Challenges to Autonomous Navigation in Complex Urban Terrain

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ABSTRACT

In the field of military Unmanned Ground Vehicles (UGV), military units are adapting their concept of operations to focus on their mission capabilities within populated cities and towns. These types of operations are referred to as MOUT (Military Operations on Urban Terrain). As more Soldiers seek to incorporate technology to enhance their mission capabilities, there then becomes a need for UGV systems to encompass an ability to autonomously navigate through urban terrains. Autonomous systems have the potential to increase Soldier safety by mitigating the risk of unnecessary enemy exposure during routine urban reconnaissance.

This paper presents the development and methodology that the military has sought to increase mission capabilities by incorporating autonomy into manned/unmanned ground vehicles. The presented solution that has been developed through the Safe Operations of Unmanned systems for Reconnaissance in Complex Environments (SOURCE) Army Technology Objective (ATO) has the ability and has been tested to safely navigate through complex urban environments. This paper will also focus on the challenges the military has faced to develop the presented autonomous UGV.

Keywords: Autonomous system, UGV, Test & Evaluation, Challenges, Urban Autonomy, Urban Terrain, MOUT, SOURCE

1. INTRODUCTION

As Warfare evolves, military technology must also evolve to support and aid current battlefield requirements and threats. The military is presently adapting its concept of operations to take advantage of the relatively new technology of Unmanned Ground Vehicles (UGV's), with a focus on their mission capabilities in populated cities and towns. These types of operations are referred to as MOUT (Military Operations on Urban Terrain). MOUT missions typically involve interaction with civilian populations, where it can be difficult to determine who is friendly, hostile, or ambivalent. Additionally, much of the environment is man-made, making it difficult to detect modifications by the enemy. This close proximity to potentially hostile forces makes operations, such as military vehicle convoys that are manually driven and occupied by Soldiers, increasingly dangerous. As more Soldiers request technology, such as UGV's, to enhance their mission capabilities, researchers and developers are pushing to increase the performance of military vehicles that can autonomously navigate through urban terrains. Autonomous systems have the potential to increase Soldier safety by mitigating the risk of unnecessary enemy exposure during routine urban missions, such as logistics and reconnaissance, by removing the Soldier from direct contact with potential enemies.

For this reason, this paper will present the development and methodology that the Army has sought to increase mission capabilities through the incorporation of autonomy to exchange manned ground vehicles for UGVs. The presented solution that has been developed through the Safe Operations of Unmanned systems for Reconnaissance in Complex Environments (SOURCE) Army Technology Objective (ATO) has the ability and has been tested to safely navigate through complex urban environments. This paper will also focus on the challenges the military has faced to develop the presented autonomous UGV.

The objective of the SOURCE ATO is to advance existing UGV technology development specifically in the area of MOUT missions. The three major experiments of the SOURCE ATO provide opportunities to advance the development and assessment methodologies for UGV's in more complex environments. The SOURCE Enhanced Experiment is the second of the three and was completed in November 2011.

The site of the SOURCE Enhanced Experiment site was the MOUT Facility in Camp Lejeune, North Carolina. The MOUT site is an urban environment including paved and gravel roads lined with one, two and three story buildings. A traffic circle and underpass are also included at the site as well as a road that loops the outer perimeter of the site. The MOUT environment is complex in that the buildings are placed closely together, and the outer loop road is densely lined with trees. The experiment included static obstacles, static and moving pedestrians (mannequins) and static and moving vehicles. The SOURCE UGV was required to autonomously operate safely, avoid the obstacles and obey normal rules of the road, during multiple scenarios within this environment. The development and methodology described in this paper includes information gained from the SOURCE Enhanced Experiment.

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14. ABSTRACT

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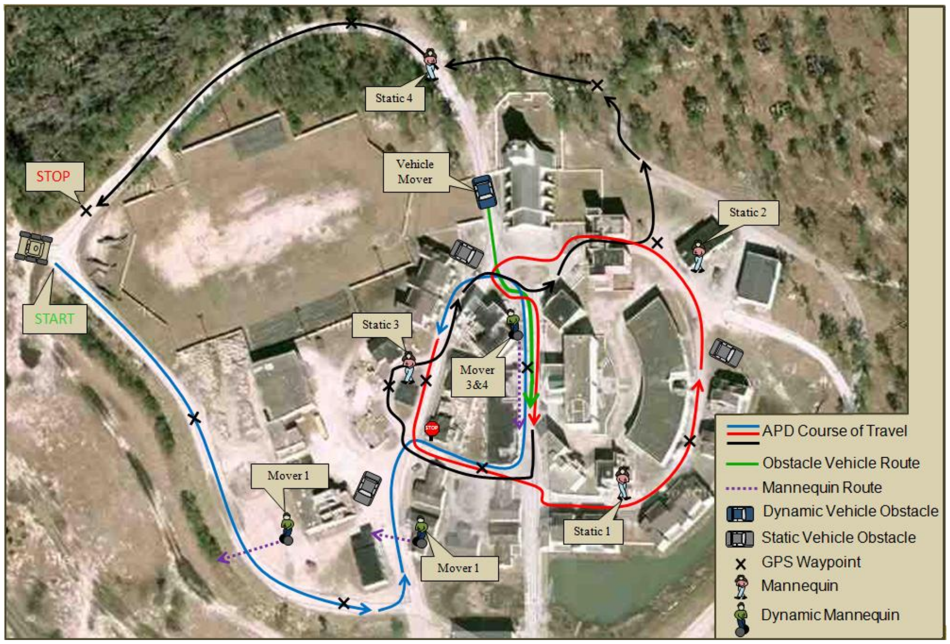

