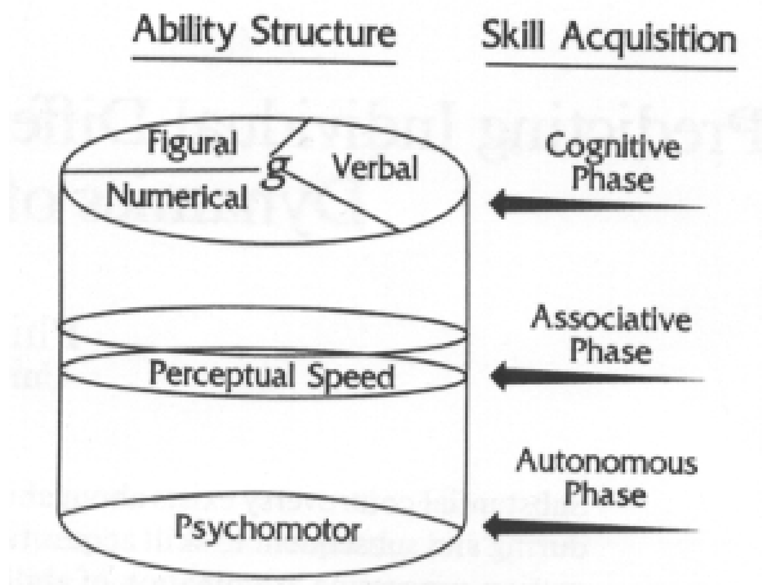

Figure 67: Ackerman's theory of Ability Determinants (from [Ackerman 92])

Ackerman's initial work led to a battery of tests that are used to evaluate potential air traffic controllers [Ackerman and Kanfer 93]. A wide range of tests (12), including things as seemingly simple as paper folding, letter/number substitution, dial reading, and necessary facts, to other tests involving spatial memory, problem solving and verbal tests were used to develop a composite of a potential controller. It is entirely possible that a similar set of attributes might also apply to TMR-type tasks, but a formal task analysis would need to be applied. This same battery of tests however may be useful, in differentiating just who might be the best controller given an accurate mapping of task criteria onto operator performance. Even more recently, he [Ackerman 99] has extended this to touch-panel testing, which potentially can provide an even more realistic interface assessment in conjunction with an operator's potential for performing in a TMR environment.

[Duncan et al 93] explored attention in the context of distraction. The test involved driving a car in an urban environment. This provides a measure for how easily distracted potential operators are, and can serve as measure of individual operator ability for TMR related tasks.

4.2.8.2 Skills needed

Air traffic controllers (ATC), who are charged with spatial management tasks TMR have been singled out as having much potentially in common with TMR operators controlling multiple vehicles. [Wickens et al 98] describe 9 ability categories that an ATC needs:

1. Spatial reasoning ability
2. Verbal reasoning ability
3. Numerical reasoning ability
4. Perceptual speed factor for coding
5. Selective attention

6. Short-term memory
7. Long-term memory
8. Time-sharing
9. Manual dexterity.

Verbal reasoning perhaps is the only one that might be extraneous to TMR. Much could be learned at looking in detail at training procedures for ATCs and seeing how similar processes could be applied in this program. Tables 13-15 illustrate task sets for and attributes of Air traffic controllers. Similar tabular analysis could be applied to TMR robot unit tasks

Task Set	Cognitive/Sensory Attributes	Number of Tasks
Entry	Coding	134
Receipt	Movement detection	3
	Spatial scanning	34
	Filtering	43
	Image/pattern recognition	42
	Decoding	157
Analysis	Visualization	7
	Short-term memory	35
	Long-term memory	10
	Deductive reasoning	107
	Inductive reasoning	16
	Probabilistic reasoning	43
	Prioritization	23
Communication	Verbal filtering	132

Table 13: Task set/Cognitive attributes for ATCs (from [Wickens et al 98]).

Attributes	Examples
Coding	Enter information into the maintenance log
Movement detection	Listen for alarm printouts
Spatial scanning	Observe status panels for status data
Filtering	Identify significant status data on status panel
Pattern recognition	Form mental picture of facility status
Decoding	Read a facility configuration display screen
Visualization	Determine operations impacts from weather picture
Short-term memory	Remember status information to record in log
Long-term memory	Remember procedures
Deductive reasoning	Determine that facility data are questionable
Inductive reasoning	Estimate impact from historical trend data
Probabilistic reasoning	Evaluate the nature of a degradation
Prioritization	Establish order for restoring equipment
Verbal filtering	Identify relevant verbal information

Table 14: Example ATC cognitive attributes (from [Wickens et al 98]).

Cognitive Functions (Higher To Lower)	Cognitive/Sensory Attributes	Number of Tasks
Plan/resolve	Prioritizing	23
Predict longer term	Inductive reasoning	16
Compare, predict shorter term	Deductive reasoning, pattern recognition, probabilistic reasoning, visualization	199
Transmit information	Coding, decoding, verbal filtering	423
Remember	Short-term memory, long-term memory	45
Identify	Filtering, movement detection, spatial scanning	80

Table 15: Hierarchy of attributes of ATCs (from [Wickens et al 98])

4.2.8.3 Tunnel Vision as basis for selection

Tunnel vision is defined by Boer [Boer 1995] as a narrowing of attention by concentrating on a part of system where the operator loses the overview. Narrowing of attention occurs as mental workload increases. At high levels of workload task-relevant stimuli are excluded. This occurs in situations for example when the operator is handling fault management. In certain cases, tunnel vision also occurs due to waiting for information. Boer suggests that it is possible to assess the proneness of operators through tests, and where necessary provide remedial training for "weak" operators. Of course if this is a criteria for selection, these "weak" operators who are prone to tunnel vision can be excluded from the population of potential TMR operators.

4.2.9 Training operators

Perhaps the best results regarding guidelines for training teleoperators and operators of autonomous systems is contained in the Final Report of a Workshop sponsored by DOE entitled "Guidelines for the Development of Training Programs for the Operation and Maintenance of Robotic Equipment" [Byrd and Duke 98]. This report, provided by John Draper from ORNL, is highly relevant to TMR as it describes in details the duties, tasks and elements for teleoperators, advanced teleoperators, and autonomous systems. These are mapped onto the knowledge, skills, and abilities sets that individuals either need to possess or be trained to possess. Relevant portions of this report are reproduced in Appendix A. These can be easily mapped onto Soldier training publications (STP) and Training Support Packages (TSPs) as used by the DOD in general. New Military Occupational Specialties (MOS) can be created for telerobotic operators, as the skill sets in this DOE study are clearly enumerated and many of which would be highly relevant to TMR. This report can provide guidance in the formulation of DOD mission training plans as well. STPs, TSPs, and mission training plans for typical infantry tasks can be found at the home page for the Army's Training and Doctrine Digital Library (http://155.217.58.58/atdls.htm). A suitable follow-on task for TMR would be to attempt to develop a TSP and STP for specific TMR relevant MOSs, e.g., robotic operation and maintenance, based on the datapool provided in the DOE report.

[Chappell and Mitchell] point out that well trained novices does not result in expert performance. Expert operators anticipate patterns of normal operation and quickly recognize prototypical failure modes, while exhibiting confidence in their ability. Various techniques can be used to train novices including computer-based instruction, low-fidelity, high-fidelity and high-fidelity with motion based simulators, Often the compression of large volumes of materials results in stress in the trainees. The authors recommend the introduction of intelligent tutoring systems to bridge the gap from trained novice to expert. These systems are tailored to the individual student's needs.

Gopher [Gopher 93] studied issues regarding the role of attention control and how to train operators to perform better. In particular, he was concerned with strategic control of attention, i.e., do people know how well they invest attention and execute related attentional strategies. Successful examples include:

- Focusing attention (voluntary selection).
- Dividing attention (coping with concurrently presented tasks).
- Switching attention (voluntary movement of control from one task to another).
- Investing graded levels of effort (dividing attention over tasks of differing priorities).

Problems that occur in people in managing attention include:

- Failure to protect primary-task performance.
- Dissociation between subjective estimates and performance measures of workload.
- Lack of adequate feedback.
- Attention capture by automatic components (subjects needed to be trained to be able to relax and release attention).
- Ability to release resources voluntarily.

Gopher developed a series of tests [Gopher 93] that are geared to enhancing an operator's ability to manage attention more effectively, a crucial role for control of multirobot missions. In particular he used videogame scenarios to develop these skills, which might account for the intuition that those who are good at video games might also be good for TMR related tasks.

[Zachary et al 98] describe a training environment for tactical teams. It provides performance assessment, cognitive diagnosis, and instructor support in addition to simulation facilities. The task domain is for the Air Defense Team component of the Navy's AEGIS command and control system. The AETS training system embeds cognitive models of each of the trainees. The value of embedding models is predicting actions and diagnosing faults. Unfortunately no data was available regarding the efficacy of this method.

Other new approaches to training [Wickens et al 98] include the use of embedded training where the training resides within the actual operational system. These embedded trainers:

1. Require operators to perform tasks in response to simulated inputs
2. Present realistic scenarios including downgraded operational modes
3. Be interactive in assessing the operators ability
4. Record performance and provide feedback.

4.2.10 Cognitive Modeling

[Kirlik et al 1993] studied human performance in a simulated task related to some potential TMR applications. In particular they looked at scout aircraft operating in dynamic and uncertain environments that could be controlled either manually via joysticks or through the designation of waypoints via a map interface. One and two person crews were studied. The scout craft in which the operator was notionally housed controlled 4 semiautonomous friendly craft with the goal of finding desirable target objects within the world. A large number of enemy craft were also present. While the task itself was somewhat contrived, it did give rise to an affordance-based model of cognition that was used to account for the human performance in the task. The outcome of the work in regards to user interfaces is that automated assistance could be designed based on the user model and that highly effective graphical representation could be created based on the affordance that the system needs to convey to the user, rather than on some arbitrary available representation. Similar modeling processes could be applied to TMR operators, that would result in analogous models to what is depicted in the Figure 68 that resulted for this particular task.

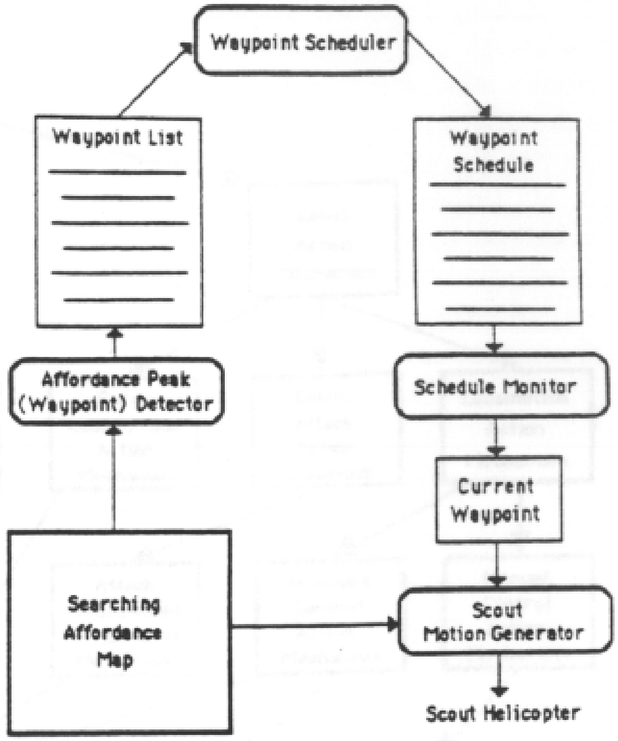

Figure 68: Kirlik's Model of Scout Search path planning (from [Kirlik et al 93])

[Callantine and Mitchell] have studied how operators select and use various automation modes to control complex dynamic systems. This methodology is potentially applicable to TMR-type tasks for tracking just how operators perform their tasks. The cognitive model on which it is based is called OFM-ACM: Operator Function Model for Systems with Automatic Control. While this system has been tested in flight cockpits for Boeing 757/767 simulators it may be extendible to other domains such as TMR as well. No explanations for actions are provided just tracking and organization of the user data itself.

4.2.11 Summary Recommendations – Human Factors

The assumptions underlying the recommendations in this section are based upon discussions with LTC John Blitch, DARPA Program Manager for the Tactical Mobile Robotics Program. We are considering a system where a field operator may be capable of controlling up to 4 TMR units simultaneously. These may be coupled with multiple operators, each capable of managing similar units. At issue is what should the interface be like in terms of managing load, what types of skills are necessary for such an operator, how could training be most effectively conducted, and how could we evaluate performance. The following recommendations speak directly to these issues in that context.

It must also be stated as there are no studies that specifically address the human factors for this task domain, the basis for these recommendations is from extrapolation of studies that typically consider only one or a few of the related issues. As such these recommendations are speculative and must be confirmed through formal studies to truly be considered well founded. They do provide a basis for generating hypotheses for subsequent formal testing in TMR scenarios, which is a strong recommendation for the TMR program. For many of the recommendations below, the reference study on which it is based is cited alongside the recommendation itself.

1. It is clear that straight teleoperation will be inadequate for such a complex task, due to the cognitive difficulties in managing multiple robotic units, with the additional complexity of conducting these operations in stressful environments. Low-level supervisory control is even questionable in terms of providing the necessary operator support. Thus specialized high-level supervisory control with the ability to treat the robots as a unit, or fully automatic (autonomous) control, with alert-based operator intervention, is likely the best course [Sheridan 93].
2. Telepresence is likely not a viable solution, due to the need for the military operator to maintain an awareness of his surroundings as a defensive posture. Thus situational awareness must be twofold: local to the operator as well as remote from the distributed robotic team.
3. Regarding specific sensory cues for inclusion in an OCU for TMR:
    a. Vibratory information can be useful to provide feedback on state achievement, or where it may increase the subjective feel of the operator to the robot's environment as in the presence of an enemy [Kontarinis and Howe].
    b. Mixed haptic/visual feedback has been demonstrated to provide enhanced control over purely visual feedback systems. Specific data is provided in Section 3.2.3 for guidance in the design of such a system based on the limitations of human spatiotemporal response.
    c. Auditory presentation (given a sufficiently quiet environment) is valuable for short simple messages that do not need to be remembered and that are involved with current events. They can be of particular value if the operator is on the move. Stereo and other forms of auditory presentation can provide 3D information regarding the source of an event (e.g., presence of target) [Burdea 96].
    d. Motion sickness in the operator is something that needs to be considered for any form of heads-up or helmet-mounted display when the operator is ambulating or driving. Coupling the visual feedback from the robot with the motion of the observer seems one of the better approaches to avoid this effect.
4. Regarding display characteristics:
    a. If the operator will be on the move and subject to vibratory stresses, bar graphs are recommended over polygonal representations as graphics, as these have been shown to be more accurately interpreted [Desombre et al 95] under these conditions.
    b. Operator stimuli should be presented in an easy to discriminate manner that reduces visual search or scanning time [Sheridan and Ferrell 74].

c. For monitoring tasks, where boredom or tedium may be a factor, means by which to keep the operator engaged with the TMR robots is important to avoid the so-called vigilance decrement. Artificial tasks can be added for this purpose [Thurman and Mitchell95]. As TMR is likely to have robots that possess a high level of autonomy, it is important that the operator not be lulled into a false sense of security.

d. Use of scene-linked symbology for heads-up displays, superimposed on returning video imagery is strongly recommended to attain real-time response for events that need such attention. The use of perspective (distance-dependent symbol size), differential motion, and natural coloration can also reduce attentional tunneling in the operator[Foyle et al, McCann et al].

e. A helmet-mounted display should not occlude the soldier's view in the field. Wrist-mounted or hand-held displays are recommended as an alternative if the HMD cannot be so designed [National Research Council].

f. Egocentric coordinate systems for displays are preferred over absolute geographic ones [McCann et al] to reduce the need for mental transformations in the operator's head. How this can be accomplished with groups consisting of multiple robots is harder to determine at this time, and warrants additional investigation.

g. The OCU must be designed recognizing that it will be used in a stressful environment, incorporating the specific stress reduction guidelines presented in Section 3.6.4 [National Research Council]. Also incorporate the other design guidelines from this NRC study in the OCU's display design (Section 3.7.2).

h. Employ a tested design methodology for OCU design, rather than an ad hoc approach. Candidates from Section 3.7.1 and 3.7.3 include [Corliss et al 68], [Johannsen 97] and [Draper et al 99]. A mission-oriented approach as advocated by [Draper 93] is recommended.

5. Regarding robot design characteristics:

    a. Camera mounting position on a TMR if used for visual feedback control can have significant impact on operator performance [Levison and Baron 97]. Human factors studies should be undertaken to evaluate just what the effects are of low-mounted ground hugging cameras on operator performance. No such study is in existence to the best of our knowledge.

6. Regarding Operator Performance:

    a. There are fundamental concerns as to whether humans are capable of managing complex distributed sensing and actuation environments at all [Murray 95]. Serious studies should be undertaken early in TMR, to evaluate if operators are potentially capable of managing as complex a task as envisioned for 4 robot units. To a degree, this will determine the requisite level of autonomy for the robots, if the task would otherwise require significant operator interaction (and not simply monitoring).

b. It does not always follow that more automation improves operator performance [Wei et al 95]. Judicious choice of automation techniques should be made in the design of TMR, avoiding the use of automation for automation's sake. This is further confirmed for TMR-like tasks for single robots operating within sewers [Laird et al 2000].

c. Human error occurs most frequently during intervention [Sheridan 93]. Special care should be engineered into the system to reduce this possibility.

d. Appropriate levels of trust must be developed between the operator and the robots, somewhere between mistrust and overtrust [Wickens et al 98]. Section 3.6.2 cites the relevant criteria which must be addressed in design and training.

e. Other human errors to which attention must be paid include:

   i. Mode error and ambiguity [Dezani et al 98]

   ii. Dual-task interference, a potentially very serious source of error for controlling groups of robots [Van Selst].

   iii. Misalignment of operator's mental model of the system with the actual system [Palmer]. This can be partially addressed through training.

7. Regarding operator selection:

   a. Different individuals have different abilities. Care should be taken in operator choice. It appears very unlikely that all soldiers will be properly suited for TMR tasks involving teams of robots, even with suitable training. Potentially, a good TMR operator may be far and few between.

   b. Test batteries exist that can be used to help determine which individuals are likely to be best suited for TMR operations. It is recommended that air-traffic controller tests be considered as a point of departure for such evaluations [Ackerman and Kanfer 93]. They appear easy to administer and likely will need to be supplemented with additional functionality. A first cut based on ATC operators regarding the skills needed for TMR is presented in Section 3.8.2 [Wickens et al 98].

   c. Specialized attentional testing to avoid including operators who are prone to attentional tunnel vision is also recommended [Boer 95].

8. Regarding operator training:

   a. In order to avoid adverse impact on response time, training should focus on familiarizing operators with relevant TMR stimuli and their presentation: to reduce their unexpectedness [Sheridan and Ferrell 74].

   b. Appendix A contains guidelines for the training for the operators for robotic equipment developed by the DOE. These guidelines should be seriously considered and expanded appropriately for TMR-related tasks [Byrd and Duke 98].

c. The use of intelligent tutoring systems integrated directly into the OCU appears to simplify in-situ training of operators [Chappell and Mitchell].

d. Tests to improve the ability of an operator to manage attention are available, which is crucial for a multirobot environment [Gopher 93]. These should be considered for applicability to TMR.

e. Training environments can also be of value (which is well-known) and perhaps TMR should consider investing in such an embedded simulation system [Wickens et al 98].

9. Evaluation:

   a. Definition of metrics for task and operator performance must be defined clearly and early in the design process. Traditional metrics include task performance time and success ratio, but measurements of operator stress, fatigue, and workload management are certainly necessary as well for TMR.

   b. The workload measurement rating system (Figure 45) or the NASA TLX workload index [Draper and Blair 96] appear to be suitable candidates for the basis of quantifying operator performance for TMR tasks.

   c. Alarm-based operator performance can be assessed using methods similar to those developed by [Kuchar and Hansman 95] (Section 3.7.4).

5. USABILITY STUDY RESULTS

5.1 Introduction And Background

This report presents an introduction to *MissionLab*, a Graphical User Interface (GUI)-based mission specification interface developed for robots and the usability experiments conducted to evaluate and improve this interface. The development of *MissionLab* is an ongoing project of the Mobile Robotics Laboratory at Georgia Tech, funded by DARPA under the Tactical Mobile Robotics Program. Initial development of the *MissionLab* software system began under funding from DARPA's Real Time Planning and Control Program for use within the Demo II program[1]. This research involves the development of a powerful graphical toolset that allows users to create, modify and test tactical missions suitable for urban warfare and that can be used for a wide variety of different types of robots. Using the features provided by the system, users can specify a series of actions that combine to form a mission, which can then be run using an actual robot in a real-world scenario, or alternatively it may be simulated graphically on a computer. Such a system, commonly described as a Robot Programming Toolset, provides both an easily learnable and highly intuitive medium to specify robot missions, while providing a convenient interface to test the mission designs in simulation and evaluate their performance.

The set of experiments described in this report were conducted in order to experimentally evaluate the usability of the *MissionLab* interface and to determine to what extent the current interface provides the level of functionality that serves as the goal of the project, i.e., determining how successful novice users are at designing military-relevant missions using the interface. In addition, these experiments serve to provide a set of data that serves as a baseline against which future versions of the system will be evaluated.

Evaluation of the usability of a system can occur at different stages in the design. In this particular case, the focus is on trying to evaluate the usability of an existing system. Although several popular evaluation techniques exist in the human-computer interaction (HCI) literature[2], the availability of a fully working model of the system facilitated the use of Usability Testing, which attempts to study and measure how representative users interact with the system while performing realistic tasks. *MissionLab* has been subjected to usability testing previously, dealing with lower level aspects of the interface[3]. This study focuses on the capturing of actual mission intention and performance by the user.

The remainder of this document discusses the conduct of these experiments and the information gained from them. Section 2 provides an introduction to the components and interface of *MissionLab*. Section 3 describes the demographics of the subjects used during the usability studies. Section 4 presents in detail the procedure of the studies and explains the tasks assigned to the subjects. Section 5 details the information gained from the usability evaluation, including the process of data collection, the analysis performed on this data, and a discussion of the results

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[1] MacKenzie, D., Arkin, R.C., and Cameron, R., "Multiagent Mission Specification and Execution", *Autonomous Robots*, 4(1), Jan. 1997, pp. 29-52.

[2] Miller, J.R. and Jeffries, R.. "Usability evaluation: Science of trade-offs", *IEEE Software*, pp. 97-102, Sept. 1992.

[3] MacKenzie, D. and Arkin, R.C., "Evaluating the Usability of Robot Programming Toolsets", *International Journal of Robotics Research*, 4(7), April 1998, pp. 381-401.

obtained from this analysis. Section 6 is a summary of a different set of usability experiments conducted at Georgia Tech that investigated changing the look-and-feel of the interface through alternate designs, to further improve the usability of the system. Section 7 summarizes our conclusions and describes potential future work in the area.

5.2 MissionLab Explained

To achieve the desired aim of producing an interactive behavior-based mission configuration system for autonomous robots, the Mobile Robotics Laboratory at Georgia Tech has developed *MissionLab*, a GUI-based visual interface that allows a user to design, modify and test robot missions on real and simulated robots.

MissionLab is a software toolset consisting of several major components. This study focuses on two in particular, CfgEdit (the configuration editor) and MLab (the *MissionLab* console).

5.2.1 CfgEdit – MissionLab Configuration Editor

This graphical user interface (GUI) permits users to specify and edit tactical missions that they wish the robots to perform. *CfgEdit* provides a graphical workspace on the screen where a user can piece together robotic tasks, behaviors, and transitions into a complete sequence that forms a coherent mission. The design format of the missions is based on Finite State Acceptors (FSAs), where the design consists of a series of actions to be performed, or states, which are linked together by a series of transitions, or triggers. A user requires no knowledge of FSA theory at all. Every mission begins with a default Start state, and the user can add states and triggers from the tactically relevant list of predesigned behaviors as they see fit. By stringing together sequences of states and triggers, a robot can be programmed to perform complex tasks in a relatively easy manner.

In cases where the mission involves simple navigation linked to a map, CfgEdit allows the user to place waypoints on a map overlay. Waypoints, as described later, are map-derived geographic transition points that a robot must pass through in a specified sequence. This allows the user to program a specific path for the robot to follow through the map. These maps, called overlays in *MissionLab*, usually consist of an aerial photograph or graphical layout of an area on which significant locations and obstacles have been marked. Using a combination of the newly developed waypoints interface and the conventional FSA-based CfgEdit interface (Figure 69), an integrated mission can be built in an efficient and well-coordinated manner. It is the goal of this usability study to ascertain just how efficient and well coordinated a user-constructed mission actually is.

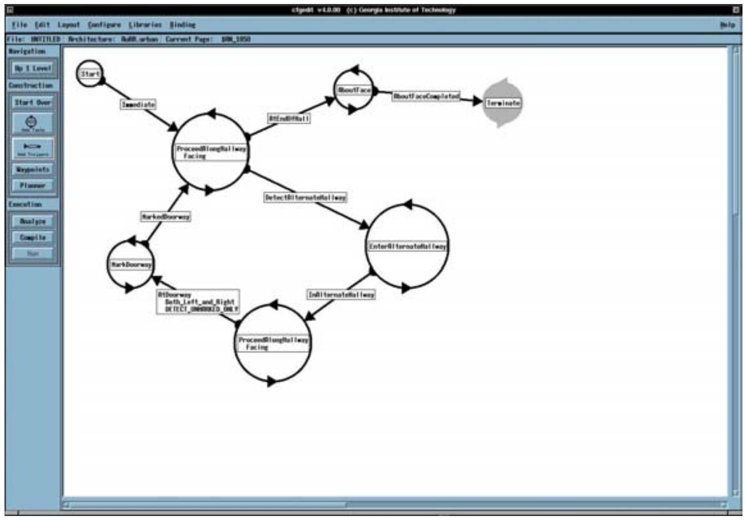


Figure 69: CfgEdit interface with simple mission depicted.

5.2.2 ***MLab*** **– MissionLab** ***Simulation and Execution Interface***

After a mission has been designed and compiled using *CfgEdit*, the *MLab* utility is used to test the execution of the mission. *MLab* allows the option of running the designed mission on either a robot or a simulated robot depicted on the computer display. For the purposes of the usability studies described in this paper, the missions were simulated on screen, as the primary goal of the study was to evaluate the users' ability to design missions, and not to evaluate the running of those missions in actual tactical areas. Although it would be desirable to do so, the logistics and time required to run subjects with actual robots for premission planning and specification was beyond the level of effort provided for this project. This is not problematic at all from the study's perspective, as this evaluation pertains only to premission operations, and not actually run-time control of robots. Those run-time studies, which relate more to Operator Control Units (OCUs) than to robot programming toolsets, are not generally applicable to the *MissionLab* system in its current embodiment, as it is not currently intended to serve as the OCU for tactical missions.

