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Unmanned Surface Vehicle Human-Computer Interface for Amphibious Operations

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

This report describes a multiyear research effort conducted by SPAWAR Systems Center Pacific (SSC Pacific) investigating Human-Computer Interface (HCI) issues associated with operating unmanned surface vehicles (USVs). An iterative user-design process was used that resulted in the development of an enhanced HCI design. The primary focus of this effort was to investigate improvements to the baseline HCI design of the SPAWAR Multi-Operator Control Unit (MOCU) software to support simultaneous operation of multiple USVs by a single operator. This effort was sponsored by the Office of Naval Research (ONR), Code 34, under the Capable Manpower Future Naval Capability (FNC) 08-03 Program. A number of significant design enhancements were made to the baseline HCI as it was adapted to support multiple USVs. The enhancements included integrated visualization of video and graphics combined with multi-modal input and output using synthetic speech output and game-controller input. Significant gains in performance times and error reduction were found with the enhanced design. Following the ONR effort, Naval Sea Systems Command (NAVSEA) LCS Mission Modules Program Office (PMS 420) supported the development of a prototype HCI design for operation of a single USV. While overall results of simulator-based usability evaluations indicate improved operator performance, the researchers conclude that improvements in on-board sensor capabilities and obstacle avoidance systems may still be necessary to safely support simultaneous operation of multiple USVs in cluttered, complex transit environments.

CONTENTS

EXECUTIVE SUMMARY	i
GLOSSARY	vi
1. INTRODUCTION AND BACKGROUND	1
2. HUMAN PERFORMANCE ISSUES	3
2.1 SUPERVISORY CONTROL	3
2.2 WORKLOAD MANAGEMENT	5
2.3 SITUATION AWARENESS.....	5
3. MOCU ARCHITECTURE AND SIMULATION DEVELOPMENT.....	7
3.1 BASELINE MOCU.....	7
3.2 BASELINE MOCU HCI.....	8
3.3 MOCU BASELINE RE-ARCHITECTURE 2008	8
3.4 MOCU MISSION SIMULATION.....	10
4. MOCU HCI ITERATIVE DESIGN PROCESS.....	12
4.1 MOCU BASELINE USABILITY EVALUATION AND HEURISTIC REVIEW	12
4.2 MOCU INTERMEDIATE DESIGNS	13
4.2.1 MOCU Preliminary Design Wrap-Around Format.....	13
4.2.2 Preliminary Designs for Graphics and Audio	14
4.2.3 User Feedback Preliminary Design	18
4.2.4 Preliminary Design Conclusions and Results	18
4.3 MOCU V3.0 AND 3.1 DESIGN	19
4.3.1 Video and Map Display Re-Design.....	20
4.3.2 Alarms and Alerts.....	22
4.3.3 Route Status Information	24
4.3.4 Contact Location and Video Integration	27
4.3.5 USV Pan-Tilt-Zoom Display	27
4.3.6 Controller Interface	28
4.3.7 Procedure Re-Design.....	31
4.3.8 Vehicle and Mission Status	32
5. HCI USABILITY TESTING.....	34
5.1 PURPOSE AND SCOPE	34
5.2 PARTICIPANTS	34
5.3 METHODOLOGY AND TEST PROCEDURES	36
5.3.1 Mission Scenario.....	36
5.3.2 Performance Measures and Data Collection	36
5.3.3 Participant Welcome and Background Questionnaire.....	36
5.3.4 MOCU Orientation and Practice	36
5.3.5 Usability Testing.....	37
5.3.6 Exit Survey and Debrief	37

5.4 RESULTS.....	38
5.4.1 Data Analysis	38
5.4.2 Phase I – One USV vs. Two USVs with Baseline HCI	39
5.4.3 Phase II – Baseline MOCU vs. MOCU v3 (Two USVs)	40
5.4.4 Phase III - MOCU v3 vs. MOCU v3.1 (Two USVs)	40
5.4.5 Phase IV - Baseline MOCU vs. MOCU v3.1 (One USV).....	41
5.4.6 Summary Comparison across All MOCU Versions.....	42
5.4.7 Results of Exit Survey	43
5.4.8 Technology Transition Exit Criteria.....	44
6. VISUAL PERFORMANCE MODEL	46
6.1 RATIONALE FOR EMBEDDED VISUAL MODELS	46
6.2 VISUAL PERFORMANCE MODEL DEVELOPMENT	46
6.2.1 Simple Search Model	46
6.2.2 Underlying Assumptions	47
6.2.3 Stimuli	47
6.2.4 Methods	47
6.2.5 Preliminary Findings.....	48
6.2.6 Discussion	48
7. CONCLUSIONS AND RECOMMENDATIONS	49
7.1 ASSESSMENT OF BASELINE MOCU	49
7.2 ASSESSMENT OF ENHANCED MOCU	49
7.3 ASSESSMENT OF GAME CONTROLLER INPUT DEVICE	49
7.4 IMPLICATIONS FOR SINGLE USV OPERATION.....	50
7.5 EASE OF USE AND TRAINING IMPLICATIONS	50
7.6 RECOMMENDATION FOR FURTHER TESTING	50
8. REFERENCES	51
APPENDIX A. SCENARIO SCRIPT	A-1
APPENDIX B. VOLUNTARY CONSENT FORM	B-1
APPENDIX C. BACKGROUND QUESTIONNAIRE.....	C-1
APPENDIX D. TRAINING PROTOCOL.....	D-1
APPENDIX E. MISSION BRIEFING	E-1
APPENDIX F. EXIT SURVEY	F-1

FIGURES

Figure 1. MOCU Baseline HCI using Both Aerial Photo and Digital Nautical Chart (DNC) Maps to Control and Monitor Land, Sea, and Air Vehicles.	8
Figure 2. MOCU v2 Architecture (Before Re-Design).	9
Figure 3. MOCU v3 Architecture (After Re-Design).	10
Figure 4. Virtual Sailor and MOCU Configuration for Mission Simulation.....	11
Figure 5. V1.0 HCI Configuration of Baseline MOCU with Simulated Ocean Video Feed...	11
Figure 6. Usability Test Display for MOCU Baseline Study.....	12
Figure 7. Screen Capture from 2009 Live USV Demonstration with Initial Map-Video Integration.	13
Figure 8. Integrated Display Visualization Design Concept for Advanced MOCU.....	14
Figure 9. Summary of Route Graphics Designs.....	15
Figure 10. Summary of Control Mode Design Graphics Designed to Map to Current Surface Craft Robot Control Mode States.	16
Figure 11. Integration of Robot Control Mode Graphics with Composite View – Route Following Mode Example Shown.	16
Figure 12. Sample Page from Video Worksheet of the Advanced MOCU Specifications....	17
Figure 13. Sample Page for Developing USV Audio Alert Messages.	18
Figure 14. HCI Design Changes Made from MOCU v2 to MOCU v3.	19
Figure 15. Replacement of Video and Map Information MOCU v2 to MOCU v3.	20
Figure 16. Rearrangement of Video Forward and Aft Video Feeds in MOCU v3.	21
Figure 17. Relocation of PTZ Camera View in MOCU v3.	21
Figure 18. Removal of Persistent Aft View Video and Enlarged Secondary USV Forward View in MOCU v3.1.	22
Figure 19. MOCU v2 Alarm Presentation (top) and MOCU v3 Alarm Graphics (bottom).	23
Figure 20. MOCU v3.1 Alert Presentation with Visual and Auditory Cues.	24
Figure 21. Route Waypoint Information in MOCU v3 shown on upper dashboard and along compass heading.	25
Figure 22. Route Insets (top) and Waypoint Countdown Insets (bottom) for v3.1.	26
Figure 23. Contact Graphics Integrated with Video Information in MOCU v3.....	27
Figure 24. PTZ On-Screen Controls and Indicators.	28
Figure 25. Functional Mapping with Game Controller User Interface.....	28
Figure 26. Typical Task Sequence with PopUp (Pie) Menu.	30
Figure 27. Shifting Primary Control between USV 1 and USV 2.	30
Figure 28. Baseline MOCU Task Procedure Sequence.	31

Figure 29. MOCU v3 Procedure Sequence Example.....	32
Figure 30. Upper Display Showing Vehicle and Mission Status.	33
Figure 31. Subject Demographics.....	35
Figure 32. Subject at MOCU Simulation Workstation.	37
Figure 33. Percent Correct Responses Controlling One USV vs.Two USVs Using Baseline MOCU.	39
Figure 34. Percent Correct Responses Controlling Two USVs Using Baseline MOCU vs. MOCU v3.	40
Figure 36. Percent Correct Responses Controlling One USV Using Baseline MOCU vs. MOCU v3.1.	42
Figure 37. Comparison of Accuracy Rates across All MOCU Versions.	43
Figure 38. Participant Responses Controlling Two USVs Using MOCU v2 vs. MOCU v3.1.	44
Figure 39. Approximate Appearance of a Test Stimulus for Target on Horizon.	47