Figure 1. Enhanced Experiment MOUT Course

2. COMPLEX ENVIRONMENT

Autonomous platforms require more robust sensing and greater intelligence as the environment becomes more complex. Urban environments often have very complex situations occurring in very constrained spaces. The autonomous platform is required to not only navigate itself through the town or village, avoiding static obstacles and structures, but also to obey the rules of the road, including the local unwritten rules, which can often only be learned by experience. The vehicle's perception system must also interpret street signs, traffic lights, and lane markings, as well as anticipate what pedestrians and other vehicles intend to do.

Urban obstacles can include curbs, speed bumps, potholes, debris, trash, street/road signs, telephone and electric poles, fire hydrants, bridges, and water. The UGV needs to safety navigate around these obstacles, without causing damage to itself or to them. Urban structures are special cases of urban obstacles, since they are more likely to contain people, whether friendly or hostile. Items in this category include buildings, bus stops, sidewalks, and markets.

Additionally, it also important for the vehicle to respond properly to objects that do not pose a threat, but this becomes especially challenging when dealing with humans or animals that may change trajectory, suddenly and without warning. The vehicle system will not be able to operate effectively if it does not put some bounds on the expected behavior of potential moving objects, including people and animals. In urban environments, the number of potential vehicle to civilian encounters increases exponentially as the urban population density increases. In a complex urban environment, the UGV will be required to detect, identify, and avoid people (and animals) in all states of motion, whether crossing the street at a crosswalk or not, walking, running, or jogging at various angles with respect to the UGV's motion, or perhaps just standing, sitting, or lying near, or even on, the roadway. Due to the random behavior of people (or animals), predicting their motion and planning routes around them can be very difficult. Even people have difficulty in performing this task, which results in many traffic accidents and fatalities throughout the world. However, fair or not, it is likely that autonomous vehicles will, at least initially, be held to a higher standard of performance than human drivers.

While the UGV is required to safely navigate itself around people, obstacles and structures, it is also necessary to maintain the rules of the road and right-of-way by identifying other vehicles operating on the road, waiting at intersections, or parked alongside the road. The rules of the road require the UGV to recognize lane markings, street signs, and traffic lights and to react accordingly. However, in a military operation, the rules of the road and who has right-of-way can change. It may be necessary for the autonomous vehicle to push its way through traffic, or even onto a sidewalk or off-road, ignoring the traditional rules-of-the-road. These situations may require more human intervention, either through direct teleoperation, semi-autonomous control, or a leader/follower arrangement.

If these were not complex enough, the vehicle must also perform in a variety of weather and lighting conditions, which can affect the UGV's sensor inputs, including bright sunshine, dust, fog, rain, snow, and darkness (self lighting). And it is not just seeing through precipitation that can be problematic; bright sunlight creates glints and glare, and rainwater and snow on the road or on obstacles can create reflective surfaces that make sensing difficult.

3. TECHNOLOGY/SENSORS

There are a variety of sensors that a UGV can use to provide information about its environment, including active systems such as RADAR, LIDAR and structured light, and passive camera systems, including stereo pairs and infrared sensors. Most of these can be used to provide a 3D model of the environment with different levels of resolution and accuracy. Camera sensors can also provide color and texture information. Other sensors can provide information about the vehicle's state, including Inertial Measurement Units (IMU), odometry and velocity sensors, to provide local position information, GPS to provide global position, various engine/motor measurements, steering angle sensors, and the sequence of steering and throttle commands. The system can also use a variety of databases, including topographical and road maps, sensor data from prior runs through the environment, and rules of the road.

The UGV fuses data from these various sources to create an internal model of its surroundings. This internal model represents everything the UGV knows about the world around it. The UGV uses this knowledge to plan its immediate actions given the higher-level mission planning and goals. The quality of the UGV's model depends on both the performance and complement of sensors available and the UGV's ability to interpret the sensor data with respect to its mission and capabilities. The intelligence portion of the problem can become a real bottleneck in the system.