MLab also allows a user to load an overlay map (Figure 70), as described in the previous section, upon which to run the simulated mission. When the user's mission runs on an overlay, symbolic objects on the overlay are recognized and treated behaviorally as real objects by the simulated robot. Thus, in a simulated mission, the robot would actually navigate around any obstacles detected on the map, and would recognize targets such as its home base or a door in a hallway. In this way, the user can evaluate the mission design chosen and determine its appropriateness without the cost and effort involved in actually performing a real robot run in every case. It also allows for the testing of scenarios from a remote location, i.e., a mission can be simulated on an overlay when it is not possible to test it in the real target location in advance. It should also be stated that the simulator capability is intended only to assist the user in validating whether or not their created mission matches their intentions. It is not intended to be a high-fidelity simulator that can provide guarantees about the robot's performance within the target environment.

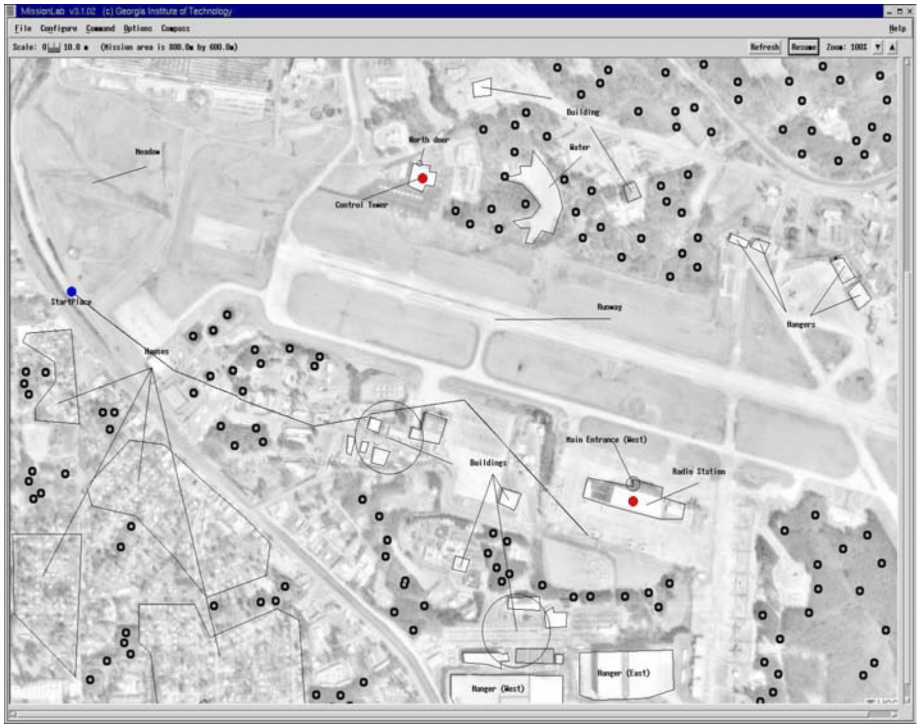


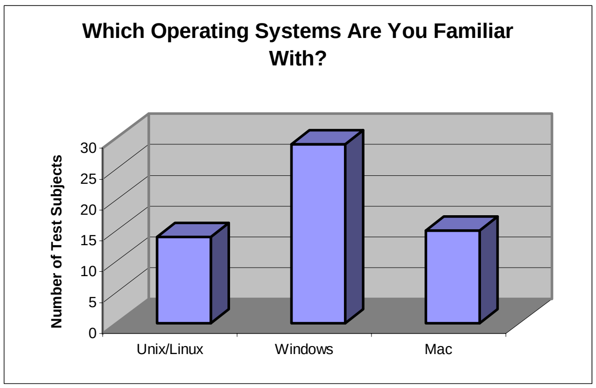
Figure 70: MLab console and simulator with overlay shown.

5.3 Subject Demographics

The Tactical Mobile Robotics (TMR) Program is geared towards designing robots and robotic interfaces that the soldier can use in the field efficiently and effectively. These soldiers may or may not have any significant technical background, and their experience with the system may consist of only a small set of tutorials or examples. It is very important, therefore, that the interface be designed and evaluated with this kind of user in mind. In gathering subjects for our study, we sought to recruit outside of the computing community. The backgrounds of our subjects included various disciplines of engineering, physics, mathematics and psychology. We also have subjects from non-scientific backgrounds, such as those in administrative positions. Importantly, we had a small number of subjects with military experience, such as ROTC students. We did recruit a fair number of technically and computer-savvy test subjects, as it is important to evaluate the performance of these groups as well, determining – if they succeed where others fail – the kinds of assumptions we are making that a subject of a non-technically oriented background might not comprehend.

Subjects were recruited via bulletin board postings in the Georgia Tech College of Computing as well as postings on general campus-wide newsgroups. While most of the subjects recruited were computer savvy in the sense that they either had a background in computer science, or they were beginning studies in that discipline, we limited our subject pool to younger students who did not have much experience in Computer Science. We compiled a total of 29 subjects, and for the purposes of evaluation, we divided them into three groups: novice, intermediate and expert. The novice group had very little or no experience with computers, and little experience with dealing with any type of machine interface, such as video games or other electronic devices. The second group, the intermediates, consisted of those subjects familiar with computers, adept at most general applications, and who interacted with these machines at some level on a routine basis. This group was mainly comprised of technically oriented, but non-Computer Science, disciplines such as engineering and physics. The final group, the experts, consists of primarily those subjects with computer programming experience or some level of education in Computer Science. This group comprised the bulk of our participants, although we tried to limit their numbers. The breakdown for each group was 8, 8, and 13 participants, respectively for the novice, intermediate, and expert levels.

The charts that follow on the next 2 pages show the breakdown of the subjects in terms of gender, major of study, education level, military experience, programming experience, operating system experience, and experience with using a computer mouse. In addition, the subjects were also asked to rate their ability to give directions.



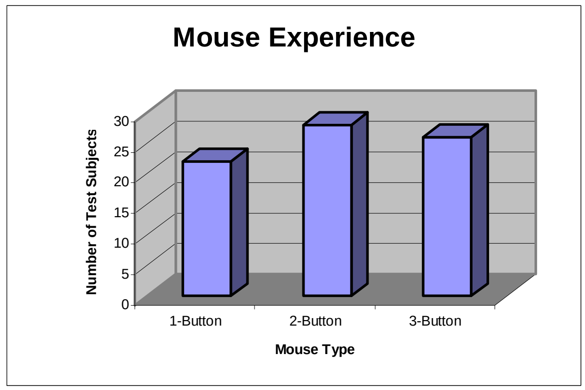
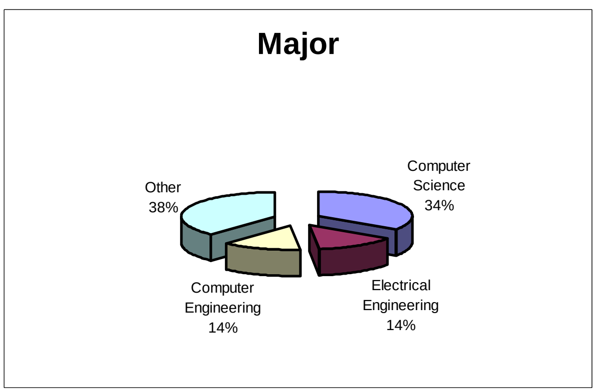


Figure 71: (Left) Operating systems experience, (Right) Mouse experience.



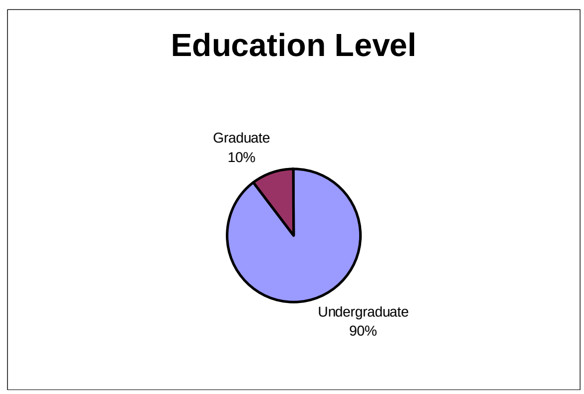
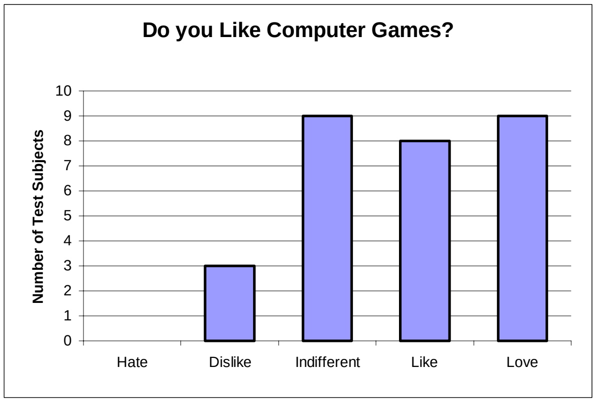


Figure 72: Education level.



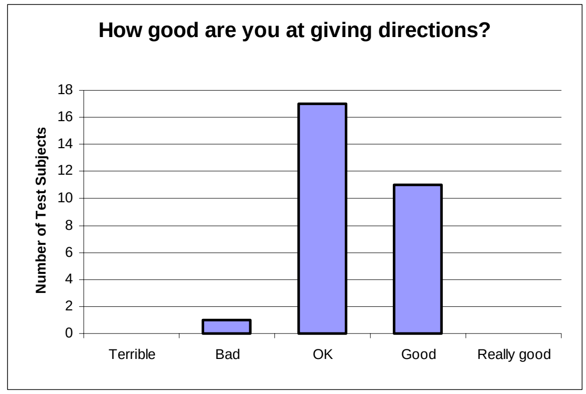
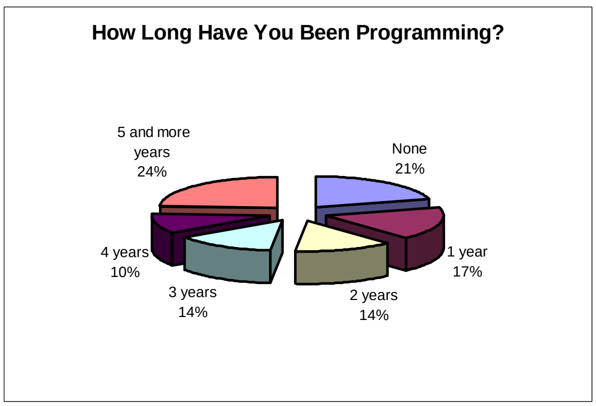


Figure 73: Participant subjective questions.



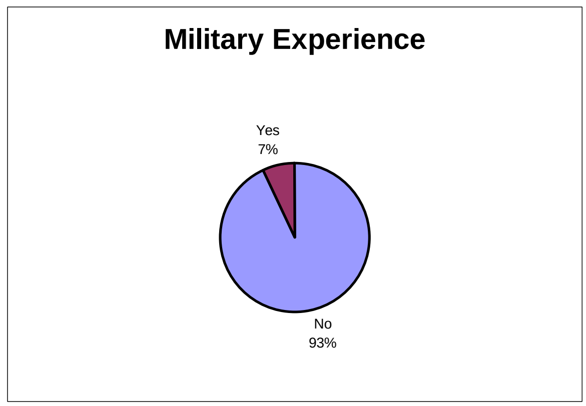


Figure 74: Experience levels.

5.4 Study Procedure

Upon entering the first phase of the study, the subject is introduced to his or her test administrator and a brief explanation of the study is given. The description of the TMR project and the objectives of the study are summarized approximately as below (some variations from the text below occur occasionally, at the discretion of the Research Assistant administering the test).

> *Tactical Mobile Robotics is a Defense Advanced Research Projects Agency funded program geared toward developing robotic technologies to be used in military scenarios. Some examples include surveillance, reconnaissance, rescue, and patrol. Our (Georgia Tech) task in this framework is to develop a suitable interface for which soldiers or other persons with minimal technical experience can configure these robots on the fly to perform tactical missions. It is therefore crucial that our interface be simple and straightforward, yet powerful and extensible. The purpose of the study is to evaluate user performance with this software given a particular mission specification and minimal a priori instruction.*

The subjects are told that they will be completing two phases. The first phase will be completed during this (their first) session, and the second phase will be completed when they return for the second time. For the first phase they are told they will complete two simple tutorials that will familiarize them with the interface and be given some instruction about building missions with the aid of waypoints chosen from a map. They will then be given two tasks for which they will use what they have learned and configure a mission according to the task specification without any help or interference from the task administrator. Once done, they will be debriefed on what they had accomplished and briefed on what to expect in phase 2 when they return at a later time.

Figure 75: Usability Laboratory.

This being said, the subjects are asked if they still want to continue, and if so, they are requested to sign a consent form outlining their rights as a study participant (Appendix C). They also complete another form detailing their background with computers and computer science (Appendix D). When the subject completes these tasks and signs the consent form, the first tutorial of the first phase begins. On completion the subject also completes a post-test questionnaire (Appendix E).

The study environment for each phase is kept consistent and uniform. The studies are conducted in the Usability Laboratory (Figure 75) at the College of Computing at Georgia Tech, where the participant is provided with an isolated area in which to perform the tasks assigned to them[4]. While the test administrator is explaining the tutorials or the required tasks to the subject, the administrator remains in the room, but once the subject begins to work on the assigned missions, the administrator leaves the room and observes proceedings through a viewing window. In

[4] Due to construction in the Usability Lab that coincided with some of our studies, some subjects were relocated to a comparable isolated area within the Manufacturing Research Center for their testing

general, subjects are encouraged to go through the entire design process by themselves, but if they reach a point where they are unable to progress, they may signal the administrator and ask for help. At the end of the allocated time, or if the subject feels they have successfully completed the mission, the administrator returns to the room and completes any additional processing that may need to be done, such as providing a post-test questionnaire or filling out subject payment receipts.

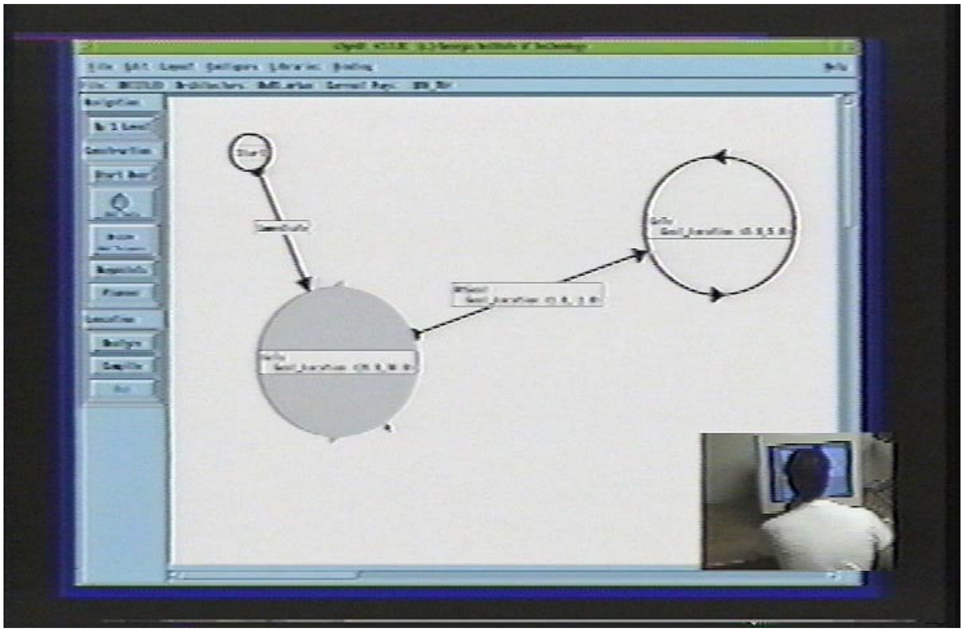


Figure 76: Image from video recording of study

The entire process of the mission design is recorded using a video camera that captures the subject's actions, overlaid onto a video image captured from the screen as the image is recorded. This composite video recording (Figure 76) provides the ability to duplicate the entire process the subject went through while designing the mission. In addition, for the purpose of analysis of the mission data, data logs are captured and saved to disk. For details regarding data capture, see Section 5.

5.4.1 Phase 1.

The Phase 1 session consisted of two tutorials intended to provide the subject with their first introduction to the *MissionLab* system. This was then immediately followed by two test tasks to assess their initial performance on the waypoint interface for mission specification. Tutorial 1-1 is a brief introduction to the *MissionLab* interface and takes approximately 5 minutes. Tutorial 1-2 is an introduction to more specific features, such as waypoints, and takes approximately 10 minutes. For each of Task 1-1 and Task 1-2 in Phase 1, the subject is allocated 20 minutes to complete the mission. At the end of this time, or if the subject believes they have successfully competed the task, the administrator returns and administers the next task.

5.4.1.1 <u>Tutorial 1-1.</u>

The first tutorial begins with a simple introduction to the *MissionLab* interface. The administrator explains to the subject the meaning of the information that is displayed when a user first loads the configuration editor (for a detailed explanation of the *MissionLab* configuration editor, please refer to the *MissionLab* User's Manual[5]). The administrator explains how the graphical editor uses icons to hide the details at each level of a mission specification hierarchy. A click of a mouse button will open a new page and progressively shows the level of detail that the mission designer (i.e., the subject) wishes to see.

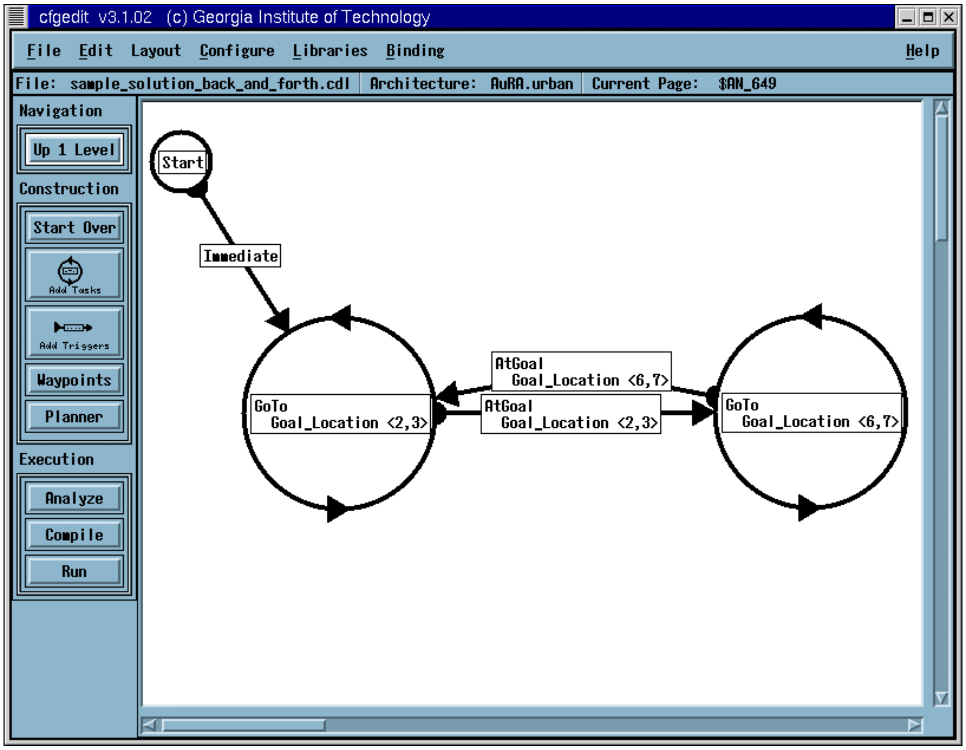


Figure 77: Sample configuration from back-and-forth tutorial.

These tests focus on the mission specification level, which is where the actual configuration of robotic behaviors is performed. A mission consists of a series of actions to be performed, which are represented at this level as circles, which we call states or tasks. The subject is then guided in the creation of two new tasks. These are *GoTo* tasks, which cause the robot to move to a location that the administrator specifies. The subject enters different location coordinates for each of these tasks. He or she then links them together by creating triggers, so that a transition between tasks can be made when a certain condition becomes true. The subject is informed that the arrows do not indicate the direction the robot is moving, but rather they say what conditions will "trigger" a robot in one task state to stop that task and start a different one in the next connected task state. The Administrator briefly discusses the concept of an FSA (or finite state automaton) for those participants who have not had education in Computer Science. Figure 77 shows the FSA typically created during tutorial 1-1.

When the subject finishes his or her configuration, the mission is compiled with the click of a button and tested by the subject in simulation (Figure 78). This first tutorial is a very simple

[5] The *MissionLab* User's Manual (and software) is available at www.cc.gatech.edu/ai/robot-lab/missionlab.

example, and does not present any problems in simulation, but later, as it is explained the participant, simulation will become more of a tool for debugging the mission specification. The subject is also taught the basics of the compile and run dialogs. For the most part, these evaluations are automated and all the necessary parameters are set beforehand, giving the user as little room for error as possible. The ideas are still explained, however, to help the subject get a better feel for the *MissionLab* system. After successful compilation and execution, the user is then freed to re-examine his or her original configuration, modify it if he or she so wishes and run it again. Otherwise, the subject is ready on to move to the second tutorial in Phase 1.

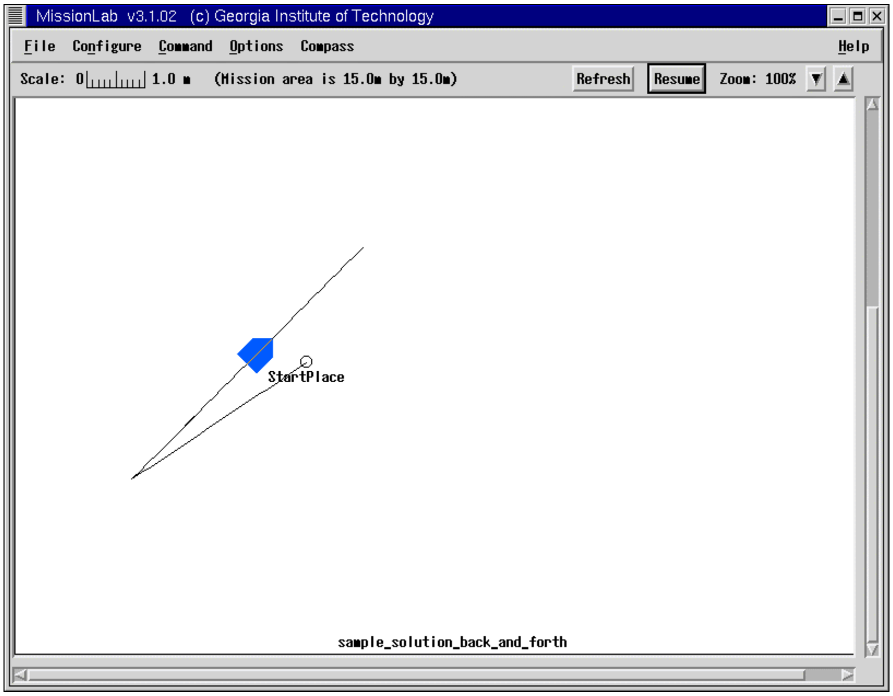


Figure 78: Simulation of back-and-forth configuration.

5.4.1.2 <u>Tutorial 1-2.</u>

In tutorial 1-2, we introduce the concept of waypoints, and instruct the subject how to build a mission plan simply by choosing points on a map. The goal of this tutorial is to show the participant that much of the design process that they had experienced in the previous tutorial can be automated by means such as waypoint selection. This allows for faster, more efficient, and more accurate mission planning.

A waypoint is loosely defined as a point through which a robot travels on its “way” to its destination. To a robot, specifying waypoints is very easy, much like giving directions to a colleague, except that the robots use precise locations instead of landmarks, although the latter could certainly be implemented with the right sensors. The administrators explain to the subjects that location coordinates chosen from a map can, at execution time, be determined by the robot from sensor modalities such as the Global Positioning System (GPS), which is what is intended in this example tutorial. The subject is provided as an overlay a satellite photograph of a part of the Georgia Tech campus (Figure 79). The subject's objective is to configure a mission plan for an individual robot that, starting from a point outside the Manufacturing Research Center (MARC) building on the Georgia Tech campus, takes the robot through a path, with certain characteristics, that leads up to the College of Computing.

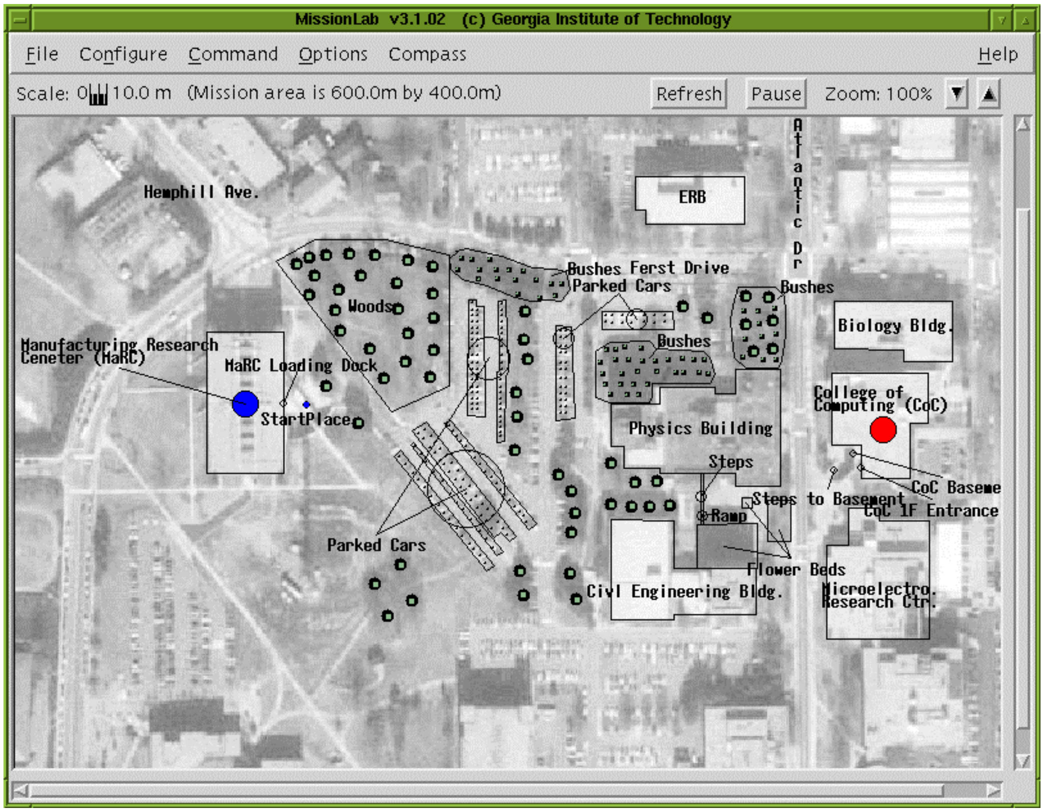


Figure 79: Overlay of Georgia Tech campus used in second tutorial.