GLOSSARY

Acronym or Term	Meaning
ACTD	Advanced Concept Technology Demonstration
AID	Advanced Interface Display
API	Application Programming Interfaces
ASW	Anti-Submarine Warfare
CM	Capable Manpower Program
CO	Commanding Officer
COA	Course of Action
DNC	Digital Nautical Chart
FNC	Future Naval Capability
HCI	Human-Computer Interface
HRI	Human-Robot Interface
HSI	Human-Systems Integration
LCS	Littoral Combat Ship
MCM	Mine Countermeasures Mission
MMWS	Multi-Modal Watchstation
MOCU	Multi-Robot Operator Control Unit
NAVSEA	Naval Sea Systems Command
NUWC	Naval Undersea Warfare Center
ONR	Office of Naval Research
OOVO	Offboard Organic Vehicle Operator
PTZ	Pan-Tilt-Zoom
SA	Situation Awareness
SME	Subject Matter Expert
SOA	Service Oriented Architecture
SSC Pacific	Space and Naval Warfare Systems Center Pacific
TAO	Tactical Action Officer
TM	Task Manager
UAV	Unmanned Aerial Vehicles
UCD	User Centered Design
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
WOO	Window of Opportunity

1. INTRODUCTION AND BACKGROUND

Unmanned Surface Vehicles (USVs) are envisioned as an integral part of the mission module packages for the Littoral Combat Ship (LCS) of the future. To date, preoperational exercises and training have focused on the USV shipboard operator controlling a single USV. However, given the small crew size on an LCS ship, mission demands may call for a single operator to control and monitor multiple USVs simultaneously. Therefore, it is vital to evaluate the effectiveness of the current user interface to gain insights into design improvements that could help support multiple USV operations.

This report describes a multiyear research effort conducted by SPAWAR Systems Center Pacific (SSC Pacific) investigating Human-Computer Interface (HCI) issues associated with operating USVs. An iterative user-centered design process resulted in development of an enhanced HCI design. The primary focus of this effort was to investigate improvements to the baseline HCI design that would support simultaneous operation of multiple USVs by a single operator. This effort was sponsored by the Office of Naval Research (ONR), Code 34, under the Capable Manpower Future Naval Capability (FNC) 08-03 Program.

This project was initiated in 2007 to address the ONR defined Capability Gap 1, “Next Generation Autonomous Systems” by the application of human factors research and engineering to the next generation control interface for the LCS HCI. The project goal was to study design factors with respect to operator Situation Awareness (SA) and interaction with the Mission Supervisor. Key technical objectives of this FNC included:

- Development of effective attention management mechanisms, including visual and auditory displays to guide user attention and maintain situation awareness based on mission conditions.
- Development of low-risk, easy-to-use interactive methods supporting both supervisory control and migration to or from manual control.
- Development of simple, efficient, and effective HCI control and displays.
- Development of multi-layer visual integration techniques to reduce user visual scanning and reduce visual and cognitive integration across separate display windows.
- Collection of human performance data to measure the impact of design factors through the iterations.
- Development of flexible, expandable multi-robot controller software architecture to enable future growth and HCI additions.

A secondary objective was:

- Development of a risk model of mission conditions based on operational environmental conditions, operating speed, and user visual performance with respect to obstacle detection and avoidance. Use the model to guide the user during varying operational conditions.

This project was conducted through a series of iterative design evolutions that involved the testing of new HCI concepts and evaluating the effects of the concepts on human performance. At the start of the project, the SSC Pacific Multi-robot Operator Control Unit (MOCU) was the “baseline” design. Initial project tasks were conducted during the 2007 to 2009 time frame as follows:

- The User-Centered Design (UCD) team conducted heuristic reviews and usability testing of the Baseline MOCU to define design qualities that could negatively impact operator

performance and estimate initial design changes required (Kellmeyer and Bernhard, 2009), (Kellmeyer, McWilliams, and Bernhard, 2009).

- Human factors guidelines and principles were applied to develop early HCI concepts which then directed the requirements for re-architecture of MOCU software into a service oriented architecture (SOA) with the capability to support the visual integration features (e.g., video and graphics) requested by the UCD team (McWilliams, 2009).

The project need for human performance testing required a simulation capability to be acquired and integrated into MOCU to allow human-in-the-loop hands-on testing within the context of operational scenarios. With the creation of a dynamic simulation and MOCU re-architecture, it became possible to study human performance interacting with simulated USVs. The following tasks were conducted during the 2010–2011 time frame:

- Task analysis for anti-submarine warfare (ASW) and mine countermeasures mission (MCM) mission domains. The ASW mission domain was cancelled during later phases of the project, but the tasks selected were also representative of work activities in the MCM mission.
- Creation of dynamic operational task scenario with at-sea mission simulation. The scenario was designed to contain varying levels of difficulty in decision tasks.
- Identification of task outcome-based metrics for collection in usability studies.
- Creation of integrated visualization design for an Advanced MOCU HCI.

Usability testing was conducted with initial versions of the Advanced HCI (McWilliams, Osga, Kellmeyer, and Viraldo, 2010):

- Definition of lessons learned and design issues to be corrected in upgrades to the Advanced MOCU HCI design.

Usability testing was conducted with the enhanced MOCU HCI (McWilliams, Osga, and Kellmeyer, 2010, McWilliams, 2011):

- Definition of a final design for transition to LCS Mission Modules with recommendations for implementation.
- Creation of transition plans and documentation to aid in the integration of the ONR FNC product with the Naval Sea Systems Command (NAVSEA) Program of Record (Powell, 2011).

On completion of the initial project, a follow-on effort, sponsored by NAVSEA LCS Mission Modules Program Office (PMS 420), was performed to design and evaluate a version of the improved HCI for control of a single USV. This work was performed during Fiscal Year 2012 (FY 12). Because this follow-on effort significantly leveraged research, experimental techniques, and resultant design concepts from the preceding ONR work, the PMS 420-sponsored work is presented within the context of the overall USV HCI ONR research effort in this comprehensive report.

2. HUMAN PERFORMANCE ISSUES

Tasks related to the monitoring and control of multiple USVs involve user skills and abilities related to situation awareness and supervisory control. The design of the MOCU HCI and functions must account for limitations in human performance and offer enhancements to guide attention during multi-tasking dynamic operations. This section of the report discusses key human performance issues related to USV control.

2.1 SUPERVISORY CONTROL

Supervisory control typically involves less operator direct manual control of systems, and increased higher levels of planning and decision-making (Sheridan, 1992). This type of control involves operators at a higher cognitive level for a knowledge-based set of behaviors where the user intermittently interacts with a computer, receiving feedback from and providing commands to a controlled process or task environment. According to Mitchell, Cummings, and Sheridan (2005), there are perhaps 10 key issues related to human performance in network-centric operations in supervisory control of systems. These include:

- Information Overload
- Appropriate Levels of Automation
- Adaptive Automation
- Distributed Decision-Making and Team Coordination
- Mitigating Complexity
- Decision Biases
- Attention Allocation
- Supervisory Monitoring of Operators
- Trust and Reliability
- Accountability

For the purposes of this project, supervisory control is assisted through the use of visual and auditory displays, alerts, and integration of critical information. Design goals are:

1. Mitigate information overload,
2. Support user situation awareness, and
3. Provide effective attention allocation.

Operator Knowledge, Skills, and Abilities with respect to Visual, Auditory, and Cognitive, dictates human performance for USV control and psychomotor performance as related to mission tasks and work pacing demands. Thus, the simulated USVs used in Human-Robotic Interface (HRI) studies were created to match the operational characteristics of the real USV platforms, and are multi-functional and re-programmable machines not requiring a constant operator inputs or corrective actions. Studies indicate that more automation is not always better with respect to operator reaction. For example, Parasurman, Mouloua, Molloy and Hilburn (1996) report that in general, studies indicate that when operators do not actively control a process they are poorer at detecting malfunctions than when they are engaged both in control and monitoring. Results are unclear though given length of tasks studied and whether operators had other manual tasks as well. Further studies appear to indicate that monitoring performance for failures is often poorer if there are other manual tasks being performed. We consider the operator to be performing USV tasks without the need for

other concurrent manual tasks. If automation monitoring is the only task, performance is not impaired (Parasurman, Molloy, and Singh, 1993). Hancock et al. (2007) state that given a control regimen such as making intermittent commands under supervisory control, the number of controllable UAVs is directly contingent on the temporal capacity of each machine for independent, autonomous action (Mouloua, Gilson, and Hancock, 2003). Thus a key factor is how much time the robot demands from the operator and what the operators' surround task environment is. Competitive tasking at the same time reduces performance for monitoring. Our work assumes the operator/monitor is not in any immediate combat danger and the USV operations are managed from a controlled shipboard command center environment. Thus, the operators on the LCS ship are dedicated to the mission functions (mine-warfare or other missions) and may be time-sharing HRI tasking with verbal communication tasks to other operators (e.g., sensor) or mission supervisors.