For example, the sensors may be of high enough resolution and dynamic range to allow humans to drive the vehicles in a reasonable fashion while viewing sensor feeds. Although communication latency and bandwidth restrictions can make teleoperation difficult, especially when accurate perception and quick decisions are necessary in complex high-speed operations, these are not insurmountable problems. However, the human operator, even with imperfect sensors, is able to draw upon years of learning and past experience to interpret the surroundings and to operate the vehicle appropriately and safely to achieve the mission objectives.

For the UGV, the most pressing technical problem remains the automated extraction and intelligent interpretation of relevant, and often subtle, information from multiple sources of data. Additionally, the UGV must manage the data in an internal model with sufficient detail and vocabulary to allow intelligent and safe behavior in complex environments.

The SOURCE test program and large autonomous UGV system provides a valuable platform to advance the technology and methodology necessary to expand the use of UGV's to meet Army missions. SOURCE UGV used for the Enhanced Experiment included a capable vehicle, a suite of multiple sensor types and an advanced SOURCE Autonomy System that leveraged technology from multiple DOD programs. The system is shown in Figure 2. The TARDEC Advanced Platform Demonstrator (APD) is the primary UGV vehicle used in the experiment. Additionally, the experiment included a commercial Jeep-based vehicle with the SOURCE Autonomy System installed.

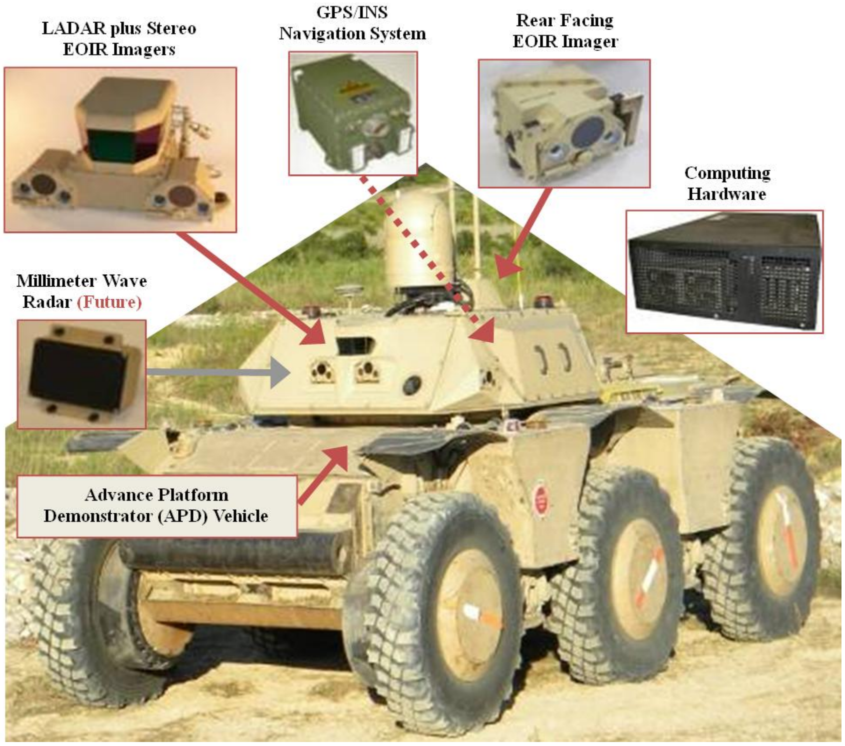

Figure 2. SOURCE UGV Is Based on the APD Vehicle and SOURCE Autonomy System

The SOURCE Autonomy System is based on technology leveraged from the Autonomous Navigation System program and advanced under the SOURCE ATO to address MOUT mission requirements. The sensor suite of the autonomy system included a high resolution scanning LADAR, stereo vision Electro Optic Infra Red (EOIR) imagers, a precision GPS/INS navigation unit and COTS computing hardware. The sensor suite provides data used for the UGV to build its model of the surroundings. A key feature for robust UGV operation in a broad range of environments is the use of a range of sensors that depend on different physical modalities for detection, including LADAR using laser ranging, visible light imagers, Long Wave Infra Red (LWIR) imagers, Stereo Vision processing and RADAR (future).

In a complex environment, given different atmospheric and environmental conditions, different lighting conditions and given objects consisting of an extremely wide range of materials, both natural and manmade, it is important to have diverse set of sensing technologies. No single sensor technology works well in all situations. Figure 3 shows the types of sensor data available from the SOURCE sensor suite. Data from all of the sensors is used to develop the SOURCE UGV's model of its surroundings. This model is used to plan it actions to achieve the mission objectives. Figure 4 shows an example of part of the internal model developed by the SOURCE UGV.