To design this class of missions for the TMR program, a waypoint chooser interface was constructed and integrated into the *MissionLab* toolset, which allows the subject to load a relevant map, and simply use the mouse to click on various points along the robot's intended path in a sequential manner. The administrator explains to the subject that waypoint navigation need not be pinpoint accurate. The path that they choose will serve as a general guideline for the robot during its actual execution. The robot will autonomously avoid local obstacles and other dynamic objects, such as pedestrians, shrubbery, and vehicles. The robot cannot, however, discern navigable terrain from any significant distance. That is why it is left to the subject to choose a path for the robot, avoiding difficult slopes and potentially dangerous places, as well as conforming to a predefined mission plan. For our tutorial, the user is instructed to guide the robot through a small wooded area, through a parking lot, through a path between two large buildings, and down a ramp. The example provides enough low level detail to illustrate how the robot is performing local obstacle avoidance, yet clearly shows directed behavior.

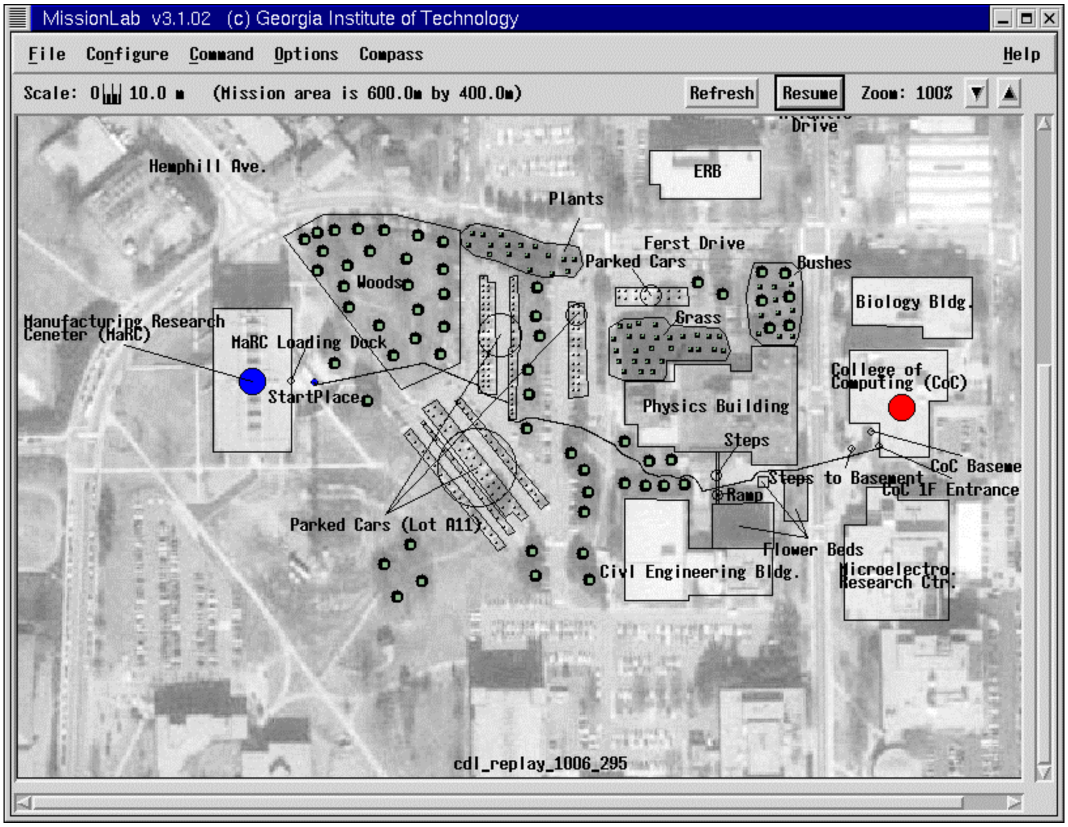


Figure 80: Simulation of second tutorial scenario.

After waypoint selection, the subject is allowed to compile and run the mission. He or she is encouraged to evaluate the success of the path that they have chosen and reconfigure it if necessary. The simulator is a powerful indicator of mission feasibility that can give great insight into what may happen to a robot in various circumstances. Subjects are encouraged to compile and simulate as much as possible and to test any configuration that might yield interesting behavior. Figure 80 shows a typical mission simulation for this task.

5.4.1.3 Task 1-1.

Now the user must perform mission specification all by them self, based on the very limited exposure they have had from *MissionLab* in tutorials 1-1 and 1-2. Task 1-1 is designed to test the user on what they have just learned. It focuses on where the waypoints are placed and how closely these placements correspond to a correctly executed mission. They are purposely given restrictions and warnings to see how it affects their mission configuration. One of the goals of the designers of the interface is to facilitate the creation of efficient and accurate mission plans. The resulting data are intended to be used in evaluating the correlation between the success of the mission, the relative experience of the subject, and the methodology they explored to arrive at the current configuration.

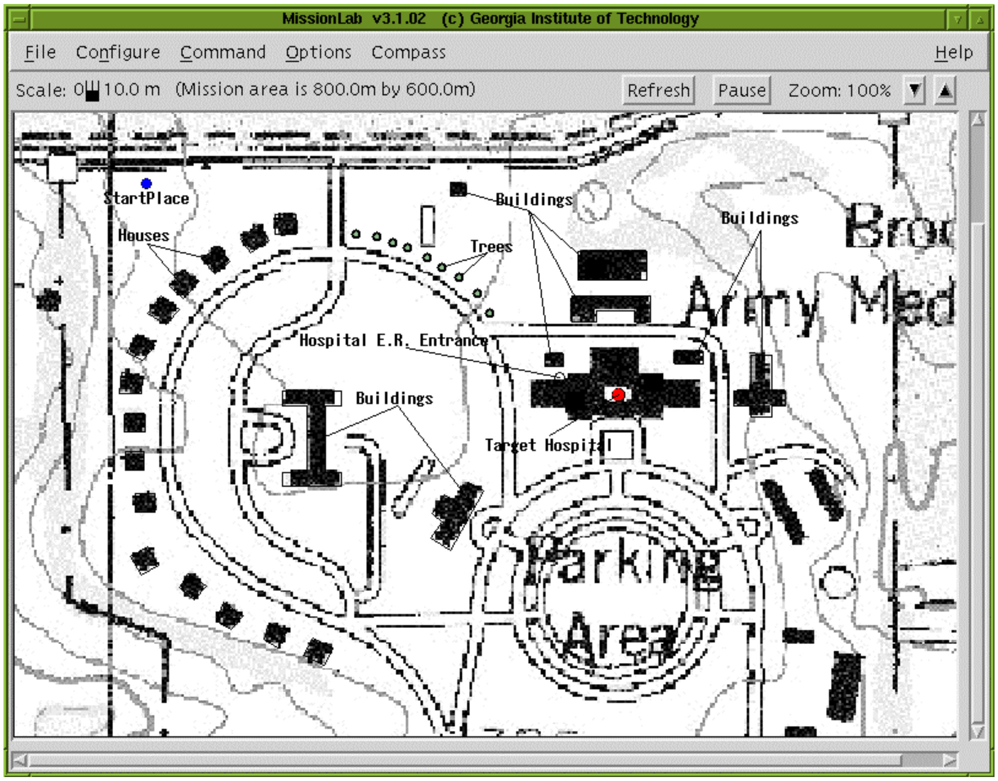


Figure 81: Fort Sam Houston overlay used in task 1-1.

Here is the mission scenario that is read to the user by the administrator immediately prior to the start of the task:

> *It is nighttime and the task is for the Tactical Mobile Robot to move as stealthily as possible from the designated start point to the Hospital Emergency entrance (marked as ER on the map). The robot should use all available cover and concealment, avoiding areas where people are likely to be at night such as houses. You can assume that all main buildings are unoccupied at this late hour, but patrols may be present on well-lit roads.*
>
> *Use the techniques you have learned today to construct a route for the robot, which allows it to move from its starting location to the Hospital Emergency Room destination as quickly as possible, while avoiding detection. Use the Fort Sam Houston Hospital overlay for this task (named hospital.ovl).*
>
> *As before do not use any more waypoints than is necessary. Definitely do not use more than a total of 15 waypoints for the mission. While creating your route, if you make a mistake or want to change your path, feel free to delete waypoints using the middle mouse button or start completely over if you want.*

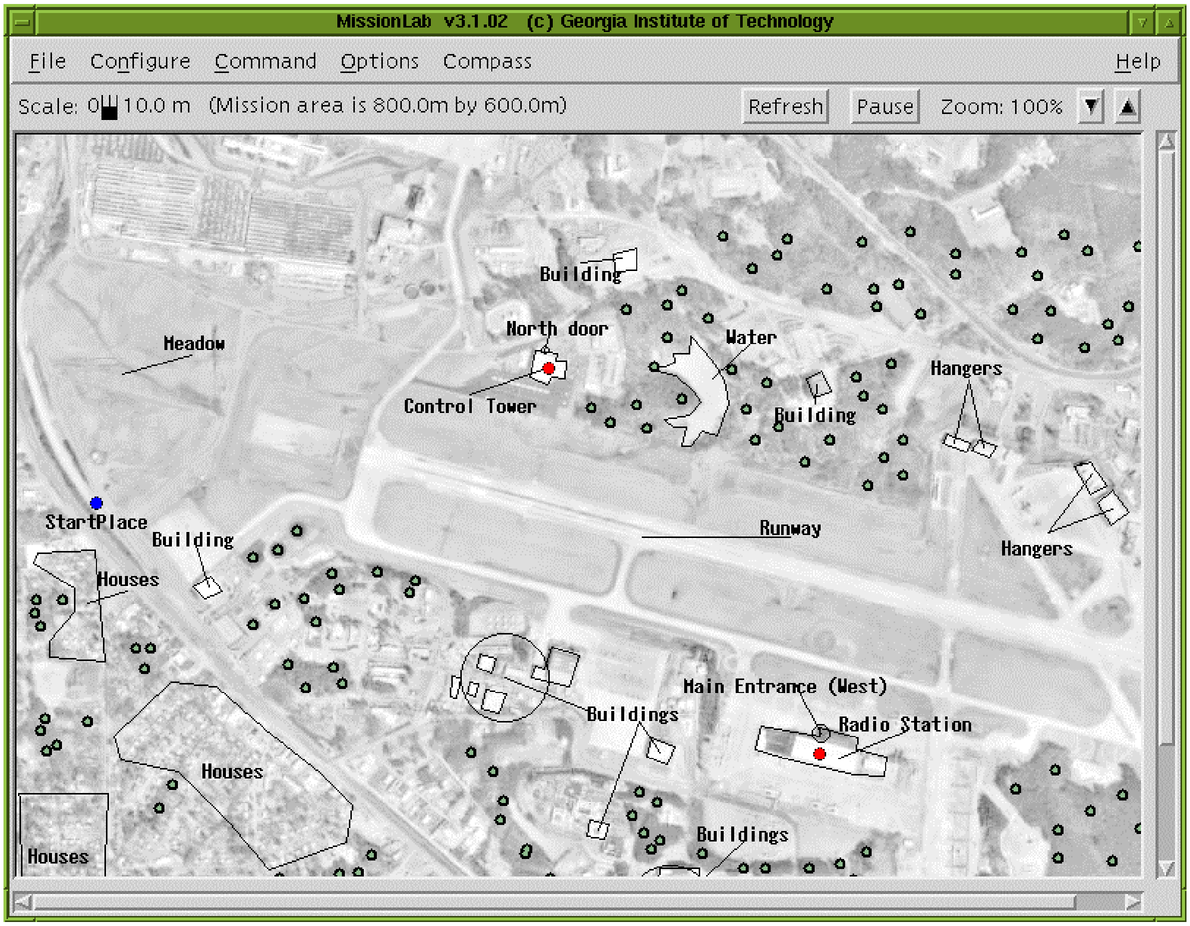


Figure 82: Airport overlay used in task 1-2.

5.4.1.4 Task 1-2.

The purpose of task 1-2 is not only to see if the subject can once again repeat what they have learned regarding waypoint mission designation in a new task-environment by constructing a suitable mission, but also to see if he or she can apply the new concept of duplicating a robot. Tutorial 1-1 demonstrated how a user might cut, copy, or paste on icon, but it was not explicitly shown how to duplicate a robot. We wish to evaluate how well the subject understands what icons represent and whether he or she can properly perform the duplication by configuring two separate but related and coordinated missions for a pair of TMR robots. As before, we evaluate the mission on efficiency, speed, and how closely the user followed the mission specification.

This is a single integrated mission involving two robots.

*An airport has been taken over by insurgents. The government requires an assessment of the situation. Two parts of the airport are of particular interest to monitor - the air traffic control tower indicated by one red dot, and the radio station indicated by a second red dot. Your task is to design a mission using waypoints, for *two* different robots starting from a common location at the start point indicated by a blue dot. For orientation, North is towards the top of the map. The first robot's mission is to observe whoever is entering or leaving the airport traffic control tower visually. The robot will approach the air traffic control tower using all available cover and concealment and take up a position viewing it from a relatively short stand-off distance off to the north of the tower looking south towards the north door of the tower. As expected, North is to the top of the map display and West is to the left.*

The second robot's mission is to position itself very closely to the door of the radio station and listen for any signs of human presence. This robot will very closely approach the radio station and take up a position just to the west side of the main door (as concealed as possible) where it can use its microphone to listen for human activity. Both of these robots have to be released simultaneously from a common starting point indicated by the blue dot.

To create a second robot, duplicate the first robot at the robot level, just under the top-level group icon. This can be done by selecting the robot with a left mouse click and then using the edit menu option, select duplicate. Move the second robot icon off of the first and then generate each robot's mission separately using waypoints. Only one compilation is needed for the entire mission, including both robots.

5.4.2 Phase 2.

Phase two consists of four tutorials and two tasks. It moves well beyond the waypoint interface into full-fledged mission specification, in some cases for very difficult tasks. The study goal here is not simply to identify what works within the interface, but also where the user experiences the greatest difficulty in order to enhance the design of *MissionLab* in future releases.

Tutorial 2-1 is a brief review of tutorial 1-1 in Phase 1, and last approximately 5 minutes. Tutorial 2-2 is an introduction to more advanced mission design with a wider variety of states and triggers, and last about 15 minutes. For Task 2-1, the subject is assigned 30 minutes to complete the task. Tutorial 2-3 introduces multi-robot missions and the problems associated with them. This takes about 5 minutes to conduct. Tutorial 2-4 introduces communication between robots and lasts 5-10 minutes. The final task, Task 2-1, is allocated 40 minutes to complete, after which 10 minutes or so are spent completing the necessary paperwork and filling out the post-test questionnaire. The entire Phase 2 session lasts for approximately 2 hours.

5.4.2.1 Tutorial 2-1

The second phase of the usability study begins with a short review of Phase 1. The subjects are asked if they recall the actions they performed in the first phase and then complete, unassisted, a back and forth robot, as they performed with assistance in the tutorial 1-1 of the first phase. If the subject needs to review some basic aspects of the interface, this is provided at this time. Before proceeding to the next tutorial, the subject is assumed to have thorough knowledge of everything he or she had done up until this point. In general phase 2 tests were conducted approximately a week after the phase 1 tests, which was a short enough time so that the subject did not forget everything they learned, but was long enough for them to need to review some basics of the process.

5.4.2.2 Tutorial 2-2

For tutorial 2-2, the user is taken through the steps required to configure a robot to find explosive devices in a minefield and safely deposit them in a designated safe area is known as the explosive ordnance disposal area, or "EOD Area". This mission is designed for a single robot. It is capable of carrying one mine at a time and need not worry about defusing them. When it has cleared all of the mines in the minefield, it is to return to its home area and terminate the mission.

In preparation for this task, the subject is introduced to four new tasks: LookFor, MoveToward, PickUp, and PutInEOD; the subject is also introduced to five new triggers: Detect, NotDetected, Near, Holding, and NotHolding. These new tools are explained once again, by a simple and effective example. The tutorial proceeds as follows.

The subject is told that the robot needs to begin looking for a particular object, and that the LookFor task accomplishes just that. Further, it is explained to the subject that he or she need not know exactly *how* a robot looks for an object as different robots may have different methods of "looking for" an object that are appropriate in varying circumstances. The user only need give the desired object to be found (mines) and understand the appropriate outcomes for this particular task, i.e., either we find a desired object or we do not.

It is very important that the subjects understand the semantics of these tasks, and while tedious, the parameters for each task are explained in detail. The subjects are told that the robot must look for mines, so we need to indicate that the specified object for this task to "Mines". It is possible that the robot may want to look for multiple objects, so it also must be understood that they must only select what they desire to find. In this case the robot is only interested in mines, so the subject must make sure that everything else is unselected within the task.

Now, two things can happen while the robot is looking for mines. The robot can detect a mine, or it can decide that there are no more mines left in its field of view. The subjects are taught the semantic differences between the triggers Detect and NotDetected. The former becomes active when a robot has detected an object of the specified type, while the latter NotDetected becomes active when a robot detects no more objects of the specified type. After explaining these concepts to the subject, it is then important to encourage him or her to begin to logically construct this mission configuration, first conceptually, and then in the configuration editor.

The study administrator carefully leads the subject in constructing this mission as a logical sequence of tasks that will repeat themselves in a number of steps. Hence it is explained that the robot should move toward the mine, and it has to get close enough to do something useful. Thus it is not enough just to add a new task, PickUp, rather the robot has to move toward the object first. Almost all subjects, without prior advisement, assume that a transition made from a LookFor task does so on the grounds that the robot is near an object. It may very well be true that instructing a robot to "move closer to an object" should be implicit in the task of picking that object up, but for testing purposes, it was not the case. So the subjects are instructed to use a new task, MoveToward, which moves the robot toward an object of particular type. Obviously in this case, we are looking for mines. A higher-level assemblage of behaviors could have been provided to the users that coupled the LookFor and MoveToward tasks together, but it was not available to the users at this time.

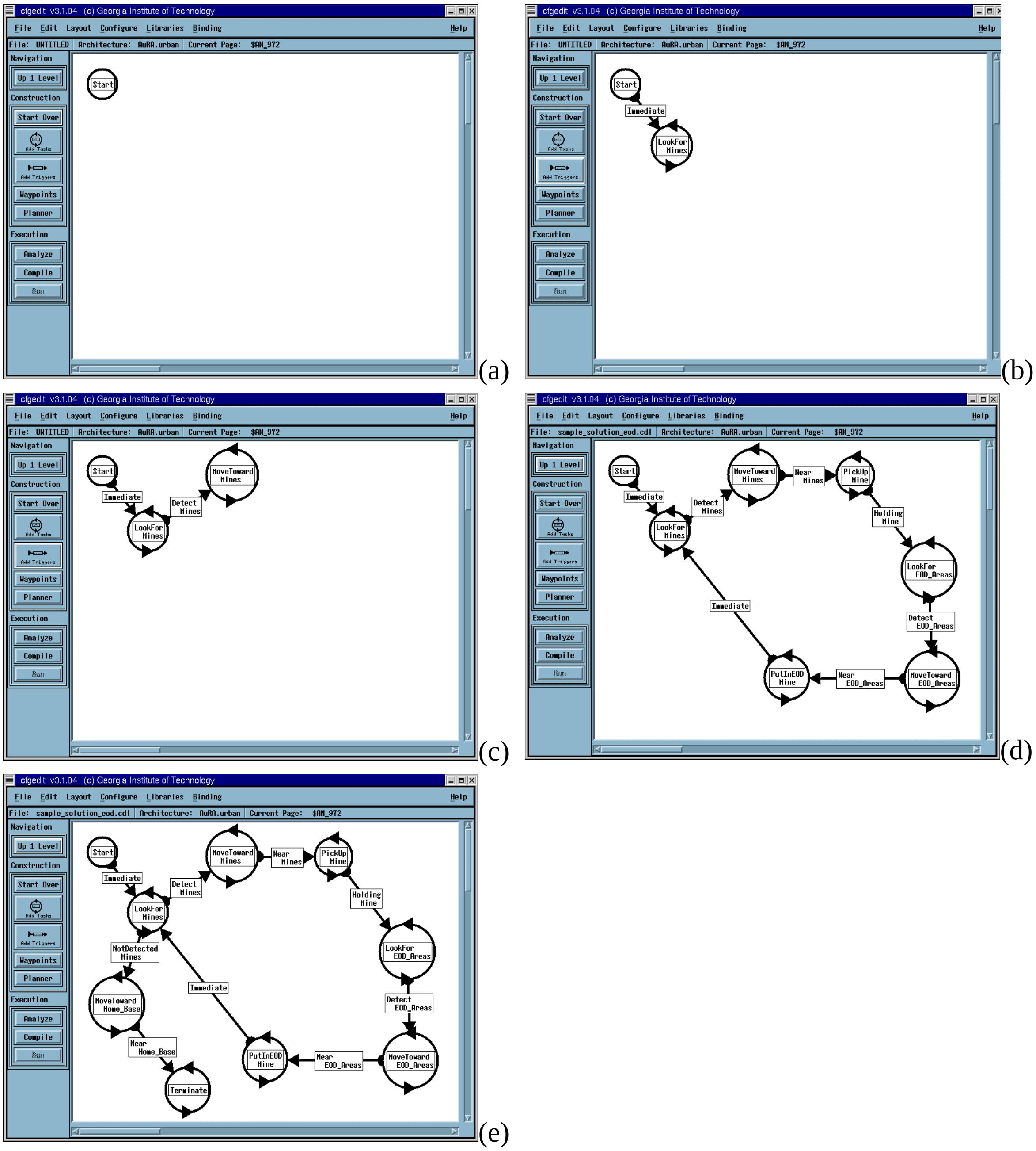


Figure 83: Sequence of screen shots for creating the EOD mission.

The next task for the user to add is PickUp. The robot needs to make a transition to this task when it is near enough to the object in question, in this case, a mine. So the administrator instructs the participant to insert a new trigger, Near, and configure the appropriate parameter as they had for the others. At each point, the study administrator makes certain that that subject understands the rationale for the pairings of tasks and triggers. The tutorial continues in the same manner, with the subject constructing MoveToward EOD Area and PutInEOD in a sequential form that matches the logical progression. Accomplishing this, and inserting a trigger that returns them to their original LookFor task when the robot has completed its disposal (the NotHolding trigger), the subject must then decide the next logical step in the mission configuration. This is a very important step in the tutorial, as the subject can now visualize the circular nature of the mission they have just developed. The robot looks, finds, moves, picks up, carries, disposes, and looks again. The subject should now start to see the usefulness of the configuration toolkit. Now, at this point a decision must be made as to how to configure the robot's behavior when it does NOT detect any more mines. We had mentioned earlier the significance of the NotDetected trigger, and now hope that the subject chooses the robot's next task to be the transition from the LookFor task using the NotDetected trigger. If the subject does not understand this, then the administrator reiterates the meanings of the Detect and NotDetected triggers so that the subject sees why they need to be used here. This is a very important step in the tutorial, because it embodies the thought processes that we want the subjects to embrace.

The next task, according to the original mission specification, is to have the robot move toward the designated home base area and terminate the mission. The subject constructs these in the same manner as before using the appropriate MoveToward configuration and Near transitions. The subject is also introduced to the Terminate state, which shuts down the robot. This completed, the subject is then ready to compile and test his or her mission. Figure 83 illustrates the entire process.

The simulated mission takes place in this case in a large field with five mines and assorted obstacles of various sizes. If the mission has been configured correctly, the robot will retrieve each mine in turn (starting with the closest mine first) and move it to the designated EOD Area. Figure 84 shows the results of a simulation.

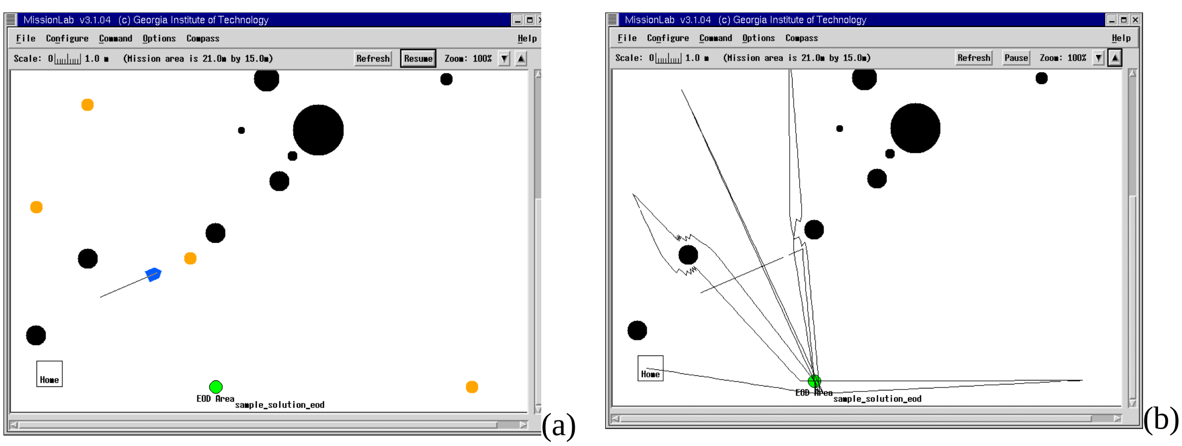


Figure 84: Simulated robot in the EOD scenario: before (a) and after (b) the completion of the mission. Orange objects are mines.