Multiple vehicle control and monitoring creates possible error conditions due to:

1. Sensory input conflict,
2. Central decision-making processing overload, and
3. Response confusion and interference (Hancock et al., 2007).

Each of these performance-shaping factors must be considered in designing controls and displays that support user shift of control and monitoring between multiple vehicles. Considering these performance issues it is likely that planning and analysis of incoming information streams from sensors (e.g., sonar) is best done by an analyst (given the full attention of visual and cognitive resources given to analyses) with vehicle control and monitoring best done by a dedicated controller. Similarly, Barnes et al. (2006) indicate from study of task distribution among a two-person team that performance was better when split by roles vs. by vehicles. For example, team workload for two USVs would be distributed by Operator A doing observation and analysis for both vehicles while Operator B does navigation/control for both vehicles. Still, the issue of workload bottlenecks for that controller/monitor must be addressed given multiple vehicles and external mission pacing.

One way to aid users is through the use of "predictive" displays, (Baldwin, Basu, and Zhang, 1998, 1999; Bejczy, Kim, and Venema, 1990; Mathan et al., 1996). Researchers studying intelligent aids for predicting of high workload periods in the control of multiple unmanned aerial vehicles (UAVs) found that users would fixate on optimizing a future schedule to the detriment of solving certain near term problems (Mitchell, Cummings and Sheridan 2005). Cummings further investigated the depiction of projected task opportunity time periods in the flight profiles of multiple Tactical Tomahawks. As determined for control of multiple tactical tomahawks in flight, the user can be aided by showing task "windows of opportunity" (WOO) where time slots are graphically shown for best operator attention to multiple missile control decisions, (Cummings and Guerlain, 2004) With regard to route planning and waypoint adjustments with USVs, it should be possible to aid users with decision support tools similar to the WOO based on projected workload (timing and concurrence) with multiple routes. The user could then adjust their task schedules in advance to balance workload before a high load condition is created. Displays developed at SSC Pacific were used together with a tactical route plot display to monitor multiple Tactical Tomahawks (UAVs) in flight (Osga et al., 2005). The graphics and color coding shown was used to draw operator attention to critical mission task path items requiring attention and management.

These principles were applied to the waypoint announcement and inset information HCI to provide advance notices to users of upcoming mission route events. Another important design goal was to integrate and overlay information such that visual scanning and search workload is limited.

2.2 WORKLOAD MANAGEMENT

Workload can be defined according to the WINDEX (Workload Index) model which describes components of workload along six dimensions: Visual Perception, Auditory Perception, Verbal Cognition, Spatial Cognition, Manual Response, and Speech Response. A recent study created a Task Network model predicting workload for ASW search operations using multiple USV sorties with multiple vehicle control (Miller, 2006). With the software and USVs used in this study it may be possible to use same or similar scenarios to measure workload with actual systems, which serves to validate the model results as well as defining system success. Workload management is a key design issue that must account for the entire gamut of operator tasks, including control, monitoring, and team communication/collaboration. The Miller study predicts high workload for communication tasks. The controller/monitor must be able to not only safely control the vehicle but also receive input and coordinate actions with the mission analyst/tasking part of the team. Osga et al. (2002) found that use of decision support visual aids in small tactical teams reduced the amount of required verbal communications as team members were able to see tasks in progress requiring less discussion of “who, when, what, how” of imminent task needs. With multiple USV operations, there are options available to management mission workload, including.

1. Reducing mission pace by slowing or delaying operations. Speed can be reduced or one vehicle delayed or placed in loiter mode while another is given full attention. These tactics may become more desirable if both USVs are in manual control mode or if surface clutter is high.
2. Using leader and follower USV path tactics. Thus one USV “clears the path” for the second, and the speed and course of the second following USV is based on the lead USV.
3. Under high-clutter conditions, completing task sequences for one USV, then placing that vehicle in loiter mode while completing a sequence for the second USV.

Tactics must be considered to adjust workload levels dependent on the operational risks and environment (e.g., visibility, clutter, waves). The scenario developed for this project contained varying workload levels simulating multiple simultaneous environmental and equipment critical events. This approach allows the analysis impact of workload demands at varying levels across HCI designs.

2.3 SITUATION AWARENESS

Situation awareness (SA) must be distributed and shared between controller and planner. SA has been described as having three major levels of awareness. Situation awareness is a conscious human process of information collection, filtering and storage, interpretation and reaction.

Jones and Endsley (2000) refer to three levels of SA as:

- Level 1: perception of the elements in the environment within a volume of time and space,
- Level 2: comprehension/understanding of their meaning, and
- Level 3: Projection of their status in the near future.

Level 1 SA tasks include visual search, filtering of important task information from peripheral visual “noise,” and auditory sampling from multiple sources. All are part of the sampling process to continually update human short-term memory regarding the current status of the environment. System aiding can be provided for various types of SA sampling, storage, and retrieval activities. Level 2 activity implies that incoming information presented is compared to the current and near-term goal-states of mission tasks and activities to determine the significance of events relative to goals. The resulting actions include decisions to start, delay, or cancel task activities. Level 3 implies

that there is temporal nature to decision making and that activities may be launched or altered based on projections into the near-term future. In USV control/monitoring tasks, this includes decisions for altering courses or waypoints to over-ride the current route plan in favor of manual control. This decision may be based on individual SA or shared SA, including the goals and intent of the mission commander or other crewmembers. There is evidence that users build a story (or mental model) based on the operating environment, expected events, and observed events, and compare this to past experiences in their decision-making training or operational experiences (Klein, 1993). Problems in mission performance may appear when errors occur in SA, producing a mismatch between the user's mental model of the situation and the actual situation. Endsley and Garland (2000) refer to "representational errors" when information has been correctly perceived but the significance of various pieces of information is not properly understood, meaning problems with Level 2 SA. In USV control, visual cues that a craft is potentially moving into a collision path may be overlooked in favor of evidence that something more important to the mission context is nearby. For example, the user may be inspecting something with the Pan-Tilt-Zoom camera and temporarily lose SA for the forward path of the USV. The system requirement, therefore, is to provide information in a manner that prompts the user to be attentive and to support ongoing SA of USV activity regarding mission needs and priorities.

3. MOCU ARCHITECTURE AND SIMULATION DEVELOPMENT

3.1 BASELINE MOCU

During the 2000-2007 time period, SSC Pacific developed an unmanned vehicle and sensor operator control interface capable of simultaneously controlling and monitoring multiple sets of heterogeneous unmanned systems. The term heterogeneous is used to describe vehicles that are dissimilar in both modality (land, air, sea, or undersea) and communications protocol. The goal was to not just minimally control, but to have full access to the vehicle/sensor and its payloads. To achieve this goal, a modular, scalable approach was developed. The modularity, scalability, and flexible user interface of the Multi-Robot Operator Control Unit (MOCU) accommodates a wide range of vehicles and sensors in varying mission scenarios. Figure 1 shows the Baseline HCI view of MOCU with air, sea, and ground vehicle monitoring and control.

To avoid time-consuming and expensive changes to a monolithic OCU to support new devices or technologies, the MOCU was designed to improve flexibility by using a modular, scalable, and flexible architecture. Modularity allows for a breadth of functionality, such as communicating in unrelated protocols or displaying video with a proprietary video codec. Modularity also allows for third-party expansion of MOCU. Scalability allows MOCU to be installed on a wide range of hardware. MOCU also allows the user to define what information is displayed and determine what control is needed for each system. The same core software is currently used on a wide variety of projects, each utilizing these attributes in its own way.

As of 2008, MOCU version 2 provided the common USV operator interface for the LCS ASW and MCM mission modules. The LCS USV operator interface was built from the prior command and control interface, MOCU version 1, that had been developed for the Spartan Advanced Concept Technology Demonstration (ACTD) USV. MOCU was also being used by the Army's PM Force Protection Systems office as the unmanned vehicle and sensor interface for a joint experiment with the Air Force Research Laboratory and to control many of the SSC Pacific developmental vehicles (land, air, sea, and undersea). For the ground robot domain, it provided a common OCU for the Urban/Cave assault ACTD for the iRobot Packbot and SSC Pacific URBOT Unmanned Ground Vehicles (UGVs). SSC Pacific had also received funding from the Defense Threat Reduction Agency (DTRA) to adapt MOCU as the user interface for a mid-size UAV for force protection of fixed site Army bases.