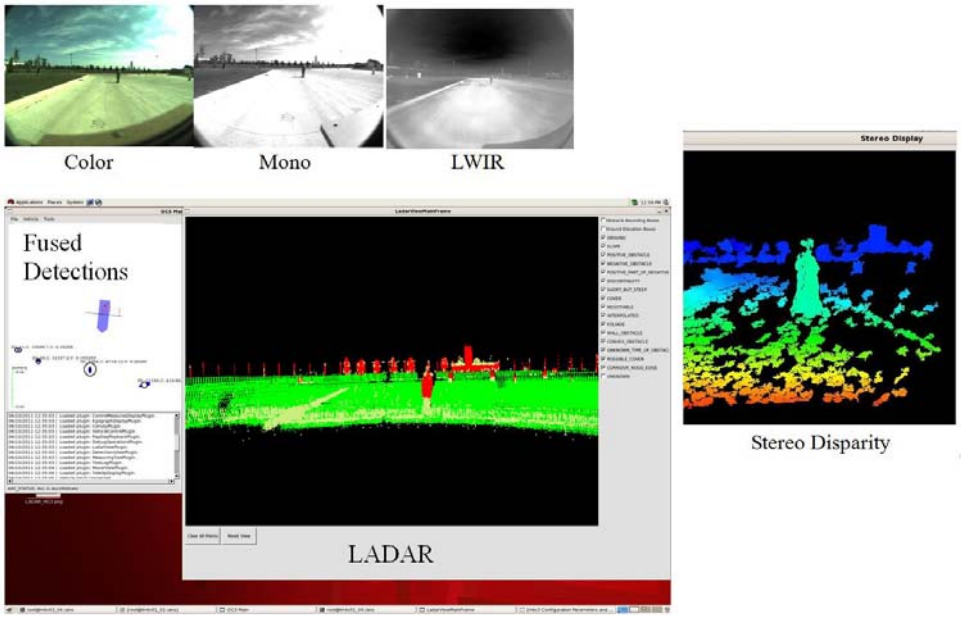

Figure 3. SOURCE Data from Multiple Sensors Is Used To Interpret Its Surroundings

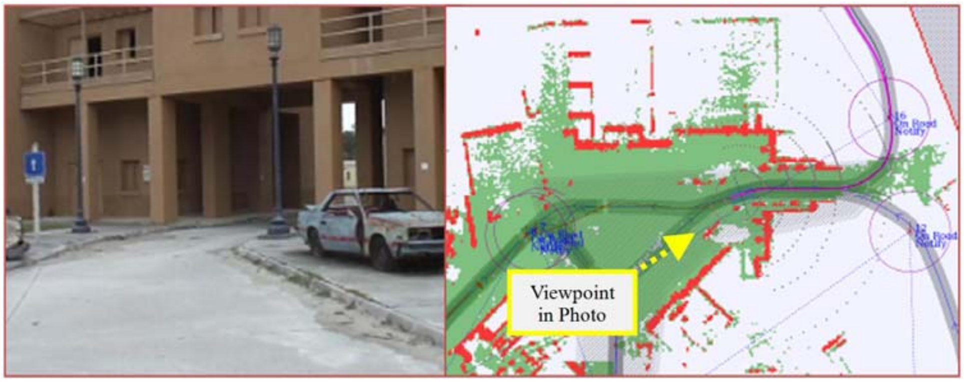

Figure 4. Internal Model Developed From Sensor Data

4. OTHER PROJECTS IN AUTONOMOUS URBAN NAVIGATION

There are a variety of civilian efforts to provide autonomous operation of vehicles in urban environments. The Google Self-Driving Car's main sensor is a LIDAR that is used to build a dense 3D model of the environment. RADAR is used for obstacle detection and avoidance and a camera is used to detect stoplights. The system is heavily dependent on a very detailed map of its route, presumably locating the position and content of relevant traffic signs and potential static obstacles. The system also depends on a database of sensor data that is collected during multiple runs along the routes that it will take. The Google Self-Driving Car has driven many thousands of miles in autonomous mode through urban environments, such as on the roads, streets and highways within and adjacent to the city of San Francisco. However, a human is always in the driver seat, in case problems occur.

The VisLab group from the University of Parma ran the VisLab Intercontinental Autonomous Challenge (VIAC) project that, in 2010, ran autonomous vehicles from Parma, Italy to Shanghai, China, almost 16,000 Km. The system had a lead vehicle that operated autonomously much of the time, but often relied on humans to perform high level path planning, since no maps were available for a significant portion of the route. The follow vehicle, driving autonomously, followed either by detecting the lead vehicle or by following GPS waypoints sent back from the lead vehicle. The sensor suite contained four laser scanners and seven cameras, as well as GPS and IMU. The follow vehicle used local sensing to refine its position relative to the GPS waypoints provided by the lead vehicle. When the lead vehicle was not in view and local sensing failed, the follow vehicle would have to stop driving autonomously.