5.4.2.3 Task 2-1.

Task 2-1 evaluates the user's ability to bring together everything that he or she has learned up to this point by attempting to generate a mission plan. This is meant to be difficult, however, and we expected a very low success rate. We wish to evaluate the parts of the interface on which the subjects spend a lot of time, attempting to improve or eliminate them. The subject has a significant amount of time (30 minutes) to finish this task; and if he or she does not, we can isolate the problem areas and devote future development efforts in that direction. It should also be recognized that correctable difficulties could arise due to the extremely limited training presented to the subjects. Subjects spend approximately one hour on Phase 2 tutorials. Presumably, a normal user of such a system would have more experience. There is little doubt that additional training with *MissionLab* would improve the ability of the users substantially.

The mission scenario for task 2-1 is as follows:

> *It is 3 AM. In a biomedical research building located in a renegade nation, a single robot has been delivered to the entry of the building and has been successfully and secretly escorted inside. It awaits command at the beginning of a hallway just inside the entrance. The task for this robot is to proceed along this hallway and search every room that has an open door for the presence of a biohazard.*
>
> *A warning about this mission: the robot has very poor knowledge of the layout of the building. Any available maps or drawings are dated and possibly inaccurate, as intelligence does not know how the current occupants may have modified the building. Therefore, we cannot use waypoints to accomplish the task as you did earlier in the Hospital Approach scenario. We do know, however, that the layout of this building is conventional. It has a linear corridor with rooms on both the left and right sides. At this early hour nobody is expected to be present in the building, so the robot can safely move about without fear of detection.*
>
> *This mission should be accomplished as follows: from its starting position the robot proceeds down the hallway. At any and every open door it encounters, it enters the room and conducts a biohazard survey. If the survey results indicate that a biohazard is present, the robot should immediately alert the user. If the survey results do not indicate the presence of a biohazard, the robot should mark the room as visited, and continue the search, surveying additional rooms as needed. At any point in the mission that the robot encounters a biohazard and alerts the user, the robot's mission is complete and it can safely terminate. If the robot reaches the end of the hallway, it should turn around and navigate back down the hallway, searching for additional rooms it may have not checked. Once the robot finds itself back at its starting position at the entrance, it should alert the user that no biohazards have been found and it may safely terminate.*

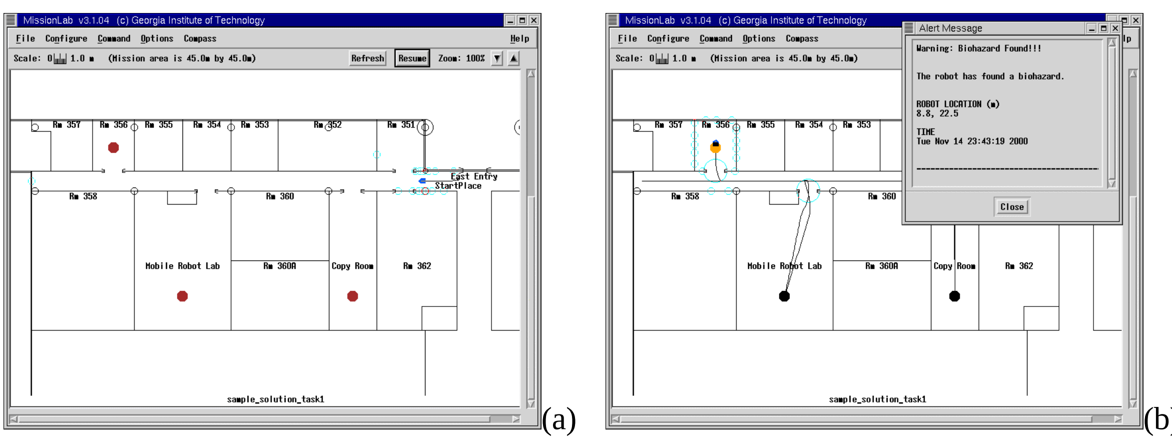


Figure 85: Example simulated robot for the Task 2-1 scenario: before (a) and after (b) the completion of the mission.

One caveat regarding the results obtained for this task is that while each subject is strictly instructed that he or she does not know the layout of the floor, if the subject runs the mission once in simulation, he or she will see what the test floor plan looks like. To alleviate this problem, subjects are instructed that their mission should work on any long hallway with corridors, and should not be specific to this particular layout. Figure 85 shows an example of a well-executed mission for this task.

5.4.2.4 Tutorial 2-3.

The next two tutorials focus on multi-robot scenarios. The purpose of tutorial 2-3 is to demonstrate two things to the subject. First, as they should have learned from task 1-2 of Phase 1, it is very easy to duplicate an entire configuration for one robot, resulting in identical configurations for two robots. Further, the user may modify either configuration to get slightly different or specialized behavior from the robots. The second point that this tutorial illustrates is that while duplicating and/or inserting additional robots can benefit the overall mission plan, for example by reducing execution time, the full potential for robotic teams is not realized until some level of communication is added to permit their coordinated effort.

To begin this tutorial, the user simply loads the explosive ordnance disposal (EOD) robot that he or she had configured earlier in tutorial 2-2, duplicates it, and runs them both in the minefield (Figure 86). The subject will observe that while both robots independently search for mines and move to dispose the detected explosives, there are situations that arise where both robots will detect the same mine, and move to pick it up, ignorant of the intentions of one another. Immediately the subject can see the need for some kind of communication mechanism and hopefully would begin to formulate the concepts as to how an interface to such a communication mechanism might look in the current environment. This serves as the lead-in to the final tutorial, which explores robot communication and message passing in the mission specification.

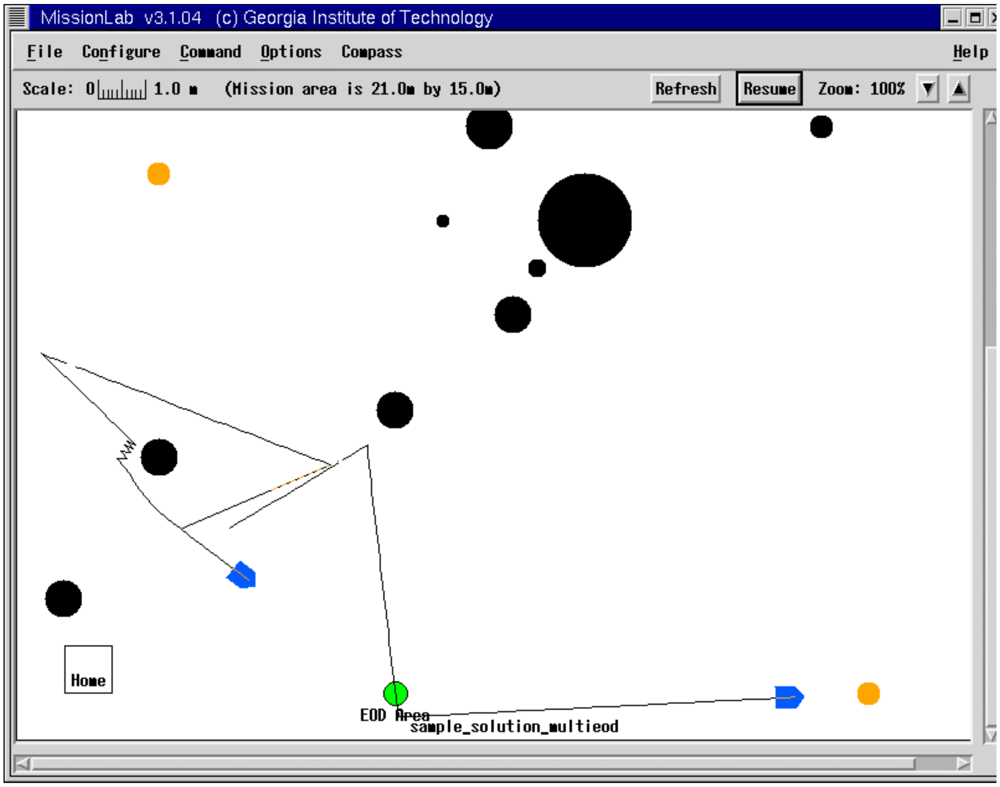


Figure 86: Two simulated robots running the EOD scenario.

5.4.2.5 <u>Tutorial 2-4</u>

For this tutorial, the user is instructed how to develop a simple mission plan where two robots are able to communicate by sending messages. These messages, whether sent or received, affect the current state of the robot and can be created in the mission specification plan just like any other task. It is first explained to the subject that two robots are to be configured for this mission. One will command the second is to follow. Together they will move to a designated point, where the first robot will dismiss the second, and the second will go on to carry out a different task. In this example, the second robot will simply move to another location.

To accomplish this, the subject is introduced to a new task and two new triggers. The new task is *NotifyRobots*, which allows a text message to be sent to another robot. In this study, we designed the mission specification such that only two robots will be utilized at once, so all communication is peer-to-peer, and we need not worry about selection of communication protocols. It is assumed that a *NotifyRobots* task simply sends the message to the only other robot. Analogous to the *NotifyRobots* task is the Notified trigger which takes a text message as a parameter and causes a task transition to occur if the received text message that matches that parameter. In this manner, robots can influence each other's state by sending appropriate messages.

To accomplish the task, the subject is instructed to configure one robot to first command the other robot to follow by executing the *NotifyRobots* task, sending a text message such as "Follow me". The second new trigger introduced is simply an exit condition for the *NotifyRobots* task, which is the trigger, *MessageSent*. For this task, the leader robot transitions to a GoTo behavior, and upon reaching its destination, transitions into another *NotifyRobots* task, whereby the other robot is dismissed. This ends the mission for the first robot, and it may safely terminate. The mission plan is simple and sequential but it illustrates how message sending is simply another task that can be designated at a high level. The leader robot's FSAS appears in Figure 87.

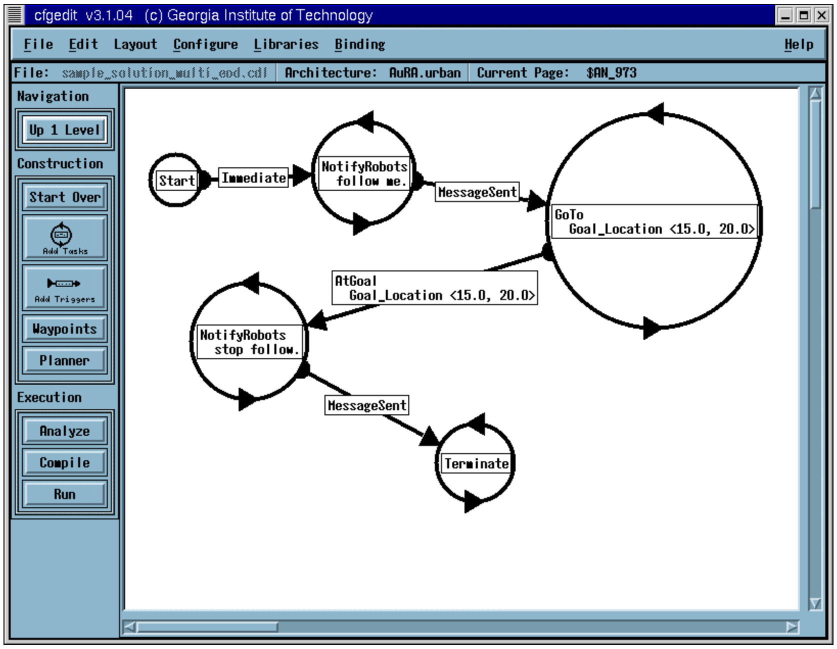


Figure 87: Sample FSA for Tutorial 2-4 (leader robot).

The subject also configures the second follower robot that will be affected by the incoming messages. So, by default, the second robot does nothing, i.e., a Stop task, until it transitions out of that task upon receiving the text message “Follow me”. The Notified trigger is used to achieve those ends. It is important to point out to the subject at this time that this is exactly how a robot can directly influence the behavior of another robot. The second robot should receive two messages, the second being the message of dismissal after which the robot may execute a different task. For our tutorial, the follower robots move to a different location to illustrate the fact that the second robot can, in a sense, take commands. Note there are no hierarchical structures or control here, the robot mission designer decides how the robot will react to messages, predicated on the needs of the mission. The follower's FSA appears in Figure 88, and the simulation in Figure 89.

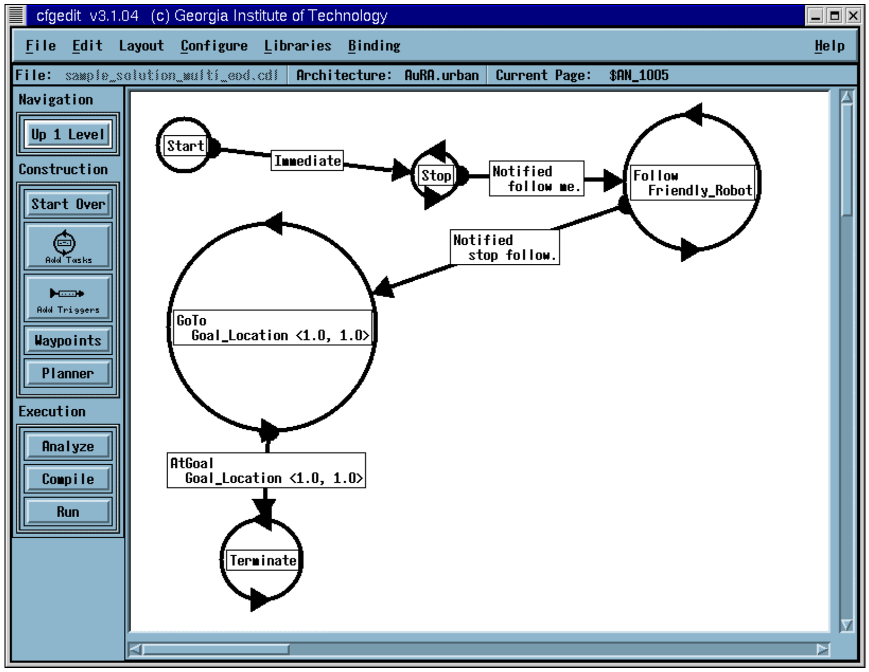


Figure 88: Sample FSA for Tutorial 2-4 (follower robot).

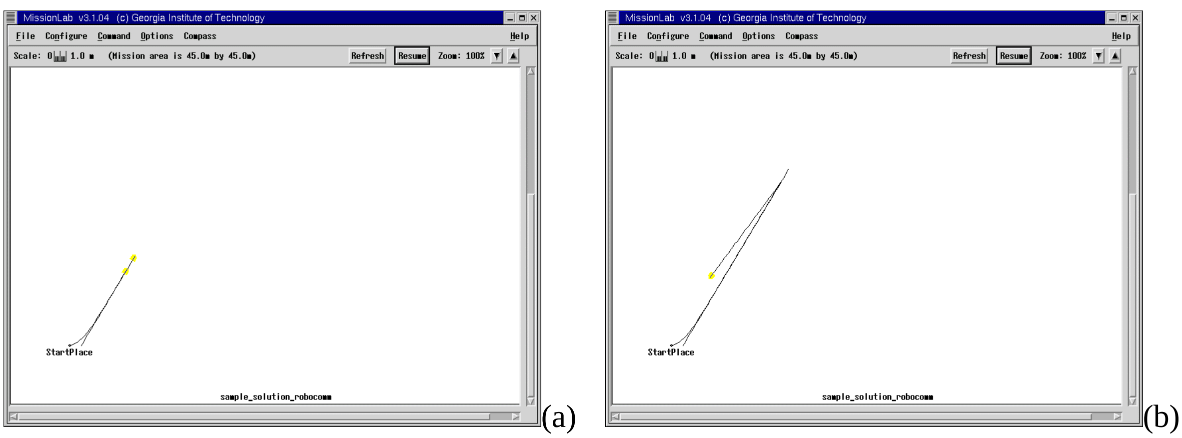


Figure 89: Simulated robots in Tutorial 2-4 scenario.

5.4.2.6 Task 2-2.

The main purpose of task 2-2 is to see how well the subject can incorporate new ideas into a given, or currently known mission plan. The mission parameters are the same as for task 2-1 except with the added twist that now two robots must communicate and work together to fulfill their mission plan. In addition, a sentry may be present which must be avoided for fear of being detected. The subject may use his or her previous solution to task 2-1 or use the administrator's solution to task 2-1 provided to them, which they may modify into a new mission. Alternatively, they can start from scratch to compose the mission if they prefer. Figure 90 shows a good solution to the problem.

This mission is the same as before, but in this case there are sentry patrols now present that may appear any time in the corridor. In this case you will need two robots that work together. While one robot is inside a room conducting the survey, the other robot remains in the hall, near the doorway to the room that the first robot is searching, looking for a sentry to appear. If a sentry is detected, then both robots should move into the same room and wait 5 minutes before resuming operations. This also holds if both robots are in the hall when the sentry appears.

You may divide the workload between the two robots any way you see fit, so long as one of them is always watching the corridor while the other is inside the room. You may also reuse your solution from Task 1, if you wish.

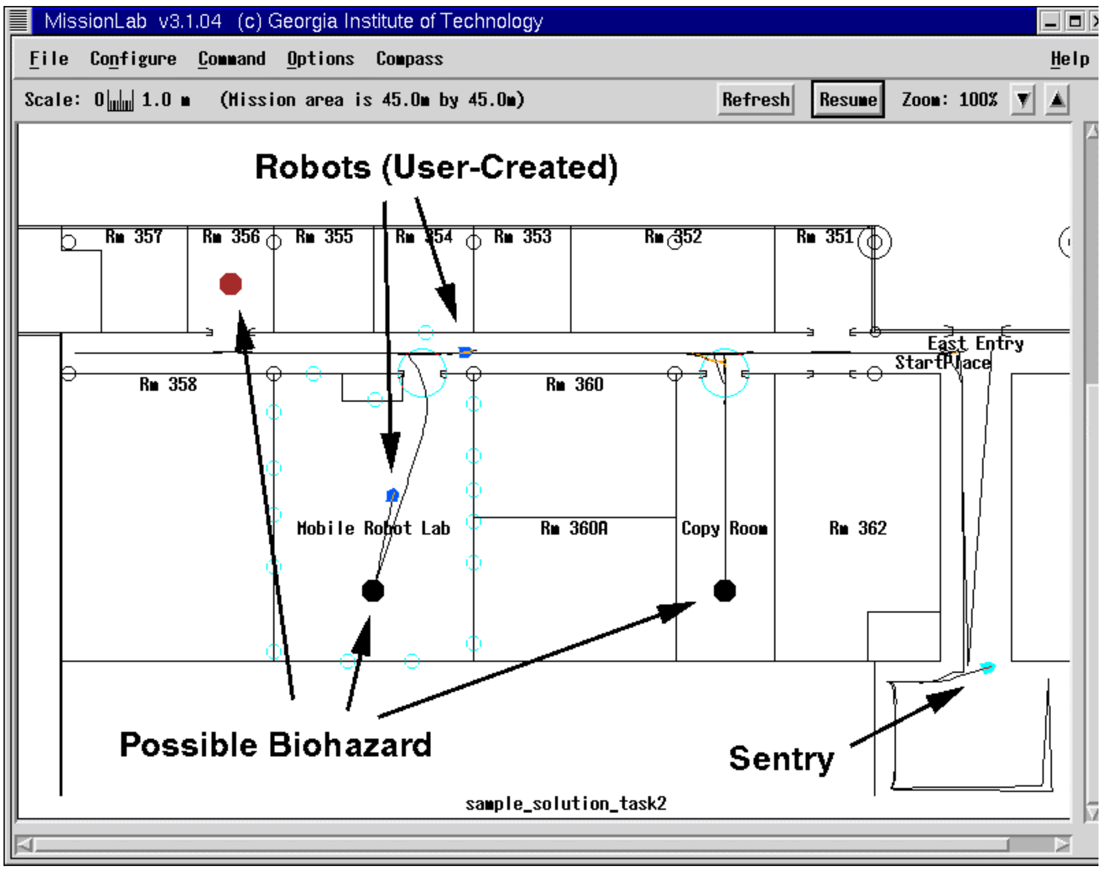


Figure 90: Team of robots executing Task 2-2 scenario.

5.5 <u>Evaluation</u>

5.5.1 Description of Data Extracted

The base dataset on which the evaluation is based was obtained by capturing the set of actions that the subjects performed during the study, and the results of these actions. This recorded data serves as a source from which various statistics can be compiled and correlations made, which results in the conclusions made at the end of this paper.

The capturing of data from the studies was essentially in two forms:

- Text data logs: These consisted of log files that recorded each action made by the user as an event, storing the corresponding parameters of the action and the time that the action was performed. Thus these log files serve as a text-based recording of the events that transpired during the process mission design and testing that the user went through. These serve as a convenient source of data from which a variety of different information can be obtained in a relatively easy manner, especially information of a quantitative nature, such as mission design times and numbers of waypoints. Details of the data extracted from these log files and the analysis performed on this data are described in the next section. A sample event log file is attached in Appendix G.
- Snapshots of the mission design: A set of CDL files was saved which recorded the current state of the mission after each action that the user performed. These files can each be loaded in CfgEdit and viewed to recreate the state of the mission at the particular time, which is also recorded. Thus the entire set of snapshots for a particular mission can be used to replicate the process the designer went through while working on the mission, thus providing insight into the mental process the subject was undergoing at the time. Sample CDL files are attached in Appendix H.

5.5.1.1 Phase 1

Table 16 shows the some averages of this data of the entire subject set for each of the Phase 1 scenarios. We have depicted the information that we see as relevant to the evaluation of our toolset. We include the number of waypoints that a subject uses in his or her mission configuration to determine if more or less waypoints contribute to the overall success of the mission. These are the waypoints that a user chooses from the given map. The numbers shown are the final number of waypoints used, not including waypoints a user may have inserted and subsequently deleted on the way. We also track the number of waypoints that a subject deletes. High numbers of deletions indicate that either our interface is cumbersome or the subject does not understand the waypoint concept.

	Hospital Approach Scenario	**Airport Incursion Scenario**
Number of Waypoints	6.10	6.24 (both robots)
Number of Waypoints Deleted	1.69	2.27 (both robots)
Number of Modifications	0.069	0.20
Modification Time	0.62 sec	0.75 sec
Total Completion Time	8 min 12 sec	15 min 59 sec
Number of Mission Restarts	0.31	1.14

Table 16: Phase 1 averages for all subjects.

The number of modifications and modification times are the times spent actually modifying the task or trigger parameters. Since waypoints are generated from a map, we do not expect these numbers to be significant, but if they are, then this indicates there is confusion on the part of the subject. Total completion time is the duration of mission configuration. The numbers are slightly skewed in the sense that this number often includes debriefing time as the test administrator uses the *MissionLab* console to point out mission mistakes and inconsistencies as well as things that a user performed correctly. Thus the numbers may be slightly larger than what would be an actual total configuration time, but they do serve as a sufficient approximation as many subjects tend to do a post evaluation on themselves in any case, even without the aid of administrators. We also included the number of configuration restarts. This is the number of times that a user completely discards his or her current configuration and begins anew. While restarts in themselves are not an indicator of a poorly designed interface, excessively high numbers of restart can indicate exactly that.

5.5.1.2 Phase 2

For Phase 2, the same data was gathered with the exception of the number of waypoints and the number of waypoints deleted, since the subjects do not use waypoints in Phase 2 scenarios. In their place, we do collect the total number of tasks and total number of triggers used in a mission configuration. This is actually analogous to counting waypoints in the Phase 1 data, as each waypoint during task generation gets mapped to a corresponding *MoveTo* task and *AtGoal* trigger anyhow. Similarly, we intend to correlate the number of tasks and triggers used to the overall success of the mission. Table 17 shows the averages across the entire subject set for each of these data elements in each of the Phase 2 scenarios.

	Single Robot Scenario	Two Robot Scenario
Number of Tasks	14.23	23.40 (both robots)
Number of Triggers	21.27	38.50 (both robots)
Modifications	36.32	69.00
Modification Time	6 min 10 sec	12 min 11 sec
Total Completion Time	33 min 3 sec	45 min 2 sec
Mission Restarts	0.180	0.127

Table 17: Phase 2 averages for all subjects.

5.5.2 Description of Analysis

In order to evaluate the performance of the subjects during the mission design, one of the key criteria is an evaluation of the quality of the missions that were designed by each subject. In order to gain this information, the final version of each mission created by each subject was restored from the recorded data logged snapshots, and evaluated independently by 3 different evaluators. Each evaluator was given a set of criteria that a particular mission was required to satisfy. These criteria were specified in the form of yes or no questions. The evaluators replayed each mission and independently provided their sets of answers to these questions. The average results obtained for each mission designed by a particular subject provided a measure to what degree of success the subject had in satisfying the design specifications that he or she was provided with. In addition, a subset of the desired criteria was obtained for each mission that identified the questions that define the access success of a mission. This gives the evaluators an idea of how likely the subject's mission configuration would succeed given the mission specification. For example, in the hospital scenario, avoiding major roads was not critical to the completion of the mission, but reaching the hospital entrance was. Hence we define what constitutes a successful mission design. This allows us to form a correlation with the quantitative data described above, resulting in some interesting conclusions regarding the particular design features that were more likely to produce a successful mission.

5.5.2.1 Phase 1

Figure 91 shows a plot of waypoints from all subjects for both the hospital and airport scenarios. From this we can graphically get a general idea of subject tendencies and interpretation of each scenario. By examining the clusters of waypoints, we can see where users had the highest tendency to place a waypoint.

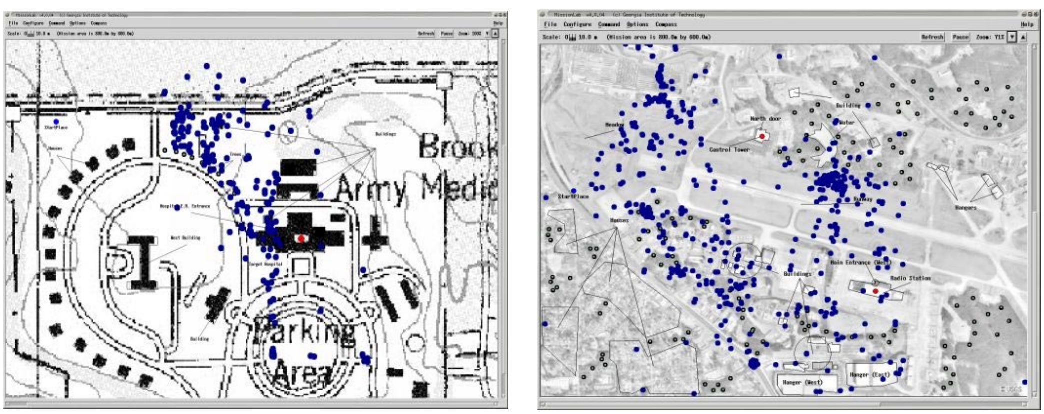


Figure 91: Clustering of waypoints for the hospital and airport scenarios.