MOCU was designed with a modular architecture to allow for orderly expansion and addition of new capabilities. Much of the functionality of MOCU resides in plug-in modules that are dynamically linked at runtime. Additional functionality can be added to an existing MOCU installation by simply copying new modules to the folder without changing any of the core MOCU code. An Application Programming Interfaces (API) document has been written that fully describes the MOCU module interface. This allows third-party developers to add their own functionality to MOCU with very little support from SSC Pacific. The API was used by the Naval Undersea Warfare Center (NUWC) Newport to develop the MOCU interface module that communicates to ASW mission planning tools. The user interface is similarly flexible. The layout and functionality of MOCU is determined via XML text configuration files. The user interface can be changed very quickly and as many times as needed, again without modifying and re-coding. This approach made MOCU an ideal platform on which to study user interface and HSI issues.

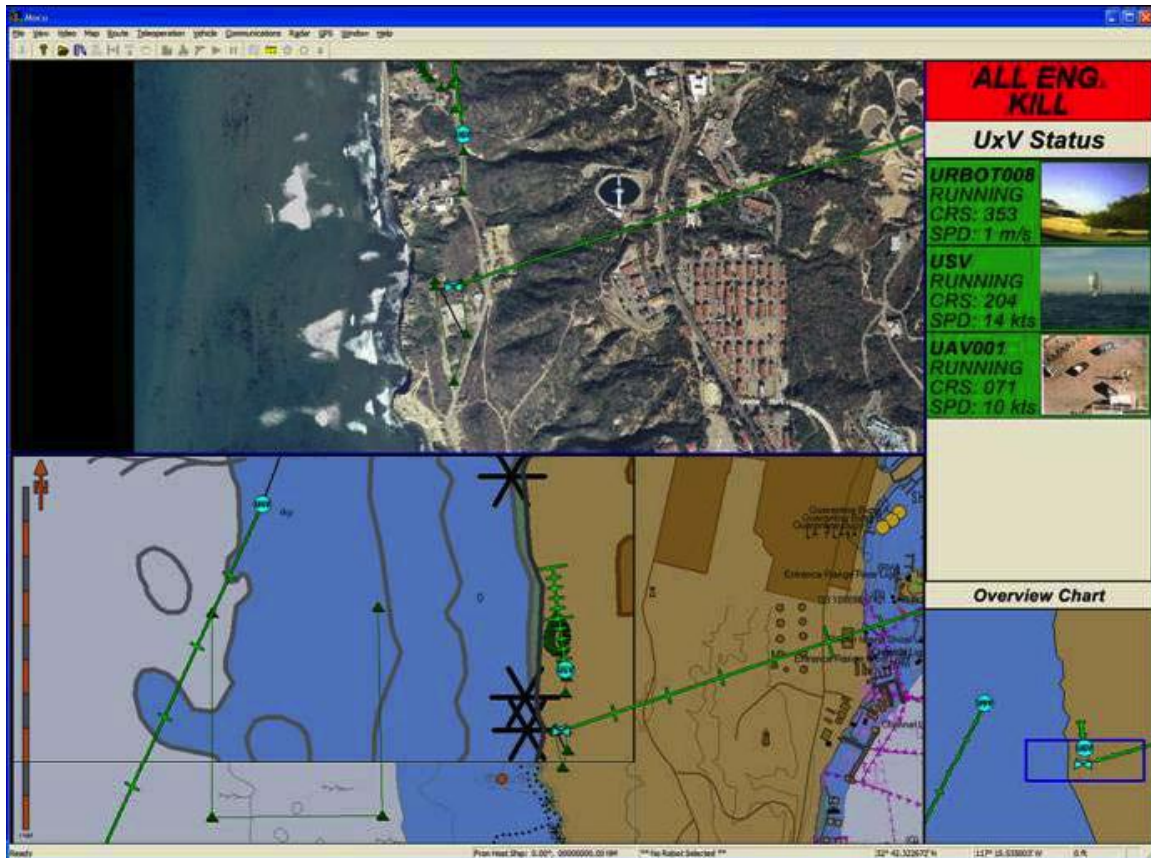


Figure 1. MOCU Baseline HCI using Both Aerial Photo and Digital Nautical Chart (DNC) Maps to Control and Monitor Land, Sea, and Air Vehicles.

3.2 BASELINE MOCU HCI

The Baseline MOCU interface is a tiled window interface with multiple window tiles that included 2D maps with USV symbol location superimposed on chart and separate satellite image backgrounds. Control Button options and Inset Chart views are included at closer range-scales than shown in the wide-area map. Video input is shown in windows of varying size. As parameters are selected by clicking on objects, drop down windows appear allowing data parameter changes through keyboard or mouse entry. The application ran on a Windows-based computer with a single monitor.. For the FNC, the application was reconfigured to run on a dual-monitor console similar to that aboard the Littoral Combat Ship (LCS).

3.3 MOCU BASELINE RE-ARCHITECTURE 2008

The MOCU v2 architecture is shown in Figure 2 before re-design. The core software of MOCU loads other modules to perform various functions, such as communicating with robots, displaying map data, decoding video, etc. The core also reads configuration files that govern what the user interface looks like as well as providing customization data that may be needed for a particular project. MOCU v2 communicates with the modules using several different APIs depending on the module type. This functionality is inherited from MOCU v1 and is supported primarily for backward compatibility. A newer more flexible interface was introduced in MOCU v2 using a publish and subscribe (“pubsub”) paradigm to share data between the MOCU core and the other modules, making it unnecessary to have specific interfaces for particular module types.

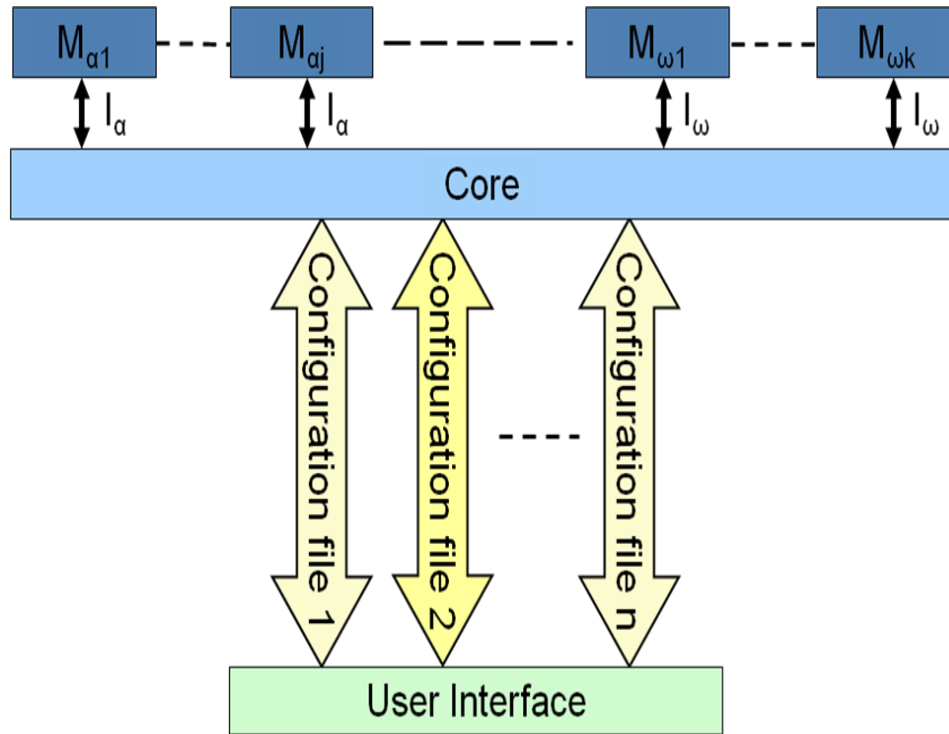


Figure 2. MOCU v2 Architecture (Before Re-Design).

While MOCU v2 offered a great deal of flexibility regarding the user interface organization, it also contained a number of deficiencies.

MOCU v2 used the Windows graphics device interface that is not very fast and cannot handle 3D graphics, making it impossible to implement a modern user interface. The core of MOCU defined the look-and-feel of the user interface, so changes to user interactions (mouse clicks, wheel movements, and keyboard accelerators) required changes to the core, which can be difficult to do and affects other projects using MOCU. Because most of the MOCU v2 modules used module-specific APIs instead of the pubsub API, their functionality was quite limited. Also, the Configuration Files were not stored in the data server — much information useful to various modules was not available.