5. TESTING

While the various demonstrations of autonomous vehicle operation in urban environments are impressive, there are still shortcomings that have not been addressed, including driving completely autonomously, without a human in the driver seat, through areas that have not be driven before or where there have been substantial modifications to the environment. It is unlikely that the Army will be satisfied with these types of demonstrations alone when making decisions on ground vehicle safety. Given the complexity of the real world it is not clear how many miles of autonomous driving would be required before the Army testing community would deem an autonomous vehicle safe to use. The purpose of this paper is to explore test methodologies that will enable the Army test community to have confidence that autonomous vehicles can operate safely.

A key safety metric for a deployable system is the Lifetime Hazard of the system. This generally takes the form of the probability of a Critical or Catastrophic Incident occurring over the expected life of a system. For UGVs, as with other complex systems, this may be determined based on evaluation of numerous constituent probabilities/frequencies of the system and its intended use. This includes:

UGV System

- Model performance probabilities at the major functional component level (hardware and software)
- Model the overall system by the combining of the constituent model analyses based on the system design and operation
- Validate models against real world testing at both the component and system levels

Mission and Environment

- Model or define aspects of the mission that affect hazards
- Account for region, environment, population, day/night operation, etc.
- Include system operation during non-mission events, including training, support, transport, staging, etc. in the analysis

The Lifetime Hazard depends on multiple aspects of the system and the related constituent probabilities/frequencies. The following notional list represents this type of analysis focused on hazards associated with encountering pedestrian(s).

Hazard Analysis Depends On The Probability/Frequency Of:

1. Encountering a pedestrian/human
    - Depends on Mission Type, Area of Operation, Population, etc.
2. UGV Detecting the pedestrian/human
    - Depends on Surroundings and Autonomy System Performance
3. UGV Planning around the pedestrian/human
    - Depends on Autonomy System Performance
4. UGV Successfully avoiding the pedestrian/human
    - Depends on Autonomy System Performance, Vehicle Response
5. Human interaction (e.g. supervised autonomy)
    - Depends on Level of Autonomy, Mission, Area of Operation
6. Pedestrian avoiding collision
    - Depends on assumptions regarding human behavior and vehicle warnings/alerts

7. Collision with Pedestrian/human
    - Depends on the above components
8. Collision resulting in a “critical” or “catastrophic” incident
    - Depends on Mission, Vehicle size/shape, Autonomy System
9. Lifetime Hazard
    - Depends on Missions, Fleet size, Operating Life, etc.

The UGV system Lifetime Hazard metric varies with vehicle size/speed, environment, mission type, region of operation, population, fleet size, etc. The same autonomy system will have different Lifetime Hazard ratings given different applications, missions, environments, modes of operation, etc. The Lifetime Hazard analysis also depends on the distribution of uses over the system lifetime (e.g. operational mission time, support time, training time, etc.). The hazard metric also depends on presumptions about pedestrian behavior. Pedestrian behavior may be affected by system design, including warning indicators or horns. Soldier pedestrian behavior is heavily influenced by training and Tactics, Techniques and Procedures (TTP’s).

As with the evaluation of any complex, probabilistic system, care must be taken in defining and executing quantitative tests to avoid introducing unintended biases into the results. In order for test metrics to be generalized, they must be collected in a way that is independent of the individual test setup, test location or scenarios.

In practice, this hazard analysis can become very challenging due to the complexity of the system and its mission. The dimensionality of the problem space is so large that exhaustive, end-to-end, testing is computationally infeasible. However, the described component approach can decouple interactions, thereby significantly reducing the dimensionality of the testing required. Additionally, one could supply a variety of inputs to the software components through, for example, a modeling and simulation environment, and then analyze the output space. The use of a modeling and simulation approach, integrated with real world testing helps development and testing costs while still retaining reliability of results.

A further complication is that the intelligence algorithms may include a learning component, by which the output may depend on the order that the inputs are presented to the system. This would lead to a combinatoric explosion in possible inputs, making the analysis nearly impossible. The technology to integrate limited learning algorithms in UGV’s is emerging in research work. However, the implications on formal system safety qualification of such systems must be addressed by the Army and the technical community. What additional qualification methods will need to be developed and employed to account for adaptable behavior?

One could also try to perform a vehicle driving “Turing Test,” where one has human judges trying to determine whether the vehicle is driven by a human or a computer. Such a test may lead to open ended questions and a subjective assessment. The question then becomes, is it sufficient for an unmanned vehicle to perform as well as a human, or will it have to perform better? Do we even want the system to perform like a human, including all the mistakes? Comparison with human performance can be problematic in and of itself because of the wide variation in human performance. Additionally, mimicking human behavior along with achieving mission performance goals adds an additional layer of requirements on the system. However, these types of comparisons are certainly important to make. These are likely to be instructive for UGV requirements development and also for guiding the direction of algorithm development.