Table 18 shows the average success rates for each Phase 1 scenario according to the results of the evaluation across the entire subject set. It makes sense that the subjects generally satisfied the mission-critical criteria more highly than all criteria because subjects that do not satisfy basic mission constraints are likely to fail on all accounts. The tasks of Phase 1 are pretty simple, and the results show that the subjects attained a fairly high success rate. One might surmise that given the simplicity of the mission specification, subjects should attain a near-100% success rate for mission-critical criteria using a well-designed interface. However, we assert that the success levels in our studies may be artificially diminished by the fact that subjects may not take the mission specification criteria completely seriously. Still, the missions were evaluated strictly. It is also worthy to note that Task 1 and Task 2 scenarios had comparable success rates, even given the fact that the subjects had to perform an action for which they had not been instructed (duplicating a robot).

	Mission-critical Criteria	All Criteria
Hospital (Task 1)	82.37 %	63.90 %
Airport (Task 2)	78.5 %	71.42 %

Table 18: Phase 1 average mission success rate.

Further analysis was done on the correlation between experience level and various quantitative data from the data logs. For Task 1, the number of waypoints used and number of waypoints deleted were about the same for the novice and expert subject groups, while the intermediate group was slightly higher in each category. The intermediate group also showed significantly higher completion times and number of restarts (the restarts probably contributed to the higher completion time). However, in the Task 2 scenario, the number of waypoints and waypoints deleted was significantly higher for the expert group, an odd circumstance given the previous results. Another strange occurrence is the fact that the average number of restarts is actually lower for the intermediate group in the Task 2 scenario, when previously it had been higher.

	Novice	Intermediate	Expert
Hospital (Task 1)			
Number. Of Way-points	5.88	6.50	6.00
Number of Waypoints Deleted	1.25	2.25	1.62
Modifications	0.00	0.25	0.00
Modification Time	0.00 sec	2.25 sec	0.00 sec
Total Completion Time	8 min 28 sec	11 min 7 sec	6 min 14 sec
Mission Restarts	0.25	0.75	0.076
Airport (Task 2)			
Number of Waypoints	5.75	5.25	7.15
Number of Waypoints Deleted	1.25	0.875	3.76
Modifications	0.375	0.125	0.154
Modification Time	0.652 sec	0.716 sec	0.833 sec
Total Completion Time	14 min 42 sec	15 min 4 sec	15 min 13 sec
Mission Restarts	1.375	0.625	1.307

Table 19: Phase 1 averages grouped by experience level.

A correlative analysis was also performed on the success levels of each experience group. As would be expected, the expert group attained the highest success level for Task 1. Strangely, however, it was the novice group who had the highest success level for Task 2, although the difference is marginal.

	Novice	**Intermediate**	**Expert**
Hospital (Task 1)			
Mission-critical criteria	83.33 %	68.05 %	90.59 %
All criteria	65.00 %	50.83 %	71.28 %
Airport (Task 2)			
Mission-critical criteria	84.72 %	73.61 %	77.77 %
All criteria	77.90 %	65.47 %	71.06 %

Table 20: Phase 1 average mission success rate grouped by experience level.

Finally, in order to determine the relevancy of the results, we correlated the various quantitative data from the data logs against the evaluated level of success of the very same mission. We divided the subject pool into two groups. The first group is the "more successful group" while the second is the "less successful group". To determine membership in either group, the entire list of *mission-critical* success levels is determined and the statistical median chosen from that list. All subjects whose success rate falls above the median belong in the first group, and those whose success rate is below the median belong to the second group. This allows for balanced grouping and eliminates the biasing effects of statistical outliers.

Table 21 illustrates the results of this correlation. Subjects used more waypoints and deleted more waypoints in the more successful missions. Numbers of modifications and modification time was much less for the more successful group, as one would expect. Total completion time for the entire mission was significantly less for the more successful missions as well. Restarts occurred less for more successful missions.

	More Successful Missions	Less Successful Missions
Hospital (Task 1)		
Number of Waypoints	7.31	5.13
Number of Waypoints Deleted	2.00	1.44
Number of Modifications	0.00	0.125
Modification Time	0.00 sec	1.12 sec
Total Completion Time	7 min 19 sec	8 min 55 sec
Mission Restarts	0.231	0.375
Airport (Task 2)		
Number of Waypoints	7.23	5.44
Number of Waypoints Deleted	3.31	1.44
Modifications	0.0769	0.313
Modification Time	0.180 sec	1.21 sec
Total Completion Time	12 min 56 sec	16 min 40 sec
Mission Restarts	0.846	1.38

Table 21: Phase 1 averages correlated with mission success rate.

5.5.2.2 Phase 2

The evaluation success levels for Phase 2 were moderate. The tasks given to the subjects in Phase 2 are specifically intended to be difficult to test the limitations of both the subject and the interface. No single subject completed either the Task 1 or Task 2 mission specification of Phase 2 with 100% accuracy, even when evaluated using only mission-critical success criteria. Given these circumstances, to say that all subjects achieved, on the average, 40-55% of mission-critical elements successfully, is significant. The subjects are getting many things right.

	Mission-critical Criteria	All Criteria
Single robot (Task 1)	55.30 %	46.56 %
Two robots (Task 2)	40.4 %	38.05 %

Table 22: Phase 2 average mission success rate.

Similarly to the Phase 1 analysis, group experience correlations were also determined for Phase 2 data. No significant correlations are immediately obvious. The intermediate group, however, again demonstrated some apparent abnormalities. The number of triggers used by the intermediate group in the Task 1 scenario was significantly less than the other two groups, yet the intermediate group also spent significantly more time doing modification of tasks and triggers.

	Novice	Intermediate	Expert
Single Robot (Task 1)			
Number of Tasks	15.83	12.60	14.09
Number of Triggers	22.67	16.80	22.54
Modifications	37.33	34.00	36.81
Modification Time	6 min 0 sec	7 min 20 sec	5 min 43.9 sec
Total Completion Time	35 min 26 sec	32 min 53 sec	33 min 50.71 sec
Mission Restarts	0.333	0.200	0.100
Two Robots (Task 2)			
Number of Tasks	24.83	23.20	22.72
Number of Triggers	36.50	39.40	39.20
Modifications	74.83	67.00	66.35
Modification Time	8 min 37 sec	8 min 38 sec	7 min 33 sec
Total Completion Time	47 min 41 sec	47 min 14 sec	42 min 34 sec
Mission Restarts	0.00	0.00	0.00

Table 23: Phase 2 averages grouped by experience level.

The same experience group correlations were also run against success evaluation. Two things are apparent. The novice mission-critical success level for Task 1 is surprisingly high. Also, in what is becoming a trend, the intermediate group performed significantly worse in terms of success rate than the other two groups.

	Novice	Intermediate	Expert
Single Robot (Task 1)			
Mission-critical Criteria	68.5 %	30.1 %	50.1 %
All Criteria	53.03 %	32.22 %	58.5 %
Two Robots (Task 2)			
Mission-critical Criteria	43.21 %	19.25 %	48.48 %
All Criteria	40.84 %	20.39 %	44.56 %

Table 24: Phase 2 success rates grouped by experience level.

Again, as in Phase 1 analysis, the correlation of mission-critical success level to quantitative data was determined as illustrated in Table 25. While neither the more successful nor less successful group used significantly more or less tasks or triggers, the more successful group made less modifications and spent less time on modification. Subjects with more successful missions in Task 1 took less total time to complete the mission specification. This is probably due to the fact that subjects who are less successful require more debriefing when they finish, as the administrator presumably has more to explain. However, in Task 2, the more successful group actually took more time to complete. This might be due to the challenging nature of Task 2; less successful subjects might give up more easily.

	More Successful Missions	Less Successful Missions
Single Robot (Task 1)		
Number of Tasks	13.29	14.75
Number of Triggers	20.71	21.00
Modifications	28.43	38.13
Modification Time	4 min 58 sec	7 min 41 sec
Total Completion Time	27 min 42 sec	41 min 36 sec
Mission Restarts	0.143	0.125
Two Robots (Task 2)		
Number of Tasks	22.00	21.60
Number of Triggers	32.40	38.30
Modifications	62.60	63.20
Modification Time	7 min 12 sec	8 min 21 sec
Total Completion Time	46 min 6 sec	42 min 18 sec
Mission Restarts	0.00	0.00

Table 25: Phase 2 averages correlated with success rate.

5.5.3 Discussion

Missions where more waypoints were used generally conformed better to the specifications provided, regardless of the number of robots that a subject is asked to configure. The fact that the more successful subjects both used more waypoints and deleted more waypoints suggests that these subjects tended to be more finicky in choosing where to place the waypoint. The concept of waypoints seems readily acceptable and usable to the subject. Subjects demonstrated no difficulty in placing or manipulating them and generally achieved a high success level in terms of mission specification criteria. Subjects tended to fare better in less open, highly specific arenas, such as the hospital scenario, where specific do's and don'ts are laid out clearly. In the airport scenario, which was less specific, there is wide variation in the placement of waypoints

There seems to be no correlations among the mission quality of subjects of varying experience levels, nor do these groupings show anything readily quantifiable. The fact that intermediate level experience groups show erratic behavior might indicate that there is further analysis yet to be done on experience groups, perhaps diversifying group membership criteria, or regrouping them completely. However, the fact that novice users can create mission configurations as successful as the expert users suggests that *MissionLab* is an effective toolkit to be used by those with little or no computer experience.

5.6 Alternative Interfaces (Additional Pilot Study)

Independent from the main usability study, an additional study that evaluated alternative user interfaces for *MissionLab* was conducted. For a series of suggested designs, prototypes were created, and evaluated against the original design. The alternative user interfaces, the evaluation methods used and the results are explained below.

5.6.1 Task Analysis

In order to create alternative interfaces, *MissionLab* was analyzed in terms of tasks that users would perform. The main focus is on the task "creation of robot missions", and it was decomposed into various subtasks using hierarchical task analysis (HTA). In the figure below, the hierarchical relations among those tasks and subtasks are shown. Task 2 and 3 (Configure the Mission and Compile the Mission, respectively) are performed within CfgEdit, while Task 4 (Test in Simulation) is done in MLab. Task 1 (Pick strategy) is done in the user's head. This hierarchical structure of the task can be applied to both indoor and outdoor missions. In this usability study, the focus concentrated on subtask 2.3 and its components: *Assemble the Mission*, which are highlighted red in the figure.

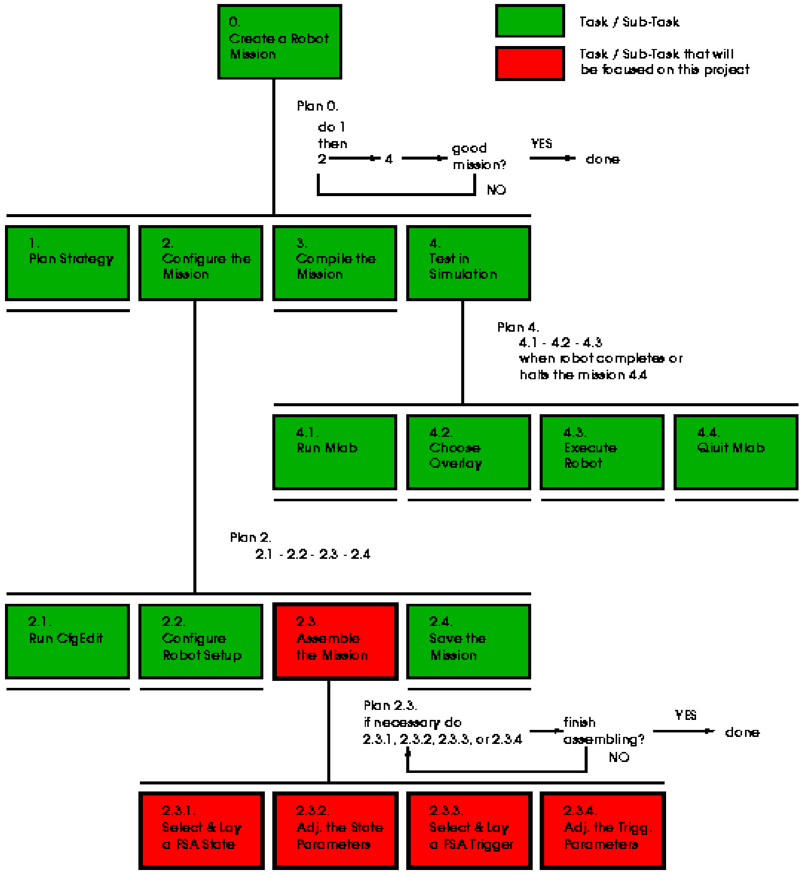


Figure 92: Hierarchical task analysis for creation of a robot mission.

5.6.2 Requirements

The requirements of the *MissionLab* user interface are derived from understanding the focus task: *Assembling the Mission*. Not only must the mission be understandable by the user who constructed it, but also it must be easily understandable by the user some time later or by other soldiers who may use a mission from a library of missions made by other people, similar to a good subroutine in a library of Java or C code. Thus we have two perspectives on requirements: the generation of missions from the building blocks in CfgEdit, and the incorporation and reuse of missions from a mission and behavior library, whether by modifying parameters or by aggregating existing missions as building blocks of a larger plan.

5.6.2.1 Functional Requirements

The functional requirements for the task are now enumerated.

1. Task Conformance in Information Entry
   The user must be able to add and remove task actions, triggers, and waypoints and subsequently modify the parameters of each of these plan-building blocks using the *MissionLab* software. A new interface must provide task conformance to the current interface.

2. Observability of Mission Display
   The user must thus be able to obtain feedback about the mission plans easily from the system: the user must be able to easily review the elements of the plan and the parameters of each plan action, trigger, and waypoint. This implies that the system should encourage plans to be generated in a predictable and consistent fashion that is easily observable.
3. Mission Modification
   The user must be able to modify a plan and plan elements at any time. Thus this interface should be predictable and constructive.
4. Standardization of Mission Elements
   Similar missions must be consistent and mission content must be generalizable. All plans must be made from the same ontology of mission building blocks: different users that implement the same plan must use the same sets of icons and parameters so that different users are trained to perform in the same manner.
5. Saving and Retrieving Missions
   The user must be able to save and retrieve missions: successful mission plans will be organized in libraries for users.
6. Mission Re-Use in Hierarchical Plans
   The user must be able to use existing missions that can be retrieved from a library of sub-plans in a new larger plan, where that library consists of existing missions as well as primitive mission building blocks.

5.6.2.2 Non-functional Requirements

The non-functional requirements of the interface appear below.

1. Robustness
   The user must be able to operate *MissionLab* very quickly in a high-stress environment. Thus robust usability guidelines must be followed: in considering the display and notation of the mission plan. This emphasizes consistency, observability, and familiarity.
2. Familiarity
   The user's knowledge and experience in military operations must be extendable to the *MissionLab* mission specification environment. The user must be able to understand the function and parameters of mission elements as relevant to the real world of the robot in a military operation.
3. Mission Commonality
   It is a requirement that successful mission plans can be reused. Thus the mission plans must be understandable, navigable, and modifiable by any soldier that is a *MissionLab* user. This is very important for communicating plans to other users and allowing good, pre-existing plans to be aggregated into a library of possible plans that need little modification from the user.
4. Clearly Distinguishable Missions
   It is a requirement that users can review existing plans, determine if they are viable for the current task, and modify the parameters of the plan building blocks to suit a new set of conditions. Thus the plan visualization scheme and notation scheme must make different plans easily distinguishable as well as clearly emphasize the key points of the plans where parameters must be changed for a new operating condition. Currently it would be difficult for a less experienced user to tell one mission apart from another, and further one mission task or trigger apart from another.
5. Time to Use
   The software should allow the user to create similar missions in less time than the current system.

5.6.3 Three Key Aspects of the Design Space

The design space of potential interfaces was broken down into three key aspects: *Input Device*, *Plans Visualization Metaphor*, *Task and Trigger Notation Metaphor*.

Input Device	Plans Visualization Metaphor	Task and Trigger Notation Metaphor
Keyboard	Free Flow	Standard Finite State Automata Notation
Mouse (Trackball)	Guided Flow	Standard Flow Chart Notation
Light Pen	Geographical Map	Military Symbols
Touch Screen	State Space	Picture Icons
McDonald's Keypad	Tree Diagram	Text
Twiddler	Pop-Up Windows	
CyberGlove		

Table 26: Input Device, Plans Visualization Metaphor, Task and Trigger Notation Metaphor

For Input Device, various devices through which users would interact with the system were listed. These devices include Keyboard, Mouse, Light Pen (a device which can read bar-codes), Touch Screen, McDonald's Keypad (a device in which the menu choices are embedded into keypads i.e., "shake" "value meal 1" "large fries"), *Twiddler*, and *CyberGlove* (a device that uses a number of angular sensors for tracking the position of fingers and hand). In terms of the output device, the users were assumed to get feedback from any arbitrary computer display including a standard monitor to MicroOpical wearable display. Input was considered in this project because it is fundamentally related to the manipulation of the graphical plan workspace. For example a highly text based interface would not do well with a touchscreen or McDonald's keypad, which function in a highly graphical environment. However, the input device can be decoupled from the plan visualization and notation metaphors in most cases. Thus we explore interesting input device choices as related to the other two design dimensions, but we could fall back on a basic mouse/keyboard interface for example. The other two design dimensions are very closely linked and cannot be so easily decoupled. Also, some of our input devices are similar to each other: a *Twiddler* is a more compact keyboard/mouse interface and a touchscreen is very similar to a "McDonald's" keypad.

In the *Plans Visualization Metaphor*, some alternative ways of assembling the robot mission and visualizing the relationships among those tasks and triggers were explored. Free Flow design allows users to place an individual task or trigger at any arbitrary point in the work space while Guided Flow will restrict the way the users place it. The current design is Free Flow with the benefit of the ability to create each mission rapidly even though, for the third person, retrieving any information from the plan may be hard since it is not consistently organized. On the other hand, Guided Flow enables enforcement of standardization in the way users plan the mission, allowing a third party to identify the nature of the mission easily, although it may limit the flexibility of planning. According to the ROTC students we interviewed, military personnel plan a mission using geographical maps while the AI community often utilizes state space to create a robot plan. Thus, these two options, Geographical Maps and State Space, were considered separately for implementation. A Tree Diagram will organize the plans in a tree-like hierarchical order, and Pop-up Windows will visualize each plan, as well as sub-plans that are components of a larger plan, in a separate pop-up window. It is very intuitive to link the pop-up windows with a tree diagram as in the case of Microsoft Windows Explorer.

In the *Task and Trigger Notation Metaphor*, various ways of identifying each task and trigger were explored. Standard Finite State Automata (FSA) Notation is the current *MissionLab* design in which the task is identified as a circle while the trigger is identified as an arrow. On the other hand, Standard Flow Chart Notation uses a box for a condition (trigger) and an arrow for an action (task). Since the military utilizes its own standardized symbols for the planning of a tactical mission, Military symbology was also considered. Furthermore, picture icons and text are also typical of current commercial software (e.g., Microsoft Word, AutoCAD, Adobe PhotoShop for picture icons; and vi, emacs, elm for text). Thus, these two notation methods were also considered as options.

The three key aspects of the design space considered above were combined and used to choose the three best alternative designs. The details of these designs are explained in the next section.

Alternative Designs	Input Device	Plans Visualization Metaphor	Task & Trigger Notation Metaphor
Current Interface Design	Keyboard Mouse	Free Flow State Space	Standard FSA Notation
Interface Design A	Twiddler	Guided Flow State Space	Picture Icons
Interface Design B	Touch Screen	Geographical Map	Military Symbols
Interface Design C	CyberGlove	Tree Diagram Pop Up Windows Free Flow State Space	Picture Icons

Table 27: Current interface design and three new interface designs in terms of three key aspects of the design space.

5.6.4 Current and alternative interface designs

5.6.4.1 Current MissionLab Interface

The current *MissionLab* interface follows the standard Unix/Linux mouse and keyboard WIMP (Windows, Icons, Menus, Pointers) format for data input. The plan visualization metaphor uses a free flowing state-space diagram, with finite state automata notation. The user can select to insert a task, a trigger or a waypoint with one of the three respective buttons to the left of the display. Actions can be inserted into the plan display editor with mouse clicks. After a task (action) is inserted, it can then be modified to represent a specific selection of the primitive actions supported by *MissionLab*; i.e., a menu appears when the right mouse button is clicked on a task. Parameters for the task are entered with the mouse and keyboard through text fields and mouse sliders. Tasks can be connected by triggers. Once the trigger button is depressed with the mouse, the pointer can be used to select two different tasks, which joins them with a trigger. The trigger parameters can be modified in a window that is accessed by clicking on the trigger in the plan display window. Waypoints can be added by clicking on the screen after depressing the waypoint button. This brings up a map and also adds actions to the plan display screen.

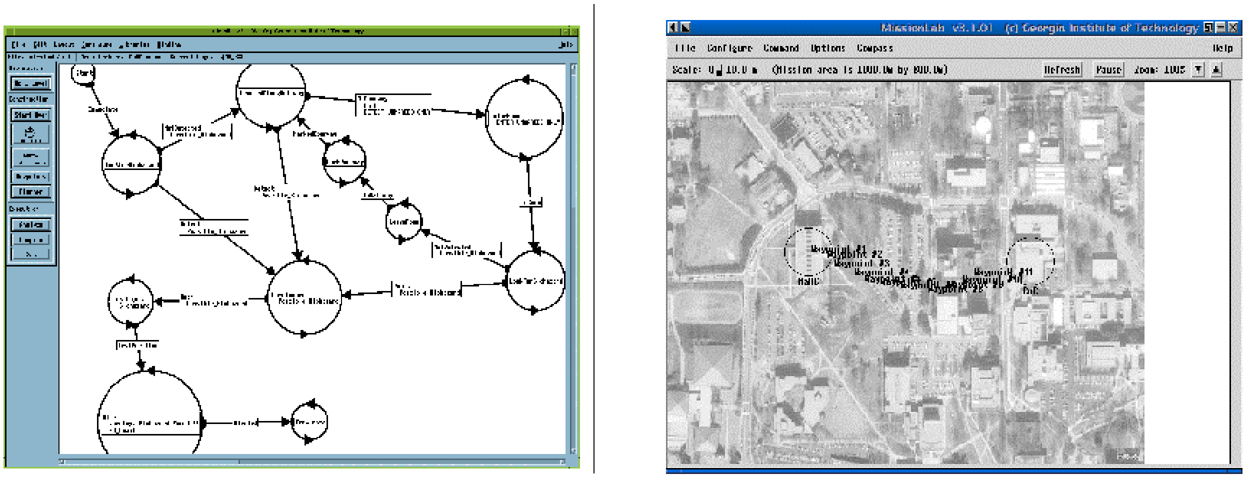


Figure 93: Current MissionLab displays. (left) Cfgedit, (right) Mlab.

5.6.4.2 Interface Design A

Interface Design A is a significant change from the current design, using a layout manager to specify where icons are placed, and picture icons for the notation of specific actions and triggers. Actions, triggers, and waypoints can be inserted by selecting an icon from a toolbar. Instead of selecting to insert an action and then modifying that action by making it a specific behavior such as "move" or detect, all such primary behaviors will be represented with an icon, much as the drawing toolbar in Microsoft Word has a button for inserting boxes, textboxes, arrows, lines, etc. All the FSA (finite state automata) items (i.e., states and triggers) were iconized. Each icon contains the symbolic picture of the action that the robot is trying to do.

1) Similar tasks were identified with the same color.
2) Instead of the single "Add Task" button which forces the user to choose a task from a list that pops up each time, each robot task (i.e., states) now has its own button, and the user can just click any of those to add a task.
3) When any of the task buttons are pressed, a layout manager places its icon automatically in the plan space: the user does not control the placement of icons in a plan except to add or delete icons.
4) The "Add Trigger" button was resized to be larger. According to Fitt's Law this will reduce the time for the user to reach to this button. Since all the tasks/states are required to have at least one trigger, this button ("Add Trigger") should be one of the most frequently used buttons. The benefit in reducing the time to reach to this button is, thus, considered significant.

The main idea behind Interface A is to make the details of the plan more observable: actions of different types, such as movement and detection, will be look different. Different triggers similarly will have different appearances. By enforcing an order on the insertion of the icons into the plan space, the plans will be more easily observable and communicable since they will be organized by a disciplined process instead of a user-created web of icons. Different plans will become far more distinguishable because they can be seen at a glance to include very different actions as the shapes of the plans can be readily seen as different. If a user desires to re-use a plan, but only change the parameters of a detect action, he/she can simply glance at the plan and rapidly find the detect icon, as it is now visually distinct. Further, selecting the icons from toolbars provides the user a faster and more intuitive interface than reading through a text description of possible actions in a menu.