The MOCU v3 architecture developed in FY 08 (see Figure 3) addressed these issues. There was no longer a MOCU “core” application that provided the majority of the functionality of MOCU. The core was replaced by a set of modules (referred to as the “core modules”) supplying the same basic functionality previously provided by the core application. Each of these is a module and only performs one function to facilitate isolated modifications.

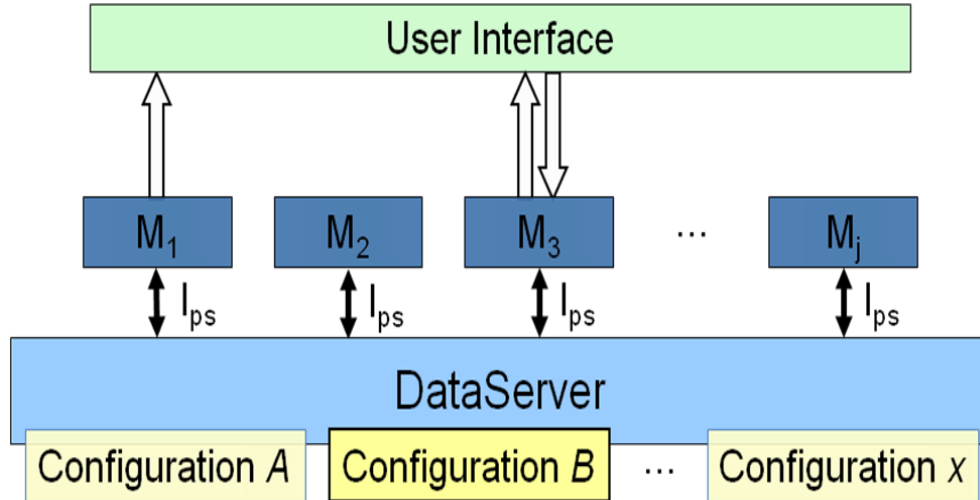


Figure 3. MOCU v3 Architecture (After Re-Design).

MOCU v3 only supports the pubsub module interface (denoted by I_{ps} in the figure) so modules have access to all the data in the system as well as the ability to communicate with other modules. The modules communicate via the DataServer module, which provides access to raw data (properties) as well as providing an inter-module communication mechanism (method calls).

Some modules interact exclusively with the DataServer (such as modules that receive information from robots or other exterior devices). Others provide display data to the user or process user input. Because the configuration information is read from external files but stored in the DataServer, all modules have access to configuration information that now gives MOCU more flexibility than in previous versions.

3.4 MOCU MISSION SIMULATION

A dynamic mission simulation is the pre-cursor to conducting human performance experiments with multiple USVs. Although the MOCU software supports operations with live USVs, cost cutbacks during the FNC time frame prohibited expensive operations with live USVs. In addition, there was only one USV available, making multiple USV operations impossible.

A list of possible simulation toolsets was compiled, organized, and rated according to essential project criteria. Presagis Corp tools and several other top candidates were investigated and demos observed. Tools were compared on cost criteria vs. requirements for supporting user-performance and usability testing. A low-cost and functionally adequate game simulator product, “Virtual Sailor,” was selected as the method of creating a simulated ocean environment to mimic the return of a video feed from the simulated USV.

Figure 4 shows the architecture employed to construct the simulation capability to support human performance studies. First, a screen capture is done on each Virtual Sailor screen at 10 Hz. Initially, the vehicle status is retrieved from the screen using optical character recognition techniques to populate simulated sensor returns and throttle/rudder commands are sent as virtual key presses to a specific Virtual Sailor module. This version used Microsoft's DirectX "Direct Play" SDK (a Microsoft utility) to ensure a common visualization across multiple virtual sailors. The Virtual Sailor software company was eventually funded to modify the base software, SNS-s70, to provide a shared-memory API to enable higher resolution vehicle status, better control of the vehicle and environment setup, and to sync the multiple instances of Virtual Sailor. Screen captures are sent as an MJPEG formatted stream when requested.

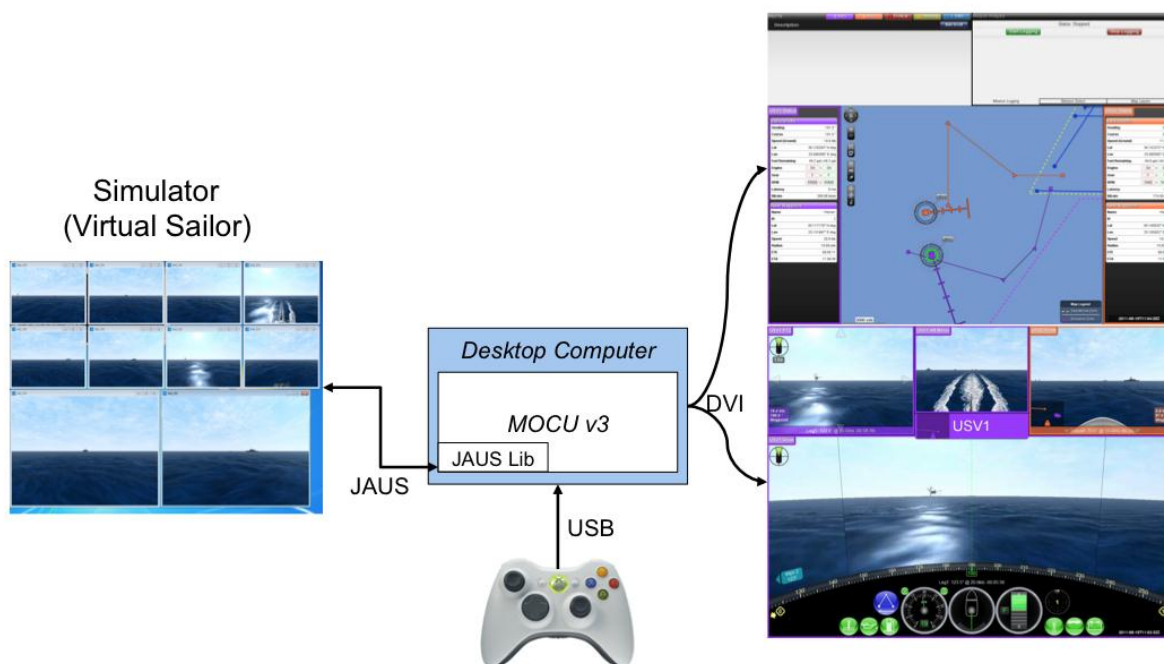


Figure 4. Virtual Sailor and MOCU Configuration for Mission Simulation.

Figure 5 shows a Baseline MOCU user-interface configuration for the simulated ocean environment along with the baseline HCI (map, USV control functions, status indicators). As the user monitors the USV path and mission progress, the simulated USV camera view can be manipulated to correspond with the simulated USV mission path and progress on MOCU.

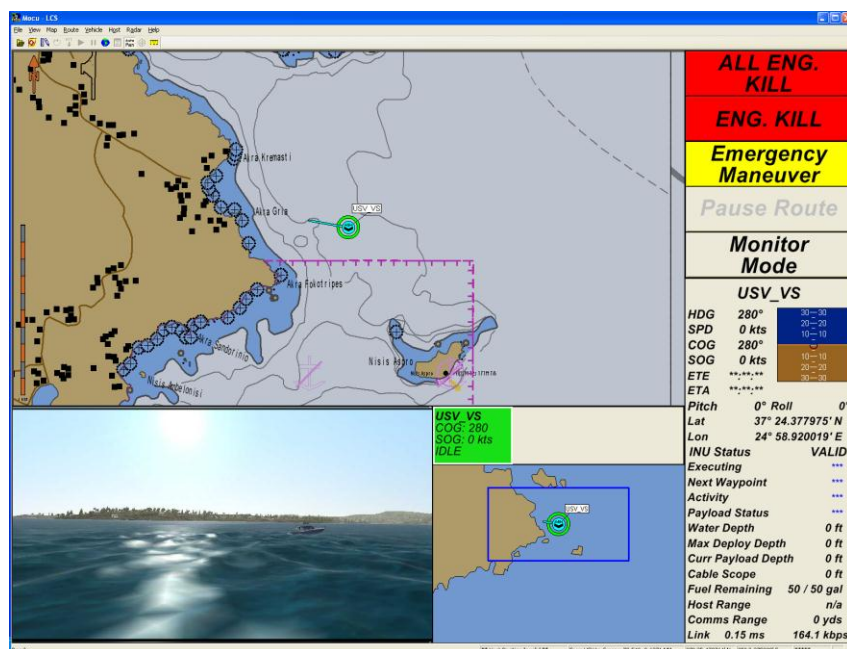


Figure 5. V1.0 HCI Configuration of Baseline MOCU with Simulated Ocean Video Feed.