Performing such a comparison leads to a variety of challenges. How does one structure a test environment to achieve reproducible results? How does one measure “how close” the UGV came to human performance and “how close” is “close enough”? How does one determine what is sufficient variation in urban environments and situations, such that the results can be successfully interpolated? Very different specific behaviors may be equally acceptable in a given situation. How does one provide the unmanned vehicle with the experience that a human driver would have? The answer to the latter question may lie in modeling and simulation, at least for the decision-making algorithms. Modeling and simulation are not sufficiently advanced for realistic simulation of electro-optical sensors, human perception, and pattern recognition capabilities. These questions, among many others, are a mere sample of the vast concerns and issues that reside on testing autonomous systems. The latter section will present the solution taken by the Army for the SOURCE ATO.

6. RESULTS OF CURRENT METHODOLOGY EXPERIMENTED

In planning for the latest SOURCE ATO experiment, much debate occurred between development and test engineers as to the right methodology for testing the safe operation of autonomous vehicles in an urban environment. Although complete agreement on what was the best procedure was not reached, the Army developed a preliminary solution with which to test the performance and behaviors of the SOURCE ATO autonomous vehicle.

When testing a large developmental UGV in an urban environment, it would initially be very unsafe to use live humans in close proximity to the vehicle, until greater confidence has been gained in the ability to detect and avoid humans. Since the UGV is the item under test, the behavior of the system cannot be presumed with sufficient safety ahead of time. Therefore, mannequins were used to represent personnel throughout the urban environment. This enabled testing of the system's ability to perform person detection and avoidance, without the danger involved if the system did not behave as expected. The team built a cart-pulley-winch system that would slide or drag the mannequins in order to represent dynamic human motion. This solution was reasonably effective, although, initially, there were some issues with test repeatability. To alleviate this problem, the mannequin systems were outfitted with a cart or a sled, depending on the terrain, and a pressure sensitive trigger device to activate the mannequin movement when the autonomous test vehicle approached a specific location. Even with the enhancements, though, it was still very difficult to confirm the behavior of the vehicle and collect the necessary data to measure the performance of the system. The SOURCE team implemented a very complex and high fidelity network across the urban environment to support high-bandwidth data collection. Each mannequin contained a GPS device that broadcast its position, trajectory, and speed, during each test run.

Figure 5. Mannequin System Used To Emulate Moving Pedestrians

A great deal of post processing is then required to align the position of the autonomous system with respect to each of the obstacles and then extract information concerning the vehicle system's performance. Even though the unmanned vehicle may have avoided an impact with an obstacle, one needs to analyze the data to determine if the vehicle properly detected the obstacle and if the trajectory to avoid the obstacle was the optimal one. The team structured the test environment to include as many mannequins-to-unmanned vehicle interactions as practical given the program logistics. These included situations where the mannequin was static in the road, at the edge of the road, on the sidewalk, far from the edge of the road, in clusters or groups, moving at various speeds parallel to the vehicle's path, both with and against its path of travel, laterally from either direction, and at various angles. The vehicle was expected to ignore mannequins whose trajectory would not bring it sufficiently close to the platform. One limitation of the mannequin winch system is the inability to conduct non-linear motions. Although the team did not devise a system for producing non-linear dynamic human obstacles, they identified potential solutions that included robotic mannequins to produce random behavior-based movements and/or waypoint following motions.

Similar to the safety concern for human obstacles, the team needed to develop a solution for simulating traffic within the urban environment. This was accomplished by utilizing other robotic vehicles that were operated either via teleoperation or had GPS waypoint following capability, but without an obstacle detection and obstacle avoidance (ODOA) system. While dynamic vehicles with random behaviors were not implemented, the team thought it would be interesting to utilize vehicle-based obstacles with ODOA in order to observe the interactions between two systems simultaneously attempting to avoid one another. The system would need to be fairly advanced and well tested before conducting such an experiment. It was thought to be too costly to expose the current system to that level of testing at its current stage of development.

In the course of the SOURCE Enhanced Experiment, the SOURCE system completed 109 different runs through the Camp Lejeune MOUT site. In addition to the core experiment runs, the team executed numerous excursions or special test runs to gather additional data to support future development as well as supporting other analysis described in this paper. The excursion runs included runs at increased speeds, runs with alternate perception algorithms enabled, and runs with a human driver tele-operating the vehicle. The runs are summarized in Table 1.