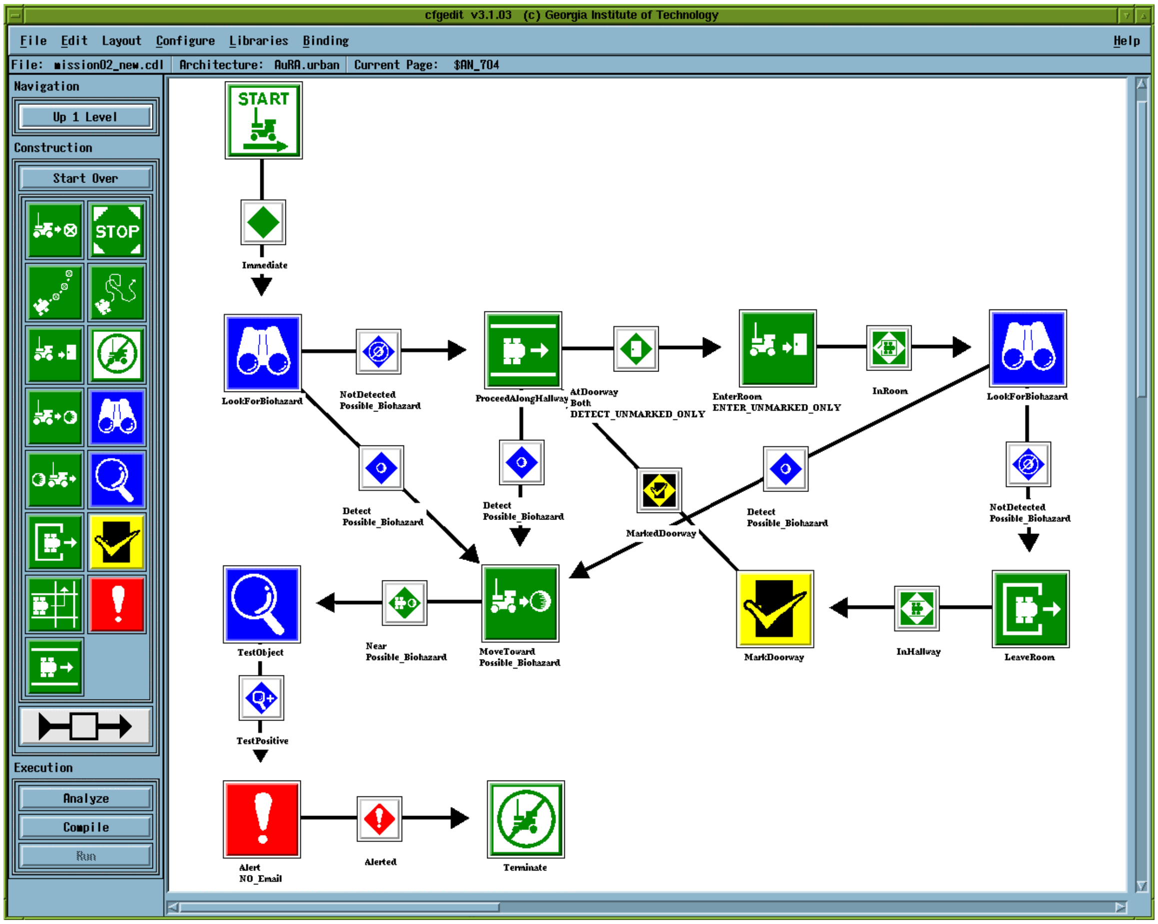


Figure 94: Interface design A.

5.6.4.3 Interface Design B (not implemented yet)

Interface Design B is a further modification of the current design, incorporating ideas from Design A as well. It incorporates a touchscreen input instead of a mouse/keyboard, a geographic map plan visualization metaphor, and military symbols. Instead of using picture icons developed to resemble the actions they represent, it was proposed to use Military symbols as icons to annotate the plan. We take this further by making the plan space directly represent a geographical map (either a symbolic overlay or an aerial photograph) instead of a state space. An example is shown below. All primary behaviors are represented with military symbols as icons. These icons can be selected from toolbars as described in Design A. However, a directed flow of icons will not be enforced. Rather, the icons are not placed in a plan-space, but in a geographical terrain map that relates actions and triggers to the actual real-world environment. A zoom feature is provided to allow a detailed set of instructions to be drawn in a small region. Icons remain the same size at all zoom levels, allowing many icons to be placed in a small area. The touchscreen interface is explored in this design to allow the user to interface with the system without a keyboard/mouse or surrogate input device. The touchscreen allows the user to directly select icons from the toolbars, place them on the map with zoom/pan features, and modify the action/trigger parameters from menus.

The principal idea behind Interface B is to make the details of the plan both more observable and distinguishable as in Interface A, but to further make them relevant to the military soldier's way of thinking. Not only will the inclusion of existing military symbols relate to the mental models of a soldier, but relating the robot behavior to an actual map instead of an abstract state-space will further bring the robot mission into reality.

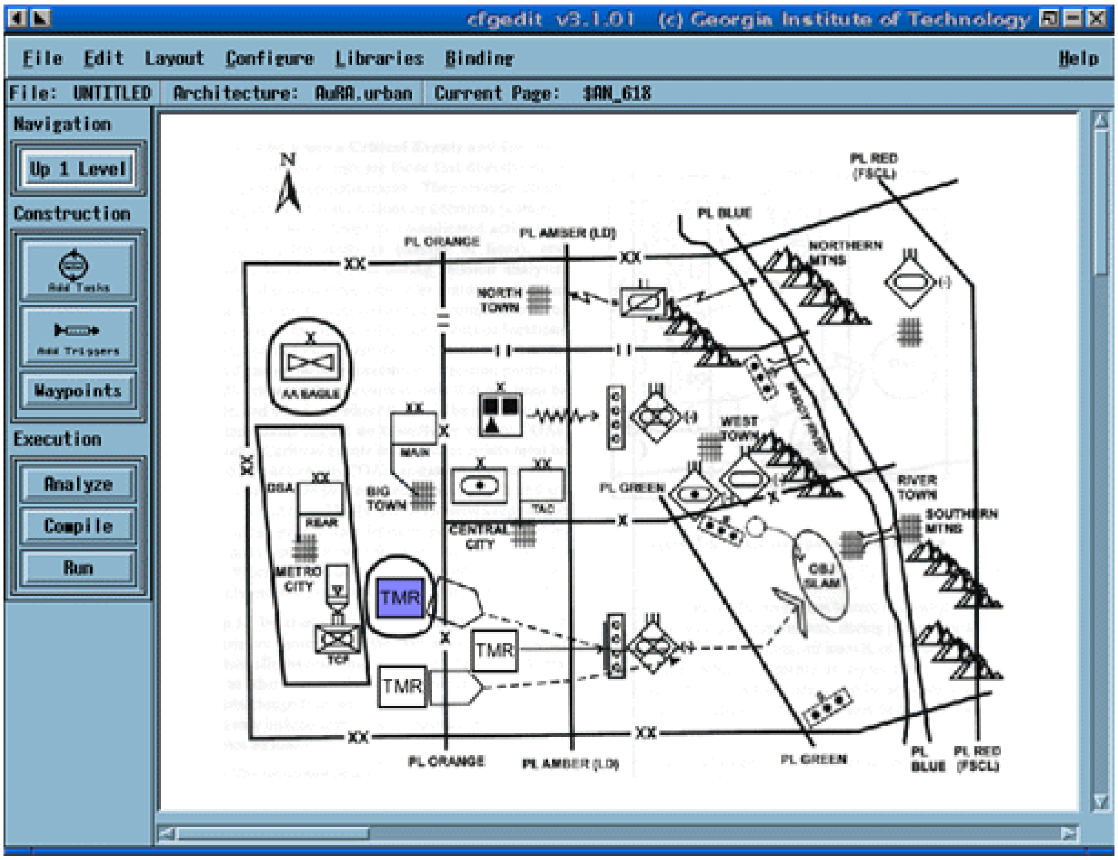


Figure 95: Interface design B.

5.6.4.4 Interface Design C (not implemented yet)

Interface Design C is a final evolution from the current design and Interface A: it includes a wearable "CyberGlove" input device, a combined tree diagram and pop-up window state space visualization metaphor, and picture icons for the notation of actions and triggers. The CyberGlove innovates over the Twiddler in moving away from a mouse and keyboard interface to natural hand movements - the user can press buttons, drag and drop icons, and use on-screen sliders and keypads with the tracking features provided in the CyberGlove software. As stated previously, the user has little need to enter sentences or large streams of characters, only numbers in certain action and trigger parameters. The CyberGlove can also be used to move a pointer across the screen: thus the CyberGlove combines the ideas of the touchscreen (except the gloves do the touching) and the mouse interface of the Twiddler. The other major point of this design is the grouping of actions and triggers into a hierarchical scheme that can be displayed much like a windows explorer screen, shown below. Thus at the highest level, a plan will consist of sub-plans that can be opened on the left tree display, and then picture icons of actions and triggers that can be viewed and interacted with on the right explorer display. The picture icons can be used as in Interface A, without a guided flow, and with the added dimension of sub-plans in a hierarchical scheme. The flow of sub-plan to sub-plan will be captured in the tree display. For example, a sub-plan could be opened to reveal a set of primary actions and triggers that link to another sub-plan. To open this sub-plan, the user would subsequently click on it to view its actions and triggers.

The principal idea of this interface design is to emphasize the usage of pre-existing plans already present in a plan library. By aggregating plans together along with new plans as they are created or primary actions and triggers in a hierarchical tree display that can also be explored in pop-up windows, a very expansive plan environment can be created that facilitates development of complex high-level robot missions. Because the plans can be grouped into hierarchies of behavior, a structured flow is not imposed as in Interface A. Rather a free-flowing plan space allows easy manipulation of icons. Otherwise, this design rationale is much like Interface A in its use of picture icons. The rationale behind the CyberGlove is also similar to those previously discussed: to move away from the conventional bulky laptop interface. If the user can learn and rapidly execute the needed commands with hand movements alone, rapid user interaction with the system can occur. Further, a wearable glove can be paired with goggles to create a very discreet interface f

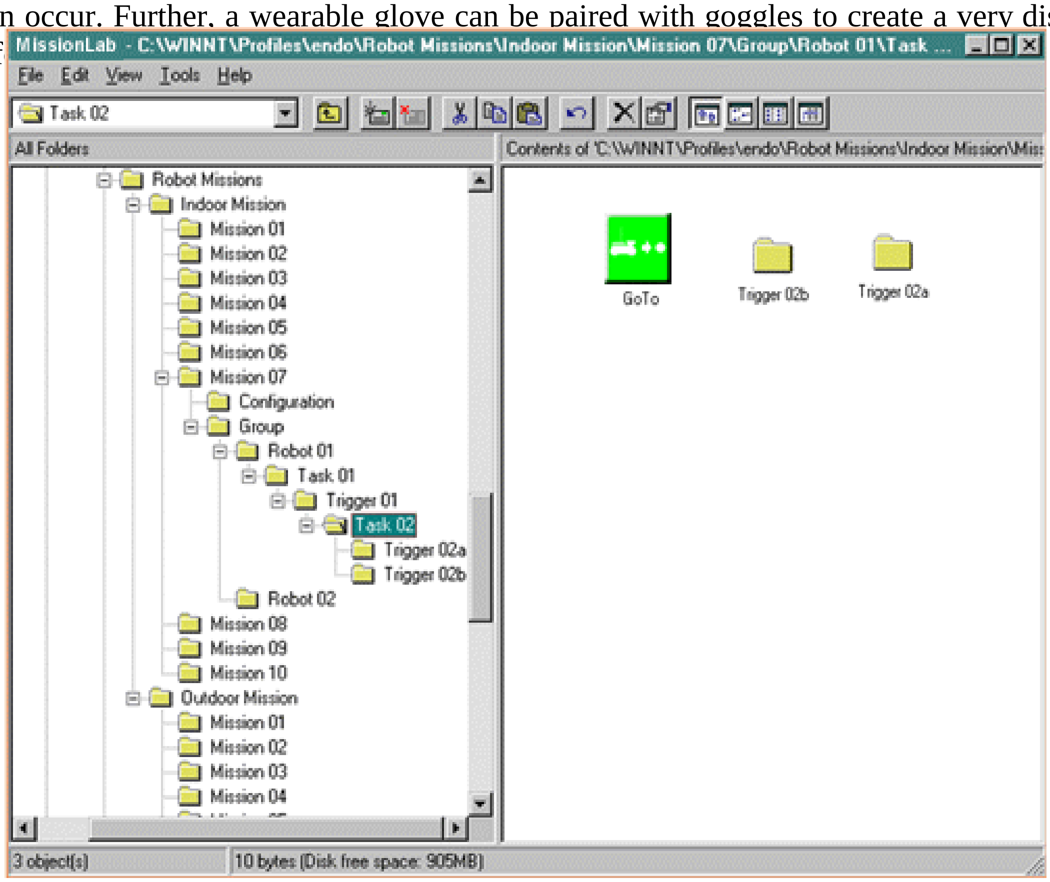


Figure 96: Interface design C.

5.6.5 Prototype Evaluations

From the suggested alternative *MissionLab* interface designs above, a prototype of Interface Design A (guided flow, FSA, and icon metaphors) was created and named Prototype 2. This prototype was, however, not interfaced with Twiddler. Instead, it takes the user's inputs from a mouse and keyboard. The current *MissionLab* interface was named Prototype 1, and the following usability study (pilot) was conducted.

5.6.5.1 Evaluation Exercise 1 - Waypoint Creation

5.6.5.1.1 Setup

In this exercise, seven test subjects were asked to create two waypoint missions using either Prototype 1 or 2. The subjects were volunteers solicited from the Georgia Tech campus, and consisted of two military personnel, two mechanical engineering graduate students, and three computer science graduate students. Six out of the seven subjects were experienced programmers, regularly using two or more computer languages for over five years. The two military personnel were experienced with battle operations, with an emphasis on directing ground troop operations. All users were experienced with WIMP interfaces such as that used in MissionLab.

The waypoint missions which subjects were asked to create were identical to the one for Phase 1 - Tasks 1-1 and 1-2 in Section 5.4.1.3 and 5.4.1.4, respectively. The study was conducted using the same format as those. The subjects were also asked to "think aloud" during the exercise, and they were recorded with a video camera. Tasks 1-1 and 1-2 were given alternately to the subjects as their user mission for prototypes 1 and 2 such that some users did mission Task 1 on first prototype, and others did mission Task 2. The subjects executed two tutorials (the same ones for Phase 1 in Section 5.4.1.1 and 5.4.1.2).

5.6.5.1.2 Results

5.6.5.1.2.1 Error Log and Video Capture

The table below provides a summary of the task completion times of the exercise; four subjects performed Task 1 and three subjects performed task 2 using Prototype 1 (the current interface); three subjects executed Task 1 and four subjects executed task 2 using Prototype 2 (the alternative interface). The task execution times were averaged and depicted in Table 28. The average time it takes for one of the mission construction steps, adding a trigger between the two states, is also shown in Table 28. Observe that there is a wide variation in user performance. Counts of user errors were very low and difficult to analyze: most users made one or two mistakes but classifying logged events as errors was difficult as the users were often exploring different functions, trying to execute the mission tasks with different sequences of low-level actions (i.e., mistakes were not easily factorable form exploration of design space for mission). Analysis of error counts was discarded as not being significant in this experiment.

	Prototype 1 (Current Interface)		Prototype 2 (Alternative Interface)	
Subject	Overall Time (sec)	Add a Trigger (sec)	Overall Time (sec)	Add a Trigger (sec)
S01	243	16	191	6
S02	74	12	76	4
S03	46	3	45	3
S04	122	3	131	2
S05	147	4	66	3
S06	133	10	148	11
S07	254	11	128	8
Average	145.6	8.4	112.1	5.3

Table 28: Results for mission construction.

5.6.5.1.2.2 Think Aloud

Users' protocols from the think aloud exercise were grouped into chunks and classified as states of successful *confirmation*, such as "I am pressing the waypoint button", as well as user *confusion*, such as "wait, what happened?" It was found that, for Prototype 1, most of the user *confusion* was not related to the FSA icons or the free-flow plan space in these test subjects. Significant points of confusion were noted: one user did not understand why it was necessary to link the initial and final triggers to the rest of the plan. The user repeatedly expressed concern over the significance of this step while using Prototype 1. Another point of significant confusion was noted in another subject when attempting to add mission waypoints, which are linked to a geographical map display. The subject could not bring up a geographical map of the mission because the subject was attempting to find a specific button indicating a "map" function. Intervention was required. The user did not expect to have the map shown automatically after clicking on the "waypoints" button. One user could not cancel an action performed before any building of the FSA plan. Intervention was again required. Of note is the fact that the users did *not* express confusion over the FSA notation or the free-flowing plan space in Prototype 1.

In the observed trials for Prototype 2, user confusion was not generally related to the picture icons or the guided-flow plan space. One user commented that the trigger picture icon resembled the military notation for a machine gun position on a map. The only other significant point of confusion in one user was in understanding the meaning of the maps ("is this line a road here?").

5.6.5.1.2.3 Feedback

Finally, the test subjects were ask to comment on their preferences between the two prototypes and justify them as much as possible. Six out of the seven test subjects responded that they preferred Prototype 2, with a picture icon and guided flow plan space. One user did not express any significant preference of one interface to the other. However, all user comments focused on the picture icons: none of the users discussed the guided vs. free-flow plan layout manager. It seems that it was entirely unnoticed. Significant user comments included:

> "I preferred the picture icons because of their smaller size - it was easier to view the entire plan."

> "The picture icons had a lower cognitive load. The text based icons would be hard to read in poor light conditions while I think that the pictures could be easily recognized."

"The picture icons are easy to remember. There is no need to remember the text names of the icons."

"All states are available in the menu at once, while viewing the plan, in the picture icon interface."

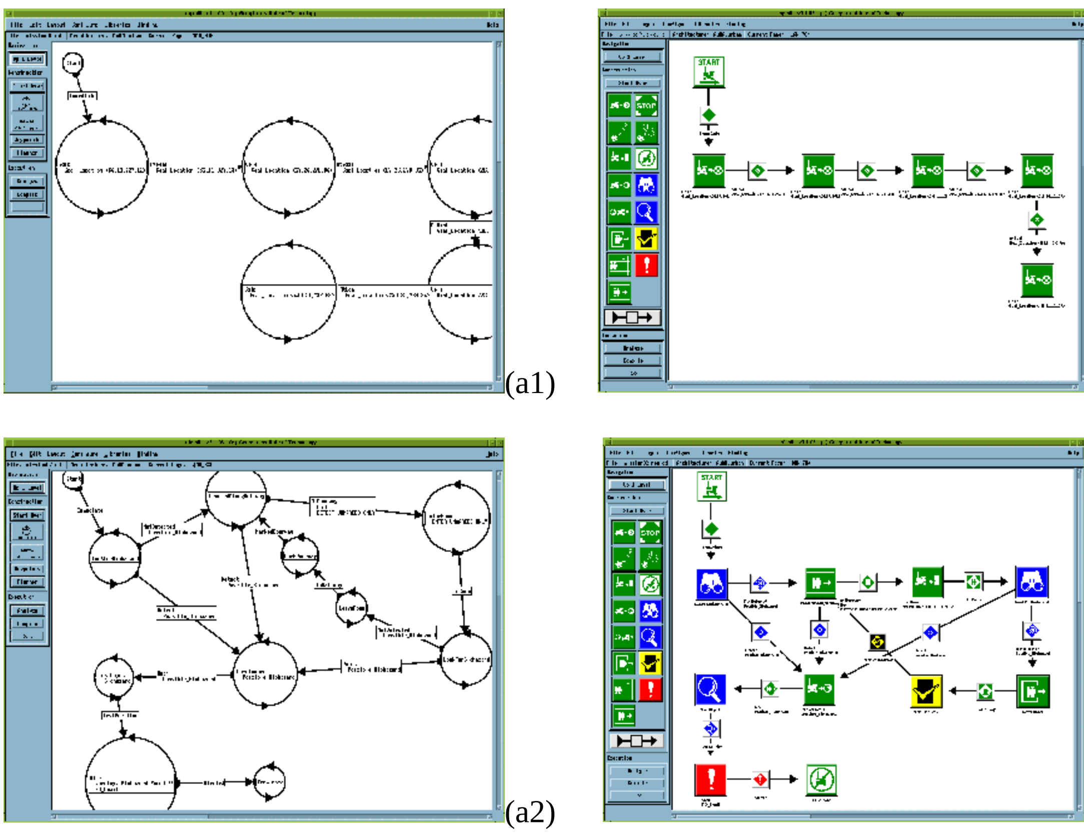
"The icons are superior because you place the state you want on the map instead of placing a generic icon and then changing it."

"At first I preferred the text icons, but after learning them, I preferred the picture icons."

5.6.5.2 Evaluation Exercise 2 - Mission Identification

Evaluation Exercise 2 is to visually compare a set of five different plans printed from the 1st and 2nd prototypes: each plan represents a distinctly different sequence of actions: we present the screenshots (Figure 97) to the test subjects and ask them to describe the plans that are represented. They are printed in color to provide all the information available on a live screen.

The rationale behind this exercise is to further explore how picture icons can be used to provide more clearly recognizable and understandable missions. We desire to compare the amount of time it takes to identify the features and general mission represented in Prototype 1 and Prototype 2 plan notation schemes, explicitly comparing the effectiveness of our picture icons to the finite state automata icons originally used.



(a1) (b1) (a2) (b2)

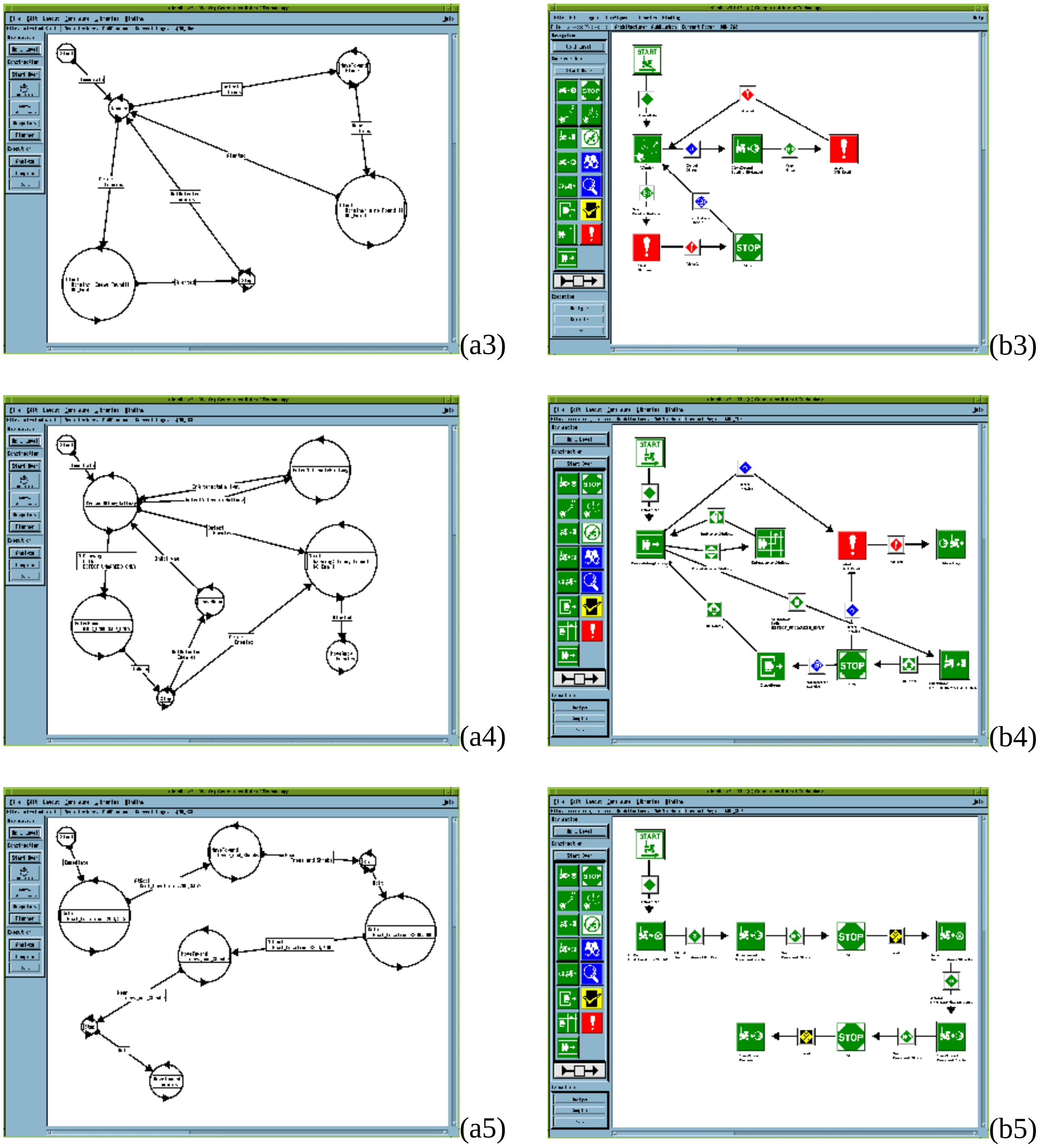


Figure 97: Screen shots used in the mission identification exercise – Prototype 1 (a's) and Prototype 2 (b's): (a1, b1) waypoints following mission; (a2, b2) indoor mission for bio-hazard detection and identification; (a3, b3) outdoor mission of detecting mines and enemies; (a4, b4) indoor mission of finding enemies; (a5, b5) outdoor mission of a sneak attack.

5.6.5.2.1 Setup

After the test subjects had used both prototypes for some time, we administered a question and answer session. As previously described, Exercise 2 asks the subjects to review a set of five plans (set 1) in the picture icon format (*MissionLab* Prototype 2) and (set 2) the Finite State

Automata (*MissionLab* prototype 1) icon notation. The plans were printed in color from the screenshots. The followings are the questions the users were asked:

1) What do you think that this robot mission is about?

2) What key features would you identify in this robot mission?

The subjects recorded their answers on the questionnaire. They were given the plans in a random order each time: the plans from set 1 and 2 were mixed together. The users could not spend more than 1 minute on each plan presented to them.

5.6.5.2.1.1 Results

The user success rates are shown in Table 29 below.

Subject	Set 2 Plan Successfully Identified (%)	Set 1 Plan Successfully Identified (%)	Overall (%)
S01	100	100	100
S02	80	80	80
S03	100	40	70
S04	60	60	60
S05	60	60	60
S06	100	100	100
S07	60	60	60
Average	80%	71%	76%

Table 29: Results for mission identification.

The quantitative results of this evaluation did not indicate a clear superiority of either plan scheme. The user responses to each plan were scored as a failure if the user did not identify one major component of the plan. Flaws with the scoring scheme and experimental plans are discussed later in a criticism of the evaluation plan. However, when questioned about their preferences, the users expressed their preference for plans generated with Prototype 2. As relevant to Exercise 2, user comments included:

"Picture icons preferred: I could tell more quickly what the mission was."

"The picture icons are easier to recognize."

"After looking at the picture icons for a while, I preferred to use them."

5.6.6 Discussion

The results above indicated that task completion times were faster using Prototype 2, with the picture icons and guided flow interface. The rate of successful plan identification was not significantly different between prototypes however. Due to problems with the experimental design, discussed below, and the low number of users tested, this data should be taken from the perspective of a formative evaluation at this point. Clear conclusions cannot be drawn from this data, although trends are indicated by the improved execution times using Prototype 2 and the slightly improved plan recognition rate with plans generated with Prototype 2. Most significant is that user feedback indicated a clear preference for the picture icons in Prototype 2 in all experiments. However, there was no clear evidence to support the use of the guided versus free flow plan space that was included in Prototype 2. Overall, we can see that users would prefer an iconified plan scheme as shown in Prototype 2. Further, our user feedback in the "think aloud" exercise indicates 1.) that the start and end triggers be automatically added to the plans during their generation and 2.) a different trigger icon should be used that is not similar to an existing military symbol.