4. MOCU HCI ITERATIVE DESIGN PROCESS

4.1 MOCU BASELINE USABILITY EVALUATION AND HEURISTIC REVIEW

In July 2008, a usability evaluation was conducted using the Baseline MOCU software. The evaluation focused on the usability of the current computer interface (see Figure 6) in supporting users who performed general functions associated with controlling a USV. The goal of the test was to identify key functions where the current interface may be inefficient, complicated, or perhaps increase workload or fail to provide adequate decision support.

Participants consisted of six sailors from the Littoral Combat Ship Anti-Subsurface Warfare Mission Package (LCS ASW MP) command in San Diego, California. These sailors were among those who would have been tasked to control the first operational USV prior to the cancellation of the USV component. An introductory training session was provided to expose each participant to the basic functionality of the MOCU controls and displays. Because the vehicle controller job rating was so new, participant experience with MOCU was minimal and varied from a few days to a few weeks. The training consisted of a 1-hour group instructional training session, followed by a 1-hour hands-on training session. A think-aloud protocol was used to capture the users' thought and decision-making processes while attempting to perform basic mission tasks.

Initial findings suggested that the design was at high risk for modal errors, given multiple modes and lack of adequate visual or auditory feedback as to what mode the USV is currently in. Numerous errors of both omission and commission were observed. Additionally, HCI navigation to access the required functionality was often difficult. These concerns were given top priority in subsequent modification and redesign. A full review of the findings and recommendations of this evaluation are provided in Kellmeyer and Bernhard (2009).

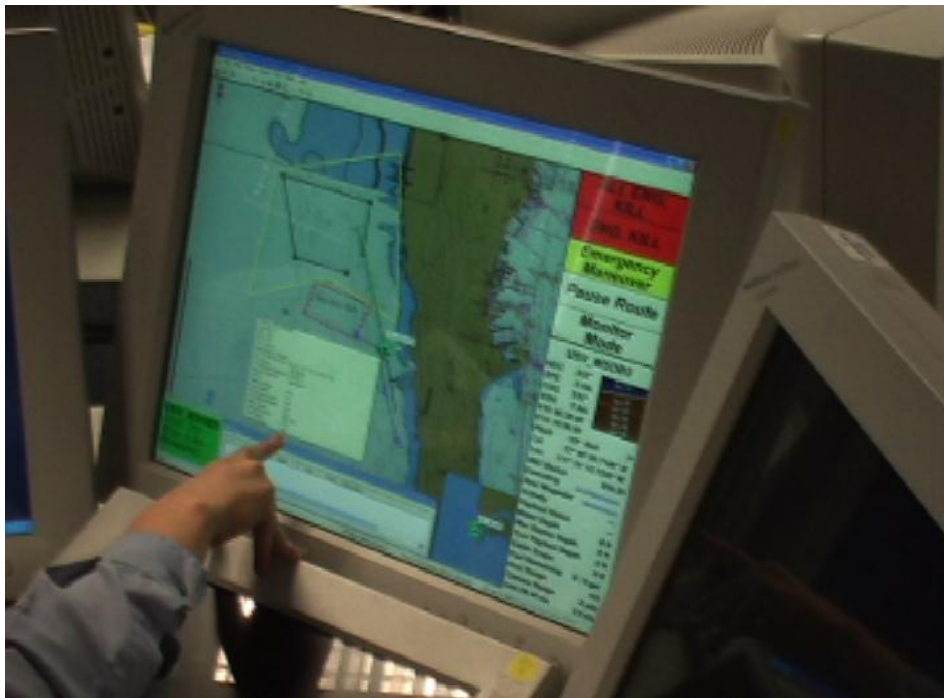


Figure 6. Usability Test Display for MOCU Baseline Study.

4.2 MOCU INTERMEDIATE DESIGNS

Based on the initial results from the heuristic review, several design concepts were explored, aimed at resolving many of the HCI issues identified. Examples are discussed below.

4.2.1 MOCU Preliminary Design Wrap-Around Format

Following the MOCU re-architecture in FY 08, FY 09 was devoted to building an advanced human-computer interaction format using the new architecture. In April 2009, the first live demonstration was conducted in San Diego Bay illustrating USV monitoring and control. Figure 7 shows a screen capture from MOCU during the operational demonstration. Personnel were located on the USV for safety purposes. The USV was launched and landed at the Shelter Island Marina and the demonstration site was located near Ballast Point at the Naval Submarine Base Point Loma. The demonstration showed that it was possible in real-time to dynamically orient a map, radar returns, and wrap around 360-degree camera views in an integrated visualization. A movie of the demonstration was delivered to ONR.

The 3D perspective map shown in Figure 8 correlated visually with a wrap-around video perspective view. A concise user interface specification was prepared that incorporated task-centered design principles with visual integration and attention management principles. The April demonstration with initial integration was a first step toward a concise design integration incorporating these principles. Figure 8 shows a concept visualization of the integrated display, representing the next phase in design leading toward MOCU v3.

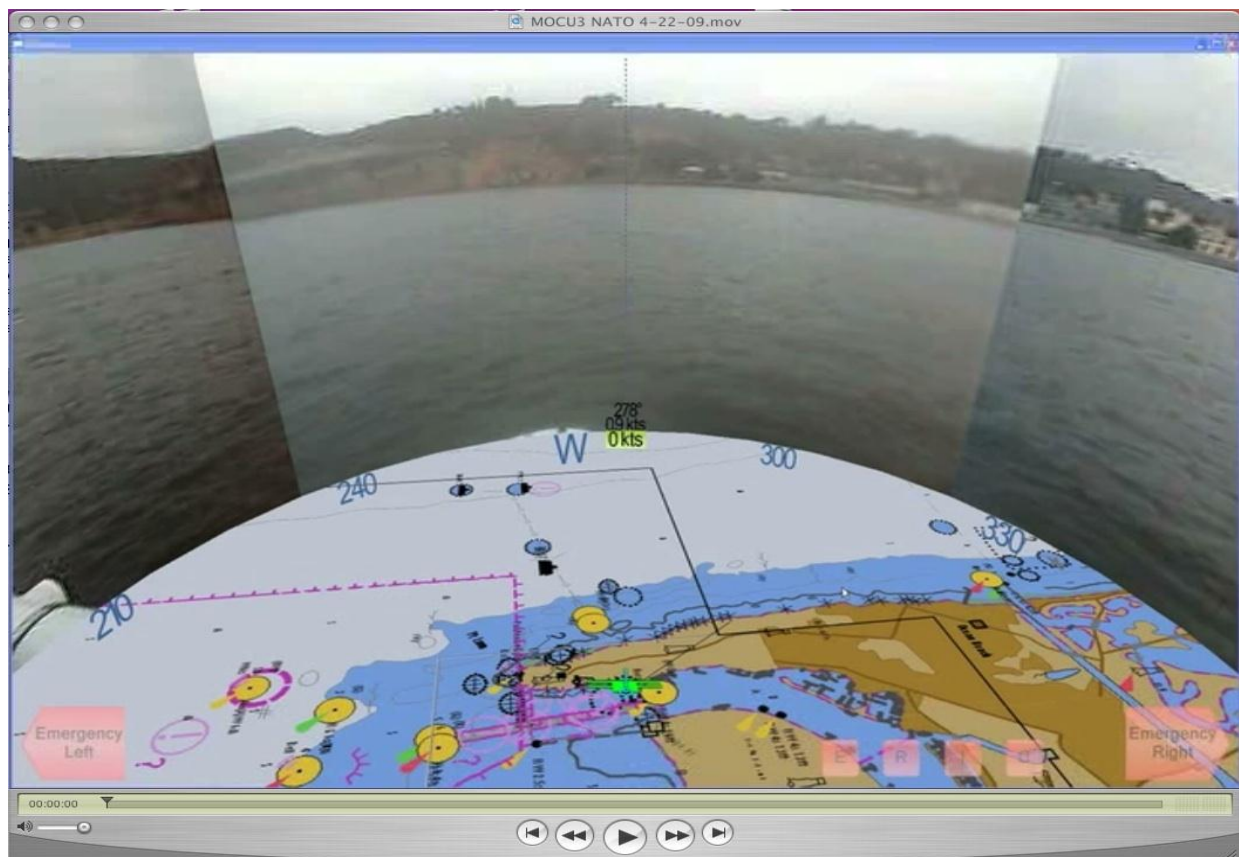


Figure 7. Screen Capture from 2009 Live USV Demonstration with Initial Map-Video Integration.