Table 1. Summary of test runs during the SOURCE Enhanced Experiment

Test Run / Date	Nominal Distance	05 Nov 11	06 Nov 11	07 Nov 11	08 Nov 11	Total
Complete Course – Movers Off	1.5 km per run	3	2	2	2	9
Complete Course	1.5 km per run	10	1	-	15*	26
Blue Course	0.5 km per run	-	11	5	-	16
Red Course	0.4 km per run	-	11	5, 5*	-	21
Black Course	0.6 km per run	-	11	5, 5*	6[#]	27
Raw Data Collection	1.5 km per run	-	2	1	-	3
Other	1.5 km per run	-	-	2[˚], 3[&]	2[@]	7
Total	**98.2 km**	**13**	**38**	**33**	**25**	**109**

** Executed run at increased speed, except in safe zone closest to base camp*

˚ Tele-op runs of entire course

& Vehicle maneuvering runs at higher speeds with mover detection disabled

 # Different sensor algorithms turned on or off

@ MapReg used for entire test run

The SOURCE Autonomy System, including data logging and test tools, provides significant capability to monitor, store and later analyze a large amount of data in real time. As described above, this provides the critical capability to review and replay data from a test run. The data can be analyzed and post processed in a wide variety of ways. It provides visibility into the real time data that result in the decisions the Autonomy System makes. It is generally not possible to deduce this information by only observing the UGV operation. This capability is by no means unique to SOURCE, but it is key to advancing the development and assessment methodologies for UGV's in more complex environments.

The data logged includes much of the internal data transmitted between major functional elements within the SOURCE Autonomy Software. This data, combined with ground truth data collected as part of the experiment runs, can be used to measure key performance values important for verifying system operation. For example, Figure illustrates several parameters assessed for a given pedestrian encounter on one specific run. This data is from the encounter with Moving Mannequin 1 during Run 24 on 6 November. The figure shows the range at which the pedestrian was initially detected, as well as the amount the UGV deviated from an ideal path to avoid the moving pedestrian.

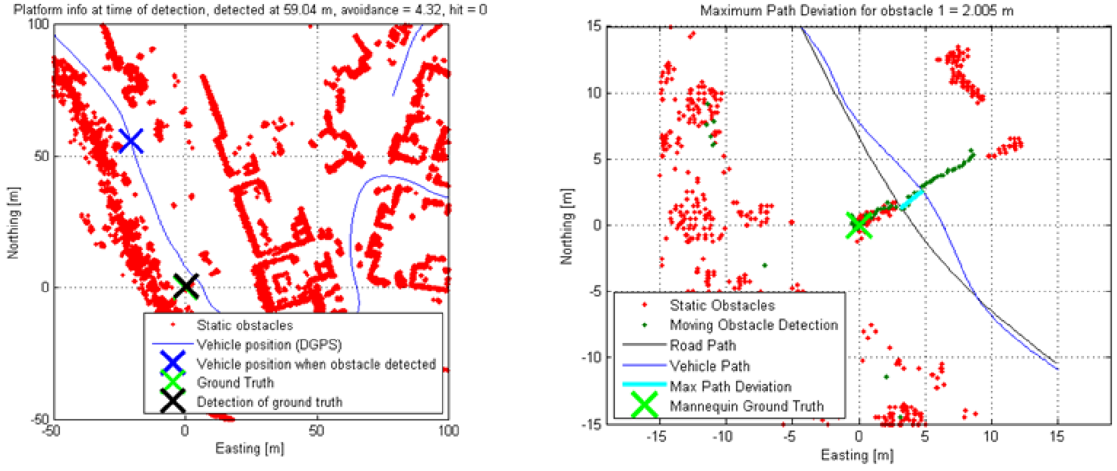

Figure 6. Example of Quantitative Results Based On Logged UGV Data With Ground Truth Data

These are only two examples of the type of quantitative assessment that may be performed if the right data is logged and maintained. The analysis of the data can also be used to investigate problems, to initiate design improvements or even to perform more advanced analyses that may not have been considered at the time of the actual test.

In addition to the quantitative, digitally logged data for each run, as described above, the SOURCE Enhanced Experiment test methodology included recording detailed notes for each run executed, including the number of times the vehicle departed the travel lane and went over the curb, each time the system paused, and every time the safety driver in the chase vehicle had to take control due to unsafe maneuvering of the APD. These notes were compiled from test personnel witnessing the runs from the test control center, as well as from personnel in the chase vehicle following the UGV on all runs.

In an attempt to provide evidence for the performance of the autonomous vehicle versus the performance of human drivers, the SOURCE team conducted a parallel test that used human operators with good driving records teleoperating the vehicle through the test course under the same conditions as the autonomous vehicle. The operators were not briefed on the route ahead of time and were given directions verbally throughout the test scenario. The operators would notify the data recorders when they saw and when they recognized an obstacle, and they were encouraged to think out loud throughout the test. The vehicle was equipped with advanced data collection software that recorded the vehicle's location, trajectory, and speed, as well as recorded the GPS locations when the operator detected and recognized obstacles. In later analyses, this enabled engineers to do a side-by-side comparison of the autonomous behaviors and the human operated behaviors.