5.7 Usability Conclusions

We have successfully evaluated the current status of the *MissionLab* interface. We wanted to target missions concerning the selection of waypoints and determine their effectiveness for mission specification. We learned that missions where more waypoints were used generally conformed better to the specifications provided, regardless of the number of robots that a subject is asked to configure. Waypoints definitely contribute to the overall success of the mission, making it simpler for users of any experience level to configure complex missions. The concept of waypoints seems readily acceptable and usable to the subject. Subjects demonstrated no difficulty in placing or manipulating them and generally achieved a high success level in terms of mission specification criteria.

We wished to draw correlations amongst the experience levels of the subject pool and the quantitative data, but there seems to be no correlations among the mission quality of subjects of varying experience levels, nor do these groupings show anything readily quantifiable. The fact that novice users can create mission configurations as successful as the expert users suggests that *MissionLab* is an effective toolkit to be used by those with little or no computer experience.

We also wished to determine a correlation in the success of highly specific, complex missions, to the number of tasks that a user uses to implement them. For all missions, however, no correlation could be ascertained, and it remains for further analysis to determine what mix (if any) of task and trigger specification leads to the consistently highest success level given the mission criteria.

As it is described in Section 5.6.6, the results from the evaluation of the alternative interface design indicated that the users are likely to create robot missions faster with the user interface employing picture icons and guided flow (Prototype 2) than the current *MissionLab* interface, which employs the free flowing state-space diagram visualization metaphor with finite state automata notation. No significant difference was found between those two in terms of the users being able to identify the mission plans created by another person. By analyzing the feedbacks obtained from the test subjects, we found that the picture icons used in Prototype 2 were much favored by the subjects than the current FSA notation. On the other hand, the users did not express favor on the use of the guided flow plan space utilized in Prototype 2. It should be noted, however, that the alternative interface design was evaluated by a small number of test subjects. Thus, clear conclusions should not be drawn at this point. We recommend further investigation of alternative interfaces, which answers the questions of:

1. What pictures correspond best to robot mission primitive actions?
2. What is the best size of the icons to optimize visibility in bad lighting while preserving small enough icons to view most or all of a plan in one plan window?
3. Should text be placed underneath the picture icons to help identify them?

4. How can missions be aggregated into sub-missions with icons?
5. Should multiple icon toolbars be used to group similar functions together by function as well as by color?
6. What pictures and colors help identify the icons best?
7. Does a layout manager improve the usability of the plan icons?

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Appendix A. Operator training

This material is reproduced from Byrd, J., and Duke, E., (Eds.) "Final Report: Guidelines for the Development of Training Programs for the Operation and Maintenance of Robotic equipment", Morgantown, WV, U.S. Department of Energy, Federal Energy Technology Center.
pp. 15,19,23,e-3-47

Appendix B. Human Factors Considerations and Display Systems

This material is reproduced from National Research Council, Tactical Display for Soldiers: Human Factors Considerations, National Academy Press, Washington, D.C., 1997. pp. 70-87.

Appendix C: Consent Form

Georgia Institute of Technology
Human Subject Consent and Release Form

1. Title of Project: Realtime Cooperative Behavior for Tactical Mobile Robot Systems

2. Purpose of Research: To make robotic systems more usable, by better understanding how users interact with them during both design and execution.

3. Participants: Approximately 20-40 participants will be used. They will be recruited primarily from within Georgia Tech and the College of Computing primarily through the use of electronic newsgroups, with possible recruitment off-campus as well at nearby military bases.

4. Duration: It is expected that each participant will have 2 sessions, each lasting approximately 1 hour, and both of the sessions occurring no more than 1 day apart.

5. Explanation of procedures to be followed: The tests will be administered in the GVU usability laboratory, the mobile robot laboratory, or at a remote site. A test administrator will describe the procedures to be used in detail to the participant prior to the start of the session.

6. Foreseeable risks or discomforts: Possible participant frustration with the system

7. Expected benefits to the participant: Learn about and contribute to the future of robotics.

8. Compensation: Participants will be paid at an hourly rate that is typical for GVU lab participants.

9. Alternate procedures: None

10. Confidentiality of records: Participant confidentiality will be preserved by referring to participants only by numbers in reports, unless it is necessary to do otherwise, and permission is granted by the participant.

11. Reports of injury or reaction should be made to Ronald C. Arkin (PI) at 404-894-8209. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

12. If you have questions about the research, call or write (PI) at:

Ronald C. Arkin
College of Computing
Georgia Institute of Technology

Atlanta, GA 30332-0280
Phone: (404) 894-8209
Fax: (404) 894-0957
Email: arkin@cc.gatech.edu

13. You have rights as a research volunteer. Taking part in this study is completely voluntary. If you do not take part, you will have no penalty. You may stop taking part in this study at any time with no penalty. If you have any questions about your right as a research volunteer, call or write:

Barbara S. Henry, ReACTT
(Research Administration, Compliance, Training, and Technologies)
Office of Sponsored Programs
Georgia Institute of Technology
Atlanta, Georgia 30332-0420
(404) 894-6944 (voice)
(404) 894-5285 (fax)

I have read and understood the information above. The researchers have answered all my questions to my satisfaction. They gave me a copy of this form. I consent to take part in this study.

Participant's Signature: ___________________________________ Date:_____________

Investigator's Signature: __________________________________ Date:_____________

Witness: ____ Date:_____________

Parent/ Guardian (if participant is a minor): ___________________ Date:_____________

Appendix D: Pre-test, background questionnaire

CONTACT INFORMATION

Name___________________________

Email___________________________

PO Box__________________________

BACKGROUND INFORMATION
What best describes you? (Please check all that apply)

[ ] Undergraduate [ ] Graduate
Semester _____ Major _________

[ ] Professor [ ] Instructor
Department___________________

[ ] Engineer

[ ] Programmer

[ ] Military

COMPUTER EXPERIENCE

What types of personal computers are you comfortable with? (Check all that apply)
[ ] Unix / Linux with X Windows [ ] Microsoft Windows (95/98/NT) [ ] Mac

Are you comfortable with mouse use?
[ ] Yes [ ] No

Which types of mouse have you used? (Check all that apply)

[ ] One button (Mac style) [ ] Two-Button (Microsoft Windows style)
[ ] Three button mouse (Unix/Linux and Microsoft windows)
[ ] No experience

Have you used a laptop before?
[ ] Yes
[ ] No

Programming experience is not necessary to participate in this study. If you do have any experience, we'd like to know more about it.

What programming languages do you know? (Please list)
____

How long have you been programming? __________________

MILITARY EXPERIENCE

Military experience is desired, but not required to participate in this study. If you do have any experience, we'd like to know more about it.

Please describe your military experience in brief:

MISCELLANEOUS

Do you enjoy video games?

[ ]-------------[ ] -----------------[ ] ---------------[ ]-----------------------[ ]

Hate They're OK Love 'em

Do you give directions well?

[ ]-------------[ ] -----------------[ ] ---------------[ ]-----------------------[ ]

I'm terrible I'm OK I'm really good.

If you are or were a student of Georgia Institute of Technology, do we have you permission to use your admission tests scores during our statistical analysis?

[ ] It's OK to use my SAT scores for this study.
[ ] I do not wish to provide my SAT scores for this study.

[ ] It's OK to use my GRE scores for this study.
[ ] I do not wish to provide my GRE scores for this study.

Thank you for filling in this form. The research assistant will get in touch with you soon. In the meantime, if you have any questions or concerns, please address them to Anirudh Moudgal, amoudgal@cc

Appendix E: Post-test questionnaire/survey

1. MissionLab was easy to use

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

2. MissionLab is visually appealing

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

3. MissionLab is good for building robot missions

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

4. MissionLab is good for testing robot missions

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

5. The computer peripherals (monitor, mouse, keyboard etc.) were easy to use

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

6. The facilities provided to the participant during the study were appropriate

[   ] Disagree ----- [ ] ----- [ ] ------[ ] ------ [ ] Agree

7. What did you like about MissionLab? (use back of sheet if necessary)

8. What did you dislike about MissionLab? (use back of sheet if necessary)

Appendix F: Administrator Scripts

Tutorial 1a: Review of Back and Forth

Synopsis

We will create a robot that goes "back-and-forth".

Setup

Start Cfgedit for user.

Say

We will first do a review of some tasks you have already learned. Do you remember how to create a back-and-forth robot?

Wait for answer. If user can demonstrate a back-and-forth robot, you may skip ahead to the next tutorial.

OK. We'll quickly review. I have started up MissionLab for you. Let's create a new robot. Do you remember how to descend the mission specification hierarchy to the mission (FSA) level? Use the middle mouse button on the group and robot icons.

See that the user does so and assist if necessary.

OK. Now we want to specify the two points between which the robot will go back and forth. Use the Add Task button on your left hand toolbar to create the two new tasks that will instruct the robot which points to move between. Place these in your work area.

In fact, the user may do this in any order they wish. The point of this exercise is to simply re-familiarize the user with the interface.

Using your right mouse button, change the default tasks to **GoTo** tasks. Do you remember how to change the coordinates using the middle mouse button?

Wait and see that the user can change the waypoints.

Create triggers signifying when to transition between these two tasks by using the Add Trigger button on your left toolbar and clicking the left mouse button on one task and dragging it to the task to which you would like to connect. Remember that these are notational triggers signifying the transitions between the tasks that the robot is executing. They in no way relate to direction.

Wait.

Now, we need to specify when to make this transition. Do you remember the trigger that you had used?

*Wait and see that the user chooses **AtGoal**. If he or she cannot get this, re-explain the concept and make sure they understand before continuing.*

You also need to specify the correct goal locations for **AtGoal**. Use the middle mouse button to pull up a dialog window that will allow you to configure these parameters.

Wait.

Do not forget to connect the **Start** state to the first task you would like the robot to execute. Once you have completed this, you may compile and run the mission. Use the empty overlay.

Wait and assist as necessary.

Congratulations! Now let's move on to something more exciting…

Tutorial 1b: Explosive Ordnance Disposal

Synopsis

You will take the user through the steps in configuring a robot to clear a minefield and safely deposit the mines in a designated safe area.

Setup

Start Cfgedit for user.

Say

In this mission you will work with one robot. This robot is tasked with collecting explosives from a minefield and disposing them in a designated safe area henceforth known as the explosive ordinance disposal, or "EOD Area". It is capable of carrying one mine at a time and need not worry about defusing them. When it has cleared all mines, then it is to return to its home area and terminate.

To accomplish this task, we will utilize four new tasks, **LookFor**, **MoveToward**, **PickUp**, and **PutInEOD**. We will also introduce five new triggers, **Detect**, **NotDetected**, **Near, Holding,** and **NotHolding**. I will explain these tasks and triggers as we use them.

First, create a new task. This will be the first task the robot begins upon execution. We want the robot to begin looking for an object. Using the right mouse button, change this task to **LookFor**. This will cause the robot to start looking for a specified object.

Wait.

We want the robot to look for mines, so we need to change the specified object for this task to "Mines". To do so, use the middle mouse button over the icon for the task. It is possible that the robot may want to look for multiple objects, so you may select more than one object. In this case we just want mines, so make sure that everything else is unselected.

Wait.

Two things can happen while the robot is looking for mines. The robot can detect a mine, or it can decide that there are no more mines left in its field of view. The trigger **Detect** becomes active when a robot has detected an object of a specified type, and the trigger **NotDetected** becomes active when a robot detects no more of a specified type. Let's say that the robot has detected a mine. Create a new task in your work area and use the right mouse button to change it. What task do you think the robot should execute next?

Wait.

The robot should move toward the mine, as it has to get close enough to pick it up, so make this new task you have just created **MoveToward**.

Wait.

Now, we need to tell the robot which type of object to move to. Use the middle mouse button to examine the parameters for this task. From the list of objects that appear, select "Mines". The robot will now move to a mine while executing this task. Is this clear?

Wait.

Since we want the robot to begin moving toward the mine as soon as it detects it, create a new trigger from **LookFor** to **MoveToward**, and make this a **Detect** trigger.

Wait.

Change the parameters of the trigger to detect "Mines" using the middle mouse button.

Wait.

Create another new task and place it in your work area. You may use the right mouse button to pull up the list of available tasks. What task should the robot do once it reaches the mine?

Wait for answer.

This task should be **PickUp**. Don't forget you need to tell the robot what type of object to pick up. What do you think this parameter is? Configure the task as such.

Wait and see that the user is able to set the "Mines" parameter for the ***PickUp*** *task.*

Great. Now, we need to define a trigger to transition from the **MoveToward** task to the **PickUp** task. Create this trigger. What do you think this trigger should be, or, in other words, when should this transition take place?

Wait for answer.

The robot needs to make this transition when it is near enough to the object in question, in this case, a mine. Make the new trigger **Near**, and configure the appropriate parameter as you did for the other two triggers.

Wait. See that the user changes the parameter to "Mine"

You've done very well so far. Do you understand what you have done up until this point?

Wait for answer.

Good. Now that we have the mine in our possession, we need to bring it the EOD area. The robot knows where the EOD area is. What task – based on what you have learned so far – do you think you will need to accomplish this?

*Wait and see that the user understands that he or she needs **MoveToward**.*

Create a new **MoveToward** task, except this time we are not moving to a mine, but we are moving an EOD area. Thus, configure this task with the appropriate parameters.

Wait and see that the user configures the task properly.

Once again, create a trigger between these tasks. When the robot has finished picking up the mine and has it in its possession. The **Holding** trigger becomes active. Make this your trigger from **PickUp** to **MoveToward** "EOD Area".

Wait.

Now, earlier when the robot was near the mine, we configured the robot to pick up the mine. What do you think the robot should do when it is near the EOD area?

Wait for answer. The answer should be "dispose of the mine".

A task exists named **PutInEOD** that accomplishes just this. Create a new task and new trigger that configures the robot to put the mine in the EOD area when the robot is sufficiently near enough to it.

*Wait and see that the user configures the **PutInEOD** task and **Near** "EOD" trigger correctly.*

Very good. Now, when the robot has disposed of the mine, we would like for it to continue collecting mines for as long as it senses that more mines are out there. So we will create a new trigger from the **PutInEOD** task back to the original **LookFor** "Mines" that you had created. Do this now.

Wait.

Since we want the robot to begin searching for mines again when it has disposed of the one it is previously holding, this trigger should be **NotHolding**, as the robot should have gotten rid of the mine it was holding.

Wait.

Now, let's say that the robot no longer detects any mines present. We want the robot to return home and terminate when it senses this. Create a new **MoveToward** task and configure it to move the robot to "Home Base".

Wait.

What is the trigger that signifies when a robot does NOT detect any object of a particular type?

Wait.

It is called **NotDetected**. Now, from which task should we make this trigger to **MoveToward** "Home Base"? What was the robot doing when it realizes no more mines are present?

*Wait and see that the user makes the trigger from **LookFor** "Mines".*

Excellent. Now when the robot is home, it should terminate. Create a terminate task.

Wait.

Create a new trigger from **MoveToward** "Home Base" to **Terminate**. What should this trigger be?

*Wait and see that the user creates and configures a **Near** "Home Base" trigger.*

Very good. You are now ready to compile and test your mission. You may begin doing so now. You will use the minefield overlay for the simulation. I will assist you if necessary.

See that the mission compiles and runs correctly and assist the user as needed.

Congratulations! You have completed a fairly complex mission. Let's save this mission configuration for later reuse. To do so, select "Save Configuration" from the File menu and type in a name in the dialog box that appears.

Wait.

Now I want you to clear the mission specification by selecting the Start Over button on the left side panel.

Wait.

Good, now reload the previous mission by selecting "Load Configuration" from the File menu and entering the name you had chosen.

Wait.

You may also do this when you first open the configuration editor. However, remember that when you load a previously saved mission, anything in your current work area will be lost.

Review Tasks and Triggers sheet before proceeding to Task 1.

Phase II, Task 1

Mission:

Search a corridor of a building for biohazards.

Task:

It is 3 AM. In a biomedical research building located in a renegade nation, a single robot has been delivered to the entry of the building and has been successfully and secretly escorted inside. It awaits command at the beginning of a hallway just inside the entrance. The task for this robot is to proceed along this hallway and search every room that has an open door for the presence of a biohazard.

A warning about this mission: the robot has very poor knowledge of the layout of the building. Any available maps or drawings are dated and possibly inaccurate, as intelligence does not know how the current occupants may have modified the building. Therefore, we cannot use waypoints to accomplish the task as you did earlier in the Hospital Approach scenario. We do know, however, that the layout of this building is conventional. It has a linear corridor with rooms on both the left and right sides. At this early hour nobody is expected to be present in the building, so the robot can safely move about without fear of detection.

This mission should be accomplished as follows: from its starting position the robot proceeds down the hallway. At any and every open door it encounters, it enters the room and conducts a biohazard survey. If the survey results indicate that a biohazard is present, the robot should immediately alert the user. If the survey results do not indicate the presence of a biohazard, the robot should mark the room as visited, and continue the search, surveying additional rooms as needed. At any point in the mission that the robot encounters a biohazard and alerts the user, the robot's mission is complete and it can safely terminate. If the robot reaches the end of the hallway, it should turn around and navigate back down the hallway, searching for additional rooms it may have not checked. Once the robot finds itself back at its starting position at the entrance, it should alert the user that no biohazards have been found and it may safely terminate.

Phase II, Tutorial 2a: Multi-Robot EOD

Synopsis

The user will simply duplicate the EOD robot that he or she created in the first tutorial and run them both in the minefield. This is intended to show the user how easy it is to duplicate missions.

Setup

Start Cfgedit for user. Load the user's previously saved mission. You may explain this process any way you like.

Say

This mission will involve the configuration of two robots. Do you remember how to create a configuration for the second robot by duplicating the first?

Wait for response and review as necessary.

Use the middle mouse button to descend to the second level of the configuration hierarchy. You should see an icon that says "Individual Robot". Use the copy and paste feature or the duplicate feature to create a second, identical robot.

Wait.

Now you have two robots that have the same configuration. Descend the mission level on the second robot. Is this the same as the one you created earlier?

Wait for answer.

Good. Go ahead and compile and run this mission using the minefield overlay as you did earlier. This time, you should see two robots collecting mines.

Wait.

This is useful for creating many robots with the same mission specifications. If desired, you could modify the individual mission specifications to create robots with similar, but not identical behavior. However, these robots are completely blind to each other's actions. In the next tutorial, you will learn how to make two robots communicate.

Show again if appropriate.

Tutorial 2b: Robot Communication

Synopsis

This mission will demonstrate to the user how one robot can send and receive messages to and from another robot. We will specify a mission where one robot will command a second robot to follow it until a goal is reached at which point the first robot will dismiss the second robot. At this point the second robot will cease following the first and continue to a second goal location.

Setup

Start Cfgedit for user.

Say

We are going to create a robot that commands another robot to follow it to a particular goal location. It will then dismiss that robot and the second robot will continue on to a second goal location.

Create a new robot. Duplicate this robot as you did in the previous tutorial

Wait.

First, let us create the configuration for the first robot. Descend to the mission (FSA) level of the first robot. We want this robot to simply move to a specified point. However, before doing so, we want to tell the other robot to follow. Create a new task using the Add Task button on the left menu. Use the right mouse button to change this task to **NotifyRobots**.

Wait.

We need to specify the notification message for this task. Use the middle mouse button to display the parameters for this task. Change the notification message to something descriptive of this task. For example, "*Follow me*" would be an appropriate choice.

Wait.

Next, we would like this first robot to move to a specified location. Create a new **GoTo** task and specify the location as coordinate (6,7). Do you remember how to do this?

Wait for answer and assist as necessary.

Create a trigger from the **NotifyRobots** task to the **GoTo** task. The default trigger is **MessageSent**. Since we want to begin moving as soon as we have notified the other robot, this is the correct trigger to use in this case.

Wait.

The next task for this robot is to tell the other robot at some point that it can stop following. Create a new **NotifyRobots** task and send an appropriate message indicating this robot's new desire. "*Stop following*" will suffice.

Wait.

We need to create a transition from the **GoTo** task. When do you think the robot should send this message?

Wait and see that the user can correctly infer that the robot should send the message when at the goal, and he or she uses the correct trigger.

The first robot's mission is now complete. Create a new task and trigger indicating that this first robot should terminate once the previous message to stop following has been sent.

Wait and see that the user can accomplish this.

You have just completed the configuration for the first robot. I will explain shortly, how a robot receives communication. Do you have any questions about anything you have done up to this point?

Wait and answer questions.

Great. Now return to the robot group configuration level and edit the configuration for the second robot. The mission for this robot is to follow the first robot wherever it goes when summoned. After it has been dismissed, it is to move to another (different) pre-specified location. Create a new task for this robot.

Wait.

By default, this robot should do nothing until summoned. So the **Stop** task is appropriate for the first task. Create an immediate transition from the **Start** state.

Wait.

Now we need a new task indicating that this robot should follow its friend robot. The **Follow** task accomplishes just this. Create a new **Follow** task in your work area.

Wait.

We need to specify whom the robot should follow. All robots that you create in this scenario are considered friendly. So in this case, we want the robot to follow the robot who summoned it, so select "Friendly Robot".

Wait.

Create a new trigger from the **Stop** task to the **Follow** task. When do you think the robot should make this transition?

Wait for answer.

The robot should make this transition when commanded by the other robot to follow. The trigger that accomplishes this is called **Notified**. Change the default trigger to this.

Wait.

You also need to specify for what the robot should have been notified. Do you remember the notification message that the first robot sent out commanding the second robot to follow? Modify the trigger to specify that message. It is important that the text match exactly. Robots are very shrewd characters!

Wait and see that the user specifies the correct message. In our example, it was "Follow me".

Excellent! Now, in our mission specification, the second task that the second robot must complete is to move to a particular location once dismissed from following. Create a **GoTo** task and specify those coordinates as (2,5).

Wait and see that this gets done.

Now, when should the robot proceed to this destination? It should do so when notified by the other robot that it has been dismissed. What was the message you used in the first robot to command the second to stop following?

In our example, it was "Stop following".

Create another new **Notified** trigger from **Follow** to **GoTo**, specifying this message.

Wait and see that the user is able to accomplish this.

This robot configuration is nearly complete. We want the robot to terminate when the goal is reached. Create the last state and trigger that accomplishes this.

*Assist the user, if necessary, in creating a **Terminate** task and an **AtGoal** trigger with location (2,5).*

Excellent. You have now completed the configuration. Go ahead and compile and run the mission. You will use the tutorial3 overlay (which is just the empty overlay, slightly modified).

Make sure the user is able to run the mission correctly. Assist if any problems occur.

Congratulations! You have completed all three tutorials and are ready for some serious mission building!

Phase II, Task 2

Mission:

Search a corridor of a building for biohazards with sentries present.

Task:

This mission is the same as before, but in this case there are sentry patrols now present that may appear any time in the corridor. In this case you will need two robots that work together. While one robot is inside a room conducting the survey, the other robot remains in the hall, near the doorway to the room that the first robot is searching, looking for a sentry to appear. If a sentry is detected, then both robots should move into the same room and wait 5 minutes before resuming operations. This also holds if both robots are in the hall when the sentry appears.

You may divide the workload between the two robots any way you see fit, so long as one of them is always watching the corridor while the other is inside the room. You may also reuse your solution from Task 1, if you wish.

Tutorial 1a: Review of Back and Forth

Synopsis

We will create a robot that goes "back-and-forth".

Setup

Start Cfgedit for user.

Say

We will first do a review of some tasks you have already learned. Do you remember how to create a back-and-forth robot?

Wait for answer. If user can demonstrate a back-and-forth robot, you may skip ahead to the next tutorial.

OK. We'll quickly review. I have started up MissionLab for you. Let's create a new robot. Do you remember how to descend the mission specification hierarchy to the mission (FSA) level? Use the middle mouse button on the group and robot icons.

See that the user does so and assist if necessary.

OK. Now we want to specify the two points between which the robot will go back and forth. Use the Add Task button on your left hand toolbar to create the two new tasks that will instruct the robot which points to move between. Place these in your work area.

In fact, the user may do this in any order they wish. The point of this exercise is to simply re-familiarize the user with the interface.

Using your right mouse button, change the default tasks to **GoTo** tasks. Do you remember how to change the coordinates using the middle mouse button?

Wait and see that the user can change the waypoints.

Create triggers signifying when to transition between these two tasks by using the Add Trigger button on your left toolbar and clicking the left mouse button on one task and dragging it to the task to which you would like to connect. Remember that these are notational triggers signifying the transitions between the tasks that the robot is executing. They in no way relate to direction.

Wait.

Now, we need to specify when to make this transition. Do you remember the trigger that you had used?

*Wait and see that the user chooses **AtGoal**. If he or she cannot get this, re-explain the concept and make sure they understand before continuing.*

You also need to specify the correct goal locations for **AtGoal**. Use the middle mouse button to pull up a dialog window that will allow you to configure these parameters.

Wait.

Do not forget to connect the **Start** state to the first task you would like the robot to execute. Once you have completed this, you may compile and run the mission. Use the empty overlay.

Wait and assist as necessary.

Congratulations! Now let's move on to something more exciting…

Tutorial 1b: Explosive Ordnance Disposal

Synopsis

You will take the user through the steps in configuring a robot to clear a minefield and safely deposit the mines in a designated safe area.

Setup

Start Cfgedit for user.

Say

In this mission you will work with one robot. This robot is tasked with collecting explosives from a minefield and disposing them in a designated safe area henceforth known as the explosive ordnance disposal, or "EOD Area". It is capable of carrying one mine at a time and need not worry about defusing them. When it has cleared all mines, then it is to return to its home area and terminate.

To accomplish this task, we will utilize four new tasks, **LookFor**, **MoveToward**, **PickUp**, and **PutInEOD**. We will also introduce five new triggers, **Detect**, **NotDetected**, **Near, Holding,** and **NotHolding**. I will explain these tasks and triggers as we use them.

First, create a new task. This will be the first task the robot begins upon execution. We want the robot to begin looking for an object. Using the right mouse button, change this task to **LookFor**. This will cause the robot to start looking for a specified object.

`Wait.`

We want the robot to look for mines, so we need to change the specified object for this task to "Mines". To do so, use the middle mouse button over the icon for the task. It is possible that the robot may want to look for multiple objects, so you may select more than one object. In this case we just want mines, so make sure that everything else is unselected.