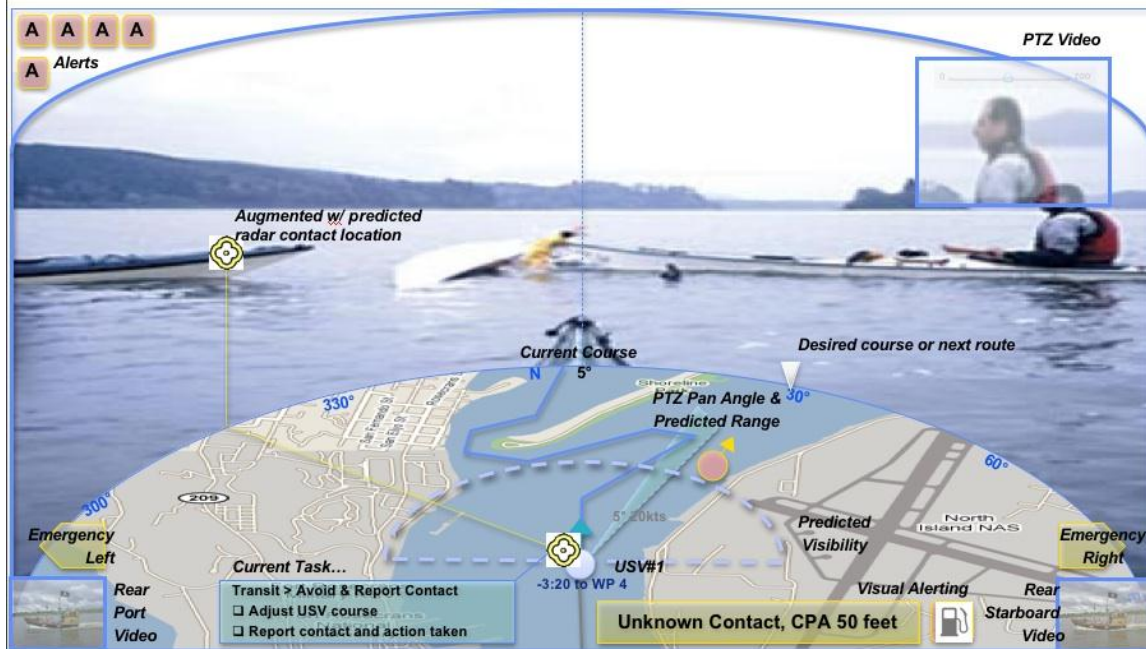


Figure 8. Integrated Display Visualization Design Concept for Advanced MOCU.

This design concept contained several important design features not found in today's state-of-art robotic user interface systems. First, radar-detected surface contacts were visually integrated with information on the video wrap-around display. Next, the task-centered approach shows current and planned tasks correlating these with voice reports prepared for delivery to the warfare commander. Thus, the interface supports the USV use in the context of the mission process and mission plan. This is distinctly different than designing an interface to "just operate a piece of equipment." In this concept, the pan-tilt-zoom (PTZ) camera is also shown as an overlay on the wide view cameras. The interface is interactive and the user can drag and relocate icons to change the view. Also, a visual model is superimposed on the map, indicating to the user the estimated visual range such that objects in view or beyond detection can be more easily estimated. Critical mission events are also shown, such as the "unknown contact" indicated. Software implementation for the next versions of MOCU captured many of the design concepts shown in this initial concept.

4.2.2 Preliminary Designs for Graphics and Audio

Initial guidelines were developed for several critical user situation awareness and robot control visualization tools. This included route monitoring and reporting graphics as shown in Figure 9. The graphics were implemented in MOCU v3 and not only depict critical events in the mission, but also indicate to the user a connection between the mission plan, current status, and upcoming tasks such as reports and decision points during the mission. A next step in design was the integration of the route and task graphics with the robot control modes. Figure 10 shows the specifications developed for each of the robot control modes. This includes route following mode, vector mode, and manual mode. This design feature addressed gaps in modal situation awareness that were found to be a critical problem in the first usability test conducted with Baseline MOCU in FY 08 (Kellmeyer,

	A	B	C	D	E	F	G
	Item Name	Description	Click	Double Click	Right Click	Roll-Over	Drag
1	180 Video Display	Shows 180 degrees of the fixed video camera. In the simplest for could show Front, Port, Starboard, Rear views. Now will require the stitching of 3 cameras. Desire to be able to center the 180 degree view on any angle. Begin with the height of the video at the center being the native vertical resolution of the video (240 pixels?).	display a pop containing estimated bearing and distance.	Centers the video on the angle of the click.	pop-up menu actions: pan PTZ to this location, mark on DNC map, snap back to forward view.	no action	Spins the 180 fixed video view. The course ring and map all to rotate also. In our paradigm up is always the direction of the fixed video being shown.
2	Fixed Video & Map Border	A line that separates the video from the map. Darren indicated that this might have to be taller than a line to hold the course numbers now shown on the map.	no action	no action	pop-up menu actions: full map view, full video view, standard view	Show sizing widget (double arrow)	Adjusts the ration of the Video vs. the Map
3	Estimated object position	Displays the estimated location in the video of a know object (DNC), a suspected object (radar or other sensor), or user defined object (ex. Hazard placed on the map). Should be able to accurate display the bearing, will need to estimate the distance (vertical location in video). Use MIL-STD 2525 symbology. May elect to add a vertical bearing line up the entire video depending on how accurately we can predict distance or if distance is not known.	Selects object, detailed pop up about known information	Center fixed video on this object.	pop-up menu actions: center PTZ, track w/ PTZ, hide	pop-up with basic object information	can not drag object within fixed video (may allow to drag to other locations like PTZ camera)
4	Video detected object	This shows an area where an object might be based on video object detection. Make this area brighter in the video. May extend a line of bearing down to the map.	select, see any details if the system has an estimate on size, bearing, distance, object type	Center fixed video on this object.	pop-up menu actions: center PTZ, track w/ PTZ, hide	pop-up with basic object information	can not drag object within fixed video (may allow to drag to other locations like PTZ camera)
5	PTZ camera window	Window to show the PTZ camera video. Located w/ the top center of the PTZ window on the top of the fixed video window at the bearing the PTZ is pointed. If the bearing of the PTZ is outside the current 180 fixed view then locate in the top left or right corner (use right if showing rear view). Show dotted line on map for bearing angle if PTZ outside current 180 fixed view.	no action	zoom in	pop-up actions: maximize, minimize, default, zoom, camera adjustments, show/hide zoom, show/hide transparency	place cross-hair in fixed video and on the map where we estimate the cursor to be. Make less transparent (25%)	Change the bearing of the PTZ camera
6	PTZ zoom widget	Transparent slider in the PTZ window. Place on the left side. Initially set to 75% transparency.	adjusts zoom	no action	hide zoom	make less transparent (50%)	Drag the slider to adjust the zoom level
7	PTZ transparency widget	Transparent slider in the PTZ window, lace on the bottom, nitally set to 75% transparency. Controls the transparency of the PTZ video window. Default is not show. If show default to 50% transparency.	adjusts PTZ video transparency	no action	hide transparency widget	make less transparent (50%)	Drag the slider to adjust the transparency level
8	PTZ Window Controls	Transparent controls for min, max, standard. Not allowed to close. Default transparency of 75%.	Sets window to Min, max, or standard size	no action	no action	make less transparent (50%)	Standard window resize widget in all corners. Only adjust w/ constant image ratio.
9	Rear Port & Starboard 90 degree fixed videos	Shows video for the next 90 degrees fixed video not shown in the forward 180 fixed video. Located at bottom left and right corners of the display. Default to 50% transparency. Quarter size of native video resolution (160x120, 80x60?).	no action	Turn forward fixe video 90 degrees in that direction	min, max, standard size	make less transparent (25%)	no action
10	Rear Window Controls	Transparent controls for min, max, standard. Not allowed to close. Default transparency of 75%.	Sets window to Min, max, or standard size	no action	no action	make less transparent (50%)	Standard window resize widget in top left corners. Not allowed to move window from bottom corner.
11							
12							
13							
14							
15							

Figure 12. Sample Page from Video Worksheet of the Advanced MOCU Specifications.

The attention management schema developed for MOCU under this project prescribes integrated auditory cues with gender-specific voices used to represent each robot (one male voice and one female voice). A demonstration held in concert with our April demo for a visiting NATO robotics group illustrated the use of Cepstral voice patterns for the Army robots at Fort Ord test facility near Monterey, CA. These voice models were subsequently purchased and incorporated into MOCU. A voice feedback library was then developed and mapped to the Cepstral synthetic speech output¹. Figure 13 shows a sample page from the USV alert taxonomy that was used as a template for deriving the specific alert messages that were subsequently incorporated using synthetic auditory speech methods. Audio cues were not included in MOCU v3.0 version but were added to Version 3.1 for the final usability test.