While maintaining the established speed limits in the urban environment, limits that ranged from 10 to 25 miles per hour, the human operators on average completed the course 2.5 to 3 times as fast as the autonomous vehicle. These results highlight key requirements tradeoffs that often arise with new technology in complex missions. In an operational UGV system, safety performance at an individual pedestrian encounter level is at odds with mission effectiveness, especially speed. This is similar to many other decision-based systems. As autonomous UGV technologies emerge, the early systems are designed to employ a "when in doubt, slow down" approach. This allows technical development to proceed while maintaining safety.

In the long term, when faced with uncertainty, should the UGV err on the side of minimizing risk or maximizing performance? Human operators will often continue on their current path of travel even if, for example, the sun glares in their face, or something else interferes with their ability to perceive the environment clearly. The SOURCE autonomous system is currently programmed to err on the side of safety rather than speed. Again, in the long term, this Risk vs. Performance tradeoff may need to be based on operator direction to the UGV, analogous to adjustable "rules of engagement". This allows the operator to balance UGV operation based on the known situation. Of course, this increases system complexity as well as difficulty in system qualification. Either the level of adaptability or the specific performance/risk trades need to be explicit in future system requirements.

7. CONCLUSION AND FUTURE RESEARCH CONSIDERATIONS

Regardless of how much data is collected and how the system performs in 100, 1,000, or even 10,000 experiments, the question still arises as to the methodology necessary to reliably measure or assign a safety level for the system and expect it to be accurate for a reasonably broad set of environments and conditions. What metrics are used and at what performance level is the vehicle approved as safe? Humans operate vehicles every day, having different ages and educational backgrounds, and often in very complex hazardous driving situations and conditions, yet the general public are comfortable with that level of risk. When you then list the same conditions and complex situations, but use an autonomously navigated and operated vehicle, the public becomes extremely hesitant and concerned with the safety of the system and its unpredictability. A mature autonomous vehicle is likely to be far more predictable then the average human driver. Autonomous vehicles do not have stressful work deadlines or personal issues rolling around in the back of their head while they are driving, and do not get distracted while talking on the telephone, singing along to music, or eating, while they are driving, yet still they are feared by the public.

Continued evolution of the Lifetime Hazard analysis presented in this paper will be valuable to achieving the necessary safety performance of UGVs in the future. This work can form the initial framework but it depends on inputs form a wide variety of key stakeholders moving forward, including the safety community, test and verification community, user community and development community. This framework augments the existing, well established, safety processes and methods by focusing on some of the unique challenges of complex, autonomous UGV systems and missions. It is important to note that key parameters in the framework depend on assumptions about mission, human-UGV encounters, reaction of humans and other characteristics outside the UGV system itself.

There is room for advancement in the area of UGV requirements definition. Clear definition of the intended mission types and expected use can help bound the complexity and cost of any particular system. UGV's may be categorized by their Level of Autonomy. The exact definitions vary somewhat but conceptually this indicates the level of decisions the UGV may make without help. At higher Levels of Autonomy, the UGV is expected to handle a broader set of conditions without human assistance. At lower Levels of Autonomy, the UGV operation depends on assistance, oversight or direct control by a human. Availability and response time of a human to assist or human safety operator to override affects both safety and mission effectiveness. The same UGV system can have a much higher level of safety if it is operated at lower level of autonomy.

As described in this paper, the test methodology for developing and assessing autonomous UGVs has multiple facets to address the broad nature of the UGV stakeholders. Continued development of the detailed test methodology is necessary to best balance the needs of all stakeholders. Again, much of this builds on established test approaches employed on other complex systems. Detailed quantitative testing at the level of key intelligent components is necessary. This testing should focus on simple, repeatable, high repetition tests. The specificity and quantity of data must support determining the key probabilities such as those defined in the Lifetime Hazard discussion above. The fidelity of the quantitative results must also support validating any probabilistic models used in the hazard analysis. These are closely coupled to the UGV system.

End-to-end test scenarios are also necessary. This focuses on more general tests and is closely coupled to the required capabilities, intended mission and environment. These include lower repetition rates, but broader, more operationally oriented tests.

Development of testing methodologies for comparison of UGV operation to human drivers is needed. There is a large number of approaches to and directions that this type of comparison can take and there is still a lot of research and investigation needed to evolve the methodology in this area.

This paper described numerous challenges to Autonomous Navigation of UGV's as the intended use and target environment becomes more complex. The SOURCE Enhanced Experiment at Camp Lejeune, NC in 2011 was used as a platform to exercise some key aspects of the development and methodology that the Army has sought to increase UGV mission capabilities. The SOURCE program will conclude with the Capstone Experiment, also at Camp Lejeune in September and October 2012. The accomplishments presented represent some initial progress in the direction necessary to help realize the goal of using autonomous systems to exchange manned ground vehicles for UGVs. Future work, beyond the SOURCE program, building on the progress presented in this paper, is necessary in both UGV technology development, as well as UGV testing and hazard assessment methodology. This work will help ensure that UGVs will effectively meet the Army's objectives.

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