`Wait.`

Two things can happen while the robot is looking for mines. The robot can detect a mine, or it can decide that there are no more mines left in its field of view. The trigger **Detect** becomes active when a robot has detected an object of a specified type, and the trigger **NotDetected** becomes active when a robot detects no more of a specified type. Let's say that the robot has detected a mine. Create a new task in your work area and use the right mouse button to change it. What task do you think the robot should execute next?

`Wait.`

The robot should move toward the mine, as it has to get close enough to pick it up, so make this new task you have just created **MoveToward**.

Wait.

Now, we need to tell the robot which type of object to move to. Use the middle mouse button to examine the parameters for this task. From the list of objects that appear, select "Mines". The robot will now move to a mine while executing this task. Is this clear?

Wait.

Since we want the robot to begin moving toward the mine as soon as it detects it, create a new trigger from **LookFor** to **MoveToward**, and make this a **Detect** trigger.

Wait.

Change the parameters of the trigger to detect "Mines" using the middle mouse button.

Wait.

Create another new task and place it in your work area. You may use the right mouse button to pull up the list of available tasks. What task should the robot do once it reaches the mine?

Wait for answer.

This task should be **PickUp**. Don't forget you need to tell the robot what type of object to pick up. What do you think this parameter is? Configure the task as such.

Wait and see that the user is able to set the "Mines" parameter for the ***PickUp*** *task.*

Great. Now, we need to define a trigger to transition from the **MoveToward** task to the **PickUp** task. Create this trigger. What do you think this trigger should be, or, in other words, when should this transition take place?

Wait for answer.

The robot needs to make this transition when it is near enough to the object in question, in this case, a mine. Make the new trigger **Near**, and configure the appropriate parameter as you did for the other two triggers.

Wait. See that the user changes the parameter to "Mine"

You've done very well so far. Do you understand what you have done up until this point?

Wait for answer.

Good. Now that we have the mine in our possession, we need to bring it the EOD area. The robot knows where the EOD area is. What task – based on what you have learned so far – do you think you will need to accomplish this?

*Wait and see that the user understands that he or she needs **MoveToward**.*

Create a new **MoveToward** task, except this time we are not moving to a mine, but we are moving an EOD area. Thus, configure this task with the appropriate parameters.

Wait and see that the user configures the task properly.

Once again, create a trigger between these tasks. When the robot has finished picking up the mine and has it in its possession. The **Holding** trigger becomes active. Make this your trigger from **PickUp** to **MoveToward** "EOD Area".

Wait.

Now, earlier when the robot was near the mine, we configured the robot to pick up the mine. What do you think the robot should do when it is near the EOD area?

Wait for answer. The answer should be "dispose of the mine".

A task exists named **PutInEOD** that accomplishes just this. Create a new task and new trigger that configures the robot to put the mine in the EOD area when the robot is sufficiently near enough to it.

*Wait and see that the user configures the **PutInEOD** task and **Near** "EOD" trigger correctly.*

Very good. Now, when the robot has disposed of the mine, we would like for it to continue collecting mines for as long as it senses that more mines are out there. So we will create a new trigger from the **PutInEOD** task back to the original **LookFor** "Mines" that you had created. Do this now.

Wait.

Since we want the robot to begin searching for mines again when it has disposed of the one it is previously holding, this trigger should be **NotHolding**, as the robot should have gotten rid of the mine it was holding.

Wait.

Now, let's say that the robot no longer detects any mines present. We want the robot to return home and terminate when it senses this. Create a new **MoveToward** task and configure it to move the robot to "Home Base".

Wait.

What is the trigger that signifies when a robot does NOT detect any object of a particular type?

Wait.

It is called **NotDetected**. Now, from which task should we make this trigger to **MoveToward** "Home Base"? What was the robot doing when it realizes no more mines are present?

*Wait and see that the user makes the trigger from **LookFor** "Mines".*

Excellent. Now when the robot is home, it should terminate. Create a terminate task.

Wait.

Create a new trigger from **MoveToward** "Home Base" to **Terminate**. What should this trigger be?

*Wait and see that the user creates and configures a **Near** "Home Base" trigger.*

Very good. You are now ready to compile and test your mission. You may begin doing so now. You will use the minefield overlay for the simulation. I will assist you if necessary.

See that the mission compiles and runs correctly and assist the user as needed.

Congratulations! You have completed a fairly complex mission. Let's save this mission configuration for later reuse. To do so, select "Save Configuration" from the File menu and type in a name in the dialog box that appears.

Wait.

Now I want you to clear the mission specification by selecting the Start Over button on the left side panel.

Wait.

Good, now reload the previous mission by selecting "Load Configuration" from the File menu and entering the name you had chosen.

Wait.

You may also do this when you first open the configuration editor. However, remember that when you load a previously saved mission, anything in your current work area will be lost.

Review Tasks and Triggers sheet before proceeding to Task 1.

Phase II, Task 1

Mission:

Search a corridor of a building for biohazards.

Task:

It is 3 AM. In a biomedical research building located in a renegade nation, a single robot has been delivered to the entry of the building and has been successfully and secretly escorted inside. It awaits command at the beginning of a hallway just inside the entrance. The task for this robot is to proceed along this hallway and search every room that has an open door for the presence of a biohazard.

A warning about this mission: the robot has very poor knowledge of the layout of the building. Any available maps or drawings are dated and possibly inaccurate, as intelligence does not know how the current occupants may have modified the building. Therefore, we cannot use waypoints to accomplish the task as you did earlier in the Hospital Approach scenario. We do know, however, that the layout of this building is conventional. It has a linear corridor with rooms on both the left and right sides. At this early hour nobody is expected to be present in the building, so the robot can safely move about without fear of detection.

This mission should be accomplished as follows: from its starting position the robot proceeds down the hallway. At any and every open door it encounters, it enters the room and conducts a biohazard survey. If the survey results indicate that a biohazard is present, the robot should immediately alert the user. If the survey results do not indicate the presence of a biohazard, the robot should mark the room as visited, and continue the search, surveying additional rooms as needed. At any point in the mission that the robot encounters a biohazard and alerts the user, the robot's mission is complete and it can safely terminate. If the robot reaches the end of the hallway, it should turn around and navigate back down the hallway, searching for additional rooms it may have not checked. Once the robot finds itself back at its starting position at the entrance, it should alert the user that no biohazards have been found and it may safely terminate.

Phase II, Tutorial 2a: Multi-Robot EOD

Synopsis

The user will simply duplicate the EOD robot that he or she created in the first tutorial and run them both in the minefield. This is intended to show the user how easy it is to duplicate missions.

Setup

Start Cfgedit for user. Load the user's previously saved mission. You may explain this process any way you like.

Say

This mission will involve the configuration of two robots. Do you remember how to create a configuration for the second robot by duplicating the first?

`Wait for response and review as necessary.`

Use the middle mouse button to descend to the second level of the configuration hierarchy. You should see an icon that says "Individual Robot". Use the copy and paste feature or the duplicate feature to create a second, identical robot.

`Wait.`

Now you have two robots that have the same configuration. Descend the mission level on the second robot. Is this the same as the one you created earlier?

`Wait for answer.`

Good. Go ahead and compile and run this mission using the minefield overlay as you did earlier. This time, you should see two robots collecting mines.

`Wait.`

This is useful for creating many robots with the same mission specifications. If desired, you could modify the individual mission specifications to create robots with similar, but not identical behavior. However, these robots are completely blind to each other's actions. In the next tutorial, you will learn how to make two robots communicate.

`Show again if appropriate.`

Tutorial 2b: Robot Communication

Synopsis

This mission will demonstrate to the user how one robot can send and receive messages to and from another robot. We will specify a mission where one robot will command a second robot to follow it until a goal is reached at which point the first robot will dismiss the second robot. At this point the second robot will cease following the first and continue to a second goal location.

Setup

Start Cfgedit for user.

Say

We are going to create a robot that commands another robot to follow it to a particular goal location. It will then dismiss that robot and the second robot will continue on to a second goal location.

Create a new robot. Duplicate this robot as you did in the previous tutorial

Wait.

First, let us create the configuration for the first robot. Descend to the mission (FSA) level of the first robot. We want this robot to simply move to a specified point. However, before doing so, we want to tell the other robot to follow. Create a new task using the Add Task button on the left menu. Use the right mouse button to change this task to **NotifyRobots**.

Wait.

We need to specify the notification message for this task. Use the middle mouse button to display the parameters for this task. Change the notification message to something descriptive of this task. For example, "*Follow me*" would be an appropriate choice.

Wait.

Next, we would like this first robot to move to a specified location. Create a new **GoTo** task and specify the location as coordinate (6,7). Do you remember how to do this?

Wait for answer and assist as necessary.

Create a trigger from the **NotifyRobots** task to the **GoTo** task. The default trigger is **MessageSent**. Since we want to begin moving as soon as we have notified the other robot, this is the correct trigger to use in this case.

Wait.

The next task for this robot is to tell the other robot at some point that it can stop following. Create a new **NotifyRobots** task and send an appropriate message indicating this robot's new desire. "*Stop following*" will suffice.

Wait.

We need to create a transition from the **GoTo** task. When do you think the robot should send this message?

Wait and see that the user can correctly infer that the robot should send the message when at the goal, and he or she uses the correct trigger.

The first robot's mission is now complete. Create a new task and trigger indicating that this first robot should terminate once the previous message to stop following has been sent.

Wait and see that the user can accomplish this.

You have just completed the configuration for the first robot. I will explain shortly, how a robot receives communication. Do you have any questions about anything you have done up to this point?

Wait and answer questions.

Great. Now return to the robot group configuration level and edit the configuration for the second robot. The mission for this robot is to follow the first robot wherever it goes when summoned. After it has been dismissed, it is to move to another (different) pre-specified location. Create a new task for this robot.

Wait.

By default, this robot should do nothing until summoned. So the **Stop** task is appropriate for the first task. Create an immediate transition from the **Start** state.

Wait.

Now we need a new task indicating that this robot should follow its friend robot. The **Follow** task accomplishes just this. Create a new **Follow** task in your work area.

Wait.

We need to specify whom the robot should follow. All robots that you create in this scenario are considered friendly. So in this case, we want the robot to follow the robot who summoned it, so select "Friendly Robot".

Wait.

Create a new trigger from the **Stop** task to the **Follow** task. When do you think the robot should make this transition?

Wait for answer.

The robot should make this transition when commanded by the other robot to follow. The trigger that accomplishes this is called **Notified**. Change the default trigger to this.

Wait.

You also need to specify for what the robot should have been notified. Do you remember the notification message that the first robot sent out commanding the second robot to follow? Modify the trigger to specify that message. It is important that the text match exactly. Robots are very shrewd characters!

Wait and see that the user specifies the correct message. In our example, it was "Follow me".

Excellent! Now, in our mission specification, the second task that the second robot must complete is to move to a particular location once dismissed from following. Create a **GoTo** task and specify those coordinates as (2,5).

Wait and see that this gets done.

Now, when should the robot proceed to this destination? It should do so when notified by the other robot that it has been dismissed. What was the message you used in the first robot to command the second to stop following?

In our example, it was "Stop following".

Create another new **Notified** trigger from **Follow** to **GoTo**, specifying this message.

Wait and see that the user is able to accomplish this.

This robot configuration is nearly complete. We want the robot to terminate when the goal is reached. Create the last state and trigger that accomplishes this.

*Assist the user, if necessary, in creating a **Terminate** task and an **AtGoal** trigger with location (2,5).*

Excellent. You have now completed the configuration. Go ahead and compile and run the mission. You will use the tutorial3 overlay (which is just the empty overlay, slightly modified).

Make sure the user is able to run the mission correctly. Assist if any problems occur.

Congratulations! You have completed all three tutorials and are ready for some serious mission building!

Phase II, Task 2

Mission:

Search a corridor of a building for biohazards with sentries present.

Task:

This mission is the same as before, but in this case there are sentry patrols now present that may appear any time in the corridor. In this case you will need two robots that work together. While one robot is inside a room conducting the survey, the other robot remains in the hall, near the doorway to the room that the first robot is searching, looking for a sentry to appear. If a sentry is detected, then both robots should move into the same room and wait 5 minutes before resuming operations. This also holds if both robots are in the hall when the sentry appears.

You may divide the workload between the two robots any way you see fit, so long as one of them is always watching the corridor while the other is inside the room. You may also reuse your solution from Task 1, if you wish.

Appendix G: Sample Event Log File

```
 0.000 : start Session
 0.000: status StartTime "955045927.004"
 128.161: event StartLoadfile
 128.218: event LoadedFile
"/net/hr1/amoudgal/mission.usability/lib/usability_test.cdl"
 185.738: start PlacingWaypoints
 185.939: start mlab
 193.047: start LoadOverlay "/net/hr1/amoudgal/usability/tests/hospital.ovl"
 193.047: end LoadOverlay
 208.799: event AddWaypoint #1 (105.432594, 449.094574)
 236.921: event AddWaypoint #2 (243.863174, 441.046265)
 259.838: event AddWaypoint #3 (313.078461, 441.046265)
 268.194: event AddWaypoint #4 (243.863174, 440.241455)
 277.030: event DeleteWaypoint # 4
 286.912: event AddWaypoint #4 (412.072449, 404.828979)
 298.826: event DeleteWaypoint # 4
 305.506: event AddWaypoint #4 (411.267609, 422.535217)
 346.490: event AddWaypoint #5 (445.875244, 291.348083)
 363.769: event DeleteWaypoint # 2
 363.769: event DeleteWaypoint: new Waypoint #2 (313.078461, 441.046265)
 363.769: event DeleteWaypoint: new Waypoint #3 (411.267609, 422.535217)
 363.770: event DeleteWaypoint: new Waypoint #4 (445.875244, 291.348083)
 370.816: event DeleteWaypoint # 2
 370.816: event DeleteWaypoint: new Waypoint #2 (411.267609, 422.535217)
 370.817: event DeleteWaypoint: new Waypoint #3 (445.875244, 291.348083)
 372.409: event DeleteWaypoint # 2
 372.409: event DeleteWaypoint: new Waypoint #2 (445.875244, 291.348083)
 374.885: event DeleteWaypoint # 2
 408.788: event AddWaypoint #2 (230.181091, 453.118713)
 421.015: event AddWaypoint #3 (345.271637, 448.289734)
 437.116: event AddWaypoint #4 (449.899384, 314.688141)
 443.281: event DeleteWaypoint # 4
 455.684: event AddWaypoint #4 (460.362183, 306.639832)
 457.468: event AddWaypoint #5 (444.265594, 291.348083)
 460.237: end mlab
```

```
460.396: end PlacingWaypoints
465.080: start AddTransition Trans5
466.238: status FirstState
469.776: end AddTransition
472.663: event StartMake
491.113: event GoodMake
494.071: event EndMake
496.996: start Run
501.986: start mlab
504.604: start LoadOverlay "hospital.ovl"
504.604: end LoadOverlay
565.380: end mlab
565.405: end Run
569.766: end Session
```

Appendix H: Sample CDL File

```
/**************************************************
*
* This CDL file
/net/hr1/amoudgal/usability/data/today/subject/hospital/cdl_replay_1005_469.77
6_added_transition.cdl was created with cfgedit
* version 3.1.02
*
**************************************************/

bindArch AuRA.urban;

instBP<222,15> |The Wheels Binding Point| $AN_623 from movement(
  base_vel = {0.1},
  v<0,0> = ,
  bound_to = base:DRIVE_W_SPIN(
        v<12,15> = FSA(
            society[Start]<50,50>|Start| = [
              Stop]<10,10>
,
            society[$AN_644]<120,300>|State1| = [
                %Goal_Location = {105.43,449.09},
                %move_to_location_gain = {1.0},
                %avoid_obstacle_gain = {1.0},
                %avoid_obstacle_sphere = {3.0},
                %avoid_obstacle_safety_margin = {0.5}
,
              GoTo]<10,10>
,
            society[$AN_646]<570,300>|State2| = [
                %Goal_Location = {230.18,453.12},
                %move_to_location_gain = {1.0},
                %avoid_obstacle_gain = {1.0},
                %avoid_obstacle_sphere = {3.0},
                %avoid_obstacle_safety_margin = {0.5}
,
              GoTo]<10,10>
,
            society[$AN_650]<1020,300>|State3| = [
                %Goal_Location = {345.27,448.29},
                %move_to_location_gain = {1.0},
                %avoid_obstacle_gain = {1.0},
                %avoid_obstacle_sphere = {3.0},
                %avoid_obstacle_safety_margin = {0.5}
,
              GoTo]<10,10>
,
            society[$AN_654]<1020,600>|State4| = [
                %Goal_Location = {460.36,306.64},
                %move_to_location_gain = {1.0},
                %avoid_obstacle_gain = {1.0},
                %avoid_obstacle_sphere = {3.0},
                %avoid_obstacle_safety_margin = {0.5}
,
              GoTo]<10,10>
,
            society[$AN_658]<570,600>|State5| = [
                %Goal_Location = {444.27,291.35},
                %move_to_location_gain = {1.0},
                %avoid_obstacle_gain = {1.0},
                %avoid_obstacle_sphere = {3.0},
                %avoid_obstacle_safety_margin = {0.5}
,
```

```
              GoTo]<10,10>
,
            rules[$AN_644]<120,300>|State1| = if [
                %Goal_Tolerance = {0.5},
                %Goal_Location = {105.43,449.09}
,
              AtGoal]<10,10>|Trans1|
 goto $AN_646,
            rules[$AN_646]<570,300>|State2| = if [
                %Goal_Tolerance = {0.5},
                %Goal_Location = {230.18,453.12}
,
              AtGoal]<10,10>|Trans2|
 goto $AN_650,
            rules[$AN_650]<1020,300>|State3| = if [
                %Goal_Tolerance = {0.5},
                %Goal_Location = {345.27,448.29}
,
              AtGoal]<10,10>|Trans3|
 goto $AN_654,
            rules[$AN_654]<1020,600>|State4| = if [
                %Goal_Tolerance = {0.5},
                %Goal_Location = {460.36,306.64}
,
              AtGoal]<10,10>|Trans4|
 goto $AN_658,
            rules[Start]<50,50>|Start| = if [
              Immediate]<10,10>|Trans5|
 goto $AN_644)<292,156>|Mission|
,
        max_vel = {0.2},
        base_vel = {1},
        cautious_vel = {0.05},
        cautious_mode = {false})<222,15>|The Wheel Actuator|
);

instBP<0,0> $AN_639 from vehicle(
  bound_to = usability_testRobot1:PIONEERAT(
usability_testRobot1:[
          $AN_623]
)<0,0>|Individual Robot|
);

NoName:[
[
    $AN_639]<10,10>|Group of Robots|
]<10,10>
```

Appendix I: Mean and Standard Deviations for Data Analysis

	Hospital Approach Scenario	Airport Incursion Scenario
Number of Waypoints	6.10 (2.73)	6.24 [both robots] (3.20)
Number of Waypoints Deleted	1.69 (3.86)	2.27 [both robots] (3.97)
Modifications	0.069 (0.371)	0.20 (0.620)
Modification Time	0.62 sec (3.39)	0.75 sec (2.08)
Total Completion Time	8 min 12 sec (4 min 18 sec)	15 min 59 sec (6 min 26 sec)
Mission Restarts	0.31 (0.660)	1.14 (1.81)

Table 30: Phase 1 averages for all subjects.

	Single Robot Scenario	Two Robot Scenario
Number of Tasks	14.23 (6.13)	23.40 (both robots) (7.94)
Number of Triggers	21.27 (8.44)	38.50 (both robots) (12.4)
Modifications	36.32 (13.9)	69.00 (22.5)
Modification Time	6 min 10 sec (2 min 18 sec)	12 min 11 sec (2 min 52 sec)
Total Completion Time	33 min 3 sec (10 min 6 sec)	45 min 2 sec (11 min 29 sec)
Mission Restarts	0.180 (0.501)	0.00 (0.00)

Table 31: Phase 2 averages for all subjects.

	Mission-critical Criteria	All Criteria
Hospital (Task 1)	82.37 % (26.7)	63.90 % (21.3)
Airport (Task 2)	78.5 % (21.0)	71.42 % (19.5)

Table 32: Phase 1 average mission success rate.

	Novice	Intermediate	Expert
Hospital (Task 1)			
Number. Of Waypoints	5.88 (3.72)	6.50 (3.78)	6.00 (3.44)
Number of Waypoints Deleted	1.25 (2.43)	2.25 (2.66)	1.62 (2.06)
Modifications	0.00 (0.00)	0.25 (0.267)	0.00 (0.577)
Modification Time	0.00 sec (0.00)	2.25 sec (2.40 sec)	0.00 sec (5.19 sec)
Total Completion Time	8 min 28 sec (1 min 49 sec)	11 min 7 sec (3 min 22 sec)	6 min 14 sec (6 min 22 sec)
Mission Restarts	0.250 (0.463)	0.75 (0.707)	0.076 (0.537)
Airport (Task 2)			
Number of Waypoints	5.75 (2.60)	5.25 (2.66)	7.15 (3.54)
Number of Waypoints Deleted	1.25 (2.05)	0.875 (2.09)	3.76 (3.31)
Modifications	0.375 (1.06)	0.125 (1.09)	0.154 (0.870)
Modification Time	0.652 sec (1.84 sec)	0.716 sec (1.84 sec)	0.833 sec (2.06 sec)
Total Completion Time	14 min 42 sec (4 min 28 sec)	15 min 4 sec (4 min 30 sec)	15 min 13 sec (7 min 5 sec)
Mission Restarts	1.375 (2.13)	0.625 (2.28)	1.307 (1.79)

Table 33: Phase 1 averages grouped by experience level.

	Novice	Intermediate	Expert
Hospital (Task 1)			
Mission-critical criteria	83.33 % (17.8)	68.05 % (24.1)	90.59 % (31.3)
All criteria	65.00 % (11.7)	50.83 % (19.1)	71.28 % (24.3)
Airport (Task 2)			
Mission-critical criteria	84.7 % (11.8)	73.61 % (16.7)	77.77 % (21.0)
All criteria	77.90 % (5.66)	65.47 % (14.5)	71.06 % (18.3)

Table 34: Phase 1 average mission success rate grouped by experience level.

	More Successful Missions	Less Successful Missions
Hospital (Task 1)		
Number of Waypoints	7.31 (1.97)	5.13 (2.70)
Number of Waypoints Deleted	2.00 (4.12)	1.44 (3.76)
Modifications	0.00 (0.00)	0.125 (0.50)
Modification Time	0.00 sec (0.00 sec)	1.12 sec (4.49 sec)
Total Completion Time	7 min 19 sec (2 min 17 sec)	8 min 55 sec (5 min 3 sec)
Mission Restarts	0.231 (0.439)	0.375 (0.465)
Airport (Task 2)		
Number of Waypoints	7.23 (3.09)	5.44 (3.73)
Number of Waypoints Deleted	3.31 (5.34)	1.44 (5.38)
Modifications	0.0769 (0.277)	0.313 (0.359)
Modification Time	0.180 sec (0.648 sec)	1.21 sec (1.25 sec)
Total Completion Time	12 min 56 sec (4 min 57 sec)	16 min 40 sec (6 min 25 sec)
Mission Restarts	0.846 (1.62)	1.38 (1.61)

Table 35: Phase 1 averages correlated with mission success rate.

	Mission-critical Criteria	All Criteria
Single robot (Task 1)	55.30 % (41.9)	46.56 % (25.8)
Two robots (Task 2)	40.4 % (31.0)	38.05 % (26.4)

Table 36: Phase 2 average mission success rate.

	Novice	Intermediate	Expert
Single Robot (Task 1)			
Number of Tasks	15.83 (3.60)	12.60 (5.50)	14.09 (4.73)
Number of Triggers	22.67 (5.82)	16.80 (9.25)	22.54 (7.74)
Modifications	37.33 (7.20)	34.00 (9.01)	36.81 (12.1)
Modification Time	6 min 0 sec (1 min 40 sec)	7 min 20 sec (2 min 13 sec)	5 min 44 sec (2 min 38 sec)
Total Completion Time	35 min 26 sec (10 min 16 sec)	32 min 53 sec (10 min 22 sec)	33 min 51 sec (10 min 33 sec)
Mission Restarts	0.333 (0.816)	0.200 (0.922)	0.100 (0.674)
Two Robots (Task 2)			
Number of Tasks	24.83 (5.04)	23.20 (5.91)	22.72 (6.91)
Number of Triggers	36.50 (5.13)	39.40 (6.64)	39.20 (8.63)
Modifications	74.83 (17.0)	67.00 (21.2)	66.35 (19.0)
Modification Time	8 min 37 sec (3 min 2 sec)	8 min 38 sec (3 min 8 sec)	7 min 33 sec (3 min 21 sec)
Total Completion Time	47 min 41 sec (5 min 55 sec)	47 min 14 sec (6 min 1 sec)	42 min 34 sec (12 min 49 sec)
Mission Restarts	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

Table 37: Phase 2 averages grouped by experience level.

	Novice	Intermediate	Expert
Single Robot (Task 1)			
Mission-critical Criteria	68.5 % (37.3)	30.1 % (54.0)	50.1 % (42.5)
All Criteria	53.03 % (23.1)	32.22 % (33.7)	58.5 % (28.0)
Two Robots (Task 2)			
Mission-critical Criteria	43.21 % (29.2)	19.25 % (41.5)	48.48 % (33.8)
All Criteria	40.84 % (22.2)	20.39 % (31.7)	44.56 % (28.2)

Table 38: Phase 2 success rates grouped by experience level.

	More Successful Missions	Less Successful Missions
Single Robot (Task 1)		
Number of Tasks	13.29 (6.58)	14.75 (7.08)
Number of Triggers	20.71 (8.08)	21.00 (8.56)
Modifications	28.43 (10.7)	38.13 (15.5)
Modification Time	4 min 58 sec (2 min 28 sec)	7 min 41 sec (3 min 39 sec)
Total Completion Time	27 min 42 sec (5 min 26 sec)	41 min 36 sec (16 min 5 sec)
Mission Restarts	0.143 (0.378)	0.125 (0.354)
Two Robots (Task 2)		
Number of Tasks	22.00 (8.89)	21.60 (10.5)
Number of Triggers	32.40 (10.6)	38.30 (16.5)
Modifications	62.60 (25.4)	63.20 (26.9)
Modification Time	7 min 12 sec (1 min 43 sec)	8 min 21 sec (3 min 14 sec)
Total Completion Time	46 min 6 sec (10 min 43 sec)	42 min 18 sec (15 min 24 sec)
Mission Restarts	0.00 (0.00)	0.00 (0.00)

Table 39: Phase 2 averages correlated with success rate.