¹ See <http://cepstral.com/> for further information on Cepstral products.

Taxonomy of Alert Messages for USV User Interface			
Category	Sub Category	Message Content	Examples
1. USV System Status	1.1 Propulsion	Caution / Abnormal <u>Cond.</u>	Starboard engine high temperature.
	1.2 Navigation and Control	Warning / Action <u>Rqd</u>	Port fuel tank empty.
	1.3 Communications	System Failure	Unable to make contact.
2. Object Contacts	2.1 Stationary Objects	Bearing / Distance	Stationary object bearing 60° NE at 500 yards.
	2.2 Moving Objects	Collision Potential	CPA 300 yards.
	2.3 Known / Unknown		Warning, collision in 20 seconds.
3. Environmental Conditions	3.1 Sea State	Caution / Warning, 1-5	Warning- sea state four conditions.
	3.2 Wind	Speed / Direction	Wind from SE at ten knots.
	3.3 Visibility	Miles / yards / feet	Visibility 500 yards.
4. USV Location	4.1 Proximity to Waypoints	2 minute / 1 minute	Approaching waypoint two in 20 seconds.
	4.2 Proximity to Mission Area	20 Seconds / Arrival	Approaching mission area in two minutes.
	4.3 Proximity to Ship - Recovery	Yards to	Vessel has entered recovery zone.
	4.4 Proximity to Ship - Launch	Yards from	Vessel is 200 yards from stern
5. USV Course / Speed Changes	5.1 Upcoming Course / Speed Changes	2 min / 1 min / 20 sec	Programmed heading change to 90° E in 20 <u>secs.</u>
	5.2 Confirm Course / Speed Changes Completed	New heading / speed	Heading change to 90° E confirmed.
	5.3 Confirm USV at Idle Speed	Yes / No	Vessel at idle speed.
6. Sensor Status	6.1 Confirm Deployed	Yes / No	Sensor has been deployed.
	6.2 Confirm Recovered		Sensor has been recovered.
	6.3 Sensor Depth	Feet / Fathoms	Sensor depth at 50 feet.
	6.4 Activation	Yes / No	Sensor is activated and transmitting.
	6.5 Tow Speed	Delta fr Min Tow Speed	Warning, increase tow speed 3 knots.
	6.6 Module Health	Snagged / Lost	Warning, bottom snag detected.
7. Control Mode Change	7.1 Confirm change to Manual Control	Yes / No	Vessel under manual control.
	7.2 Confirm change to Auto Mode		Vessel in auto mode, proceeding to waypoint 3.
	7.3 Confirm change to Vector Mode		Vessel in vector mode, heading 90°E.
	7.4 Confirm change to Sea Keeping Mode		Vessel in sea keeping mode.
	7.5 POCO Control / OOV Manual Control		Handoff to POCO control successful.
8. Event Report Prompts	8.1 ID Reportable Events in Mission Planning	Yes / No	Give status alert message, followed by "Report"

Figure 13. Sample Page for Developing USV Audio Alert Messages.

4.2.3 User Feedback Preliminary Design

Users gathered to review paper wireframe designs of the preliminary “wrap around” design concepts in August 2009. Four ASW Sonar Technicians, all of whom had received training and had some experience in operating USVs for ASW, made up the review team. Operators expressed several concerns regarding the overall concept of the integrated display, including:

- Loss of video data (only about 75%) of 360-degree field they currently have.
- Want 90-degree direct starboard/port views “to see anything coming at them from the side.”
- Concerned about video distortion from video wrap.
- Want a larger rear view mirror – maybe stretched across bottom of screen.
- Loss of SA when digital nautical chart (DNC) moves relative to USV heading.
- Of paramount importance is location of LCS home ship to quickly orient to its location.

4.2.4 Preliminary Design Conclusions and Results

Results from initial user interviews with the “wrap around” design resulted in decisions to consider re-design and orientation of the map (chart) components of the HCI. The initial design considered the map view and orientation as aligning and integrated with the video. The user’s perspective for the map was noted as not being from the USVs point-of-view, but from ownship orientation and the USV being a separate off-board vehicle/sensor. This perspective aligns with an overall command and control larger area point of view, and less focused on the immediate robot locale. The comments noted on video prompted the design for MOCU v3 to include integrated PTZ and rear-view cameras,

combined with the front and side views. User feedback with respect to alarms and warnings prompted the use of summary warnings for equipment alerts, and avoidance of audio alarms for v3.0.

4.3 MOCU V3.0 AND 3.1 DESIGN

FY 10 and 11 work focused on continued software development of MOCU based on human factors guidelines developed in FY 08 and FY 09 and usability tests conducted in FY 09. The MOCU components included video (360-degree view, rear view, PTZ), mission plan graphics, map/geographics, task and event indicators, and post mission analysis. Significant changes in design included:

- Relocation and re-design of map and video windows
- Re-design of alerts and alarms
- Enhanced display of route status
- Integration of contact location and video
- Re-design of the PTZ camera display and controls
- Adoption of a game hand-held controller device
- Procedure re-design
- Vehicle and mission status information

Figure 14 shows the overall HCI design changes that were made from Baseline MOCU v2 to MOCU v3. The left side of the figure shows the upper and lower displays for MOCU Baseline V2 and the right side shows the same displays for MOCU v3.

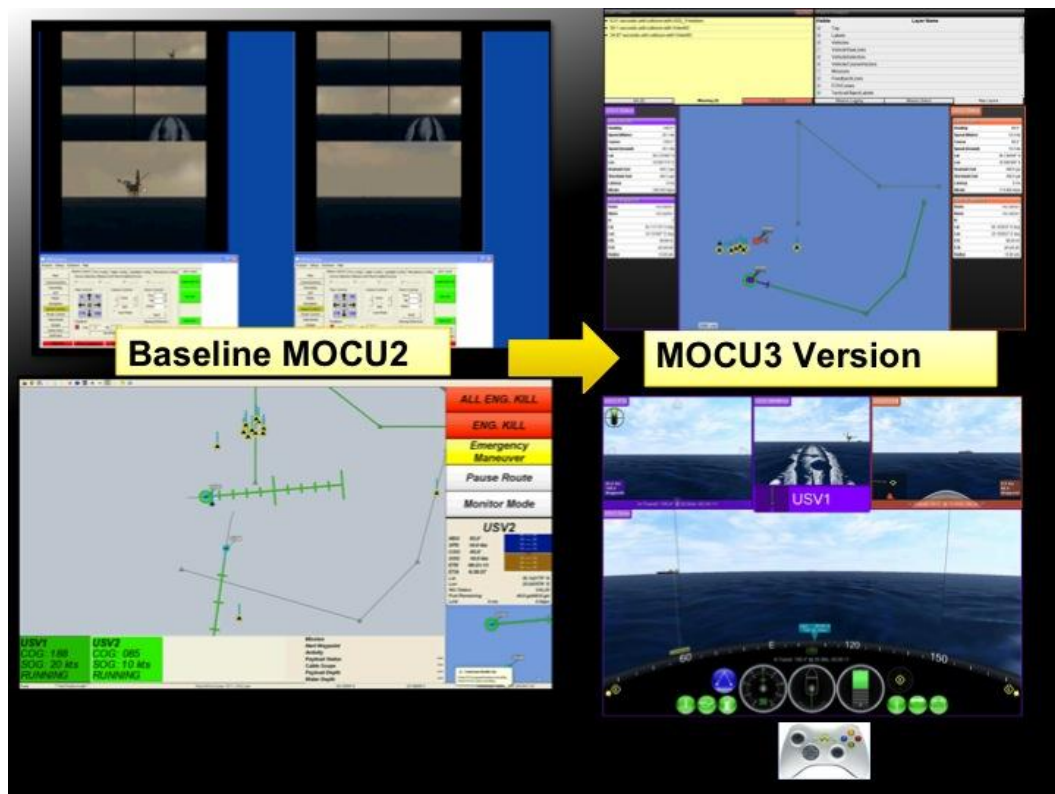


Figure 14. HCI Design Changes Made from MOCU v2 to MOCU v3.

4.3.1 Video and Map Display Re-Design

The relative visual focus time shared between video and map displays favored the most frequently used display being in the primary lower display position. Thus, the video camera images were moved to the lower display in MOCU v3 as shown in Figure 15. The map information was moved to the upper display. The video information was also rearranged due to confusion about camera image content. Figure 16 shows the baseline configuration of the video feeds for MOCU v3 design. The port, forward, and starboard camera images are “stitched” together, configured left to right to provide a 180 degree windshield type view. The aft view was placed top center of the lower display, similar to the placement of a rear view mirror in an automobile. This redesign follows basic human factors principles of orientation and compatibility of displays with the information spatial orientation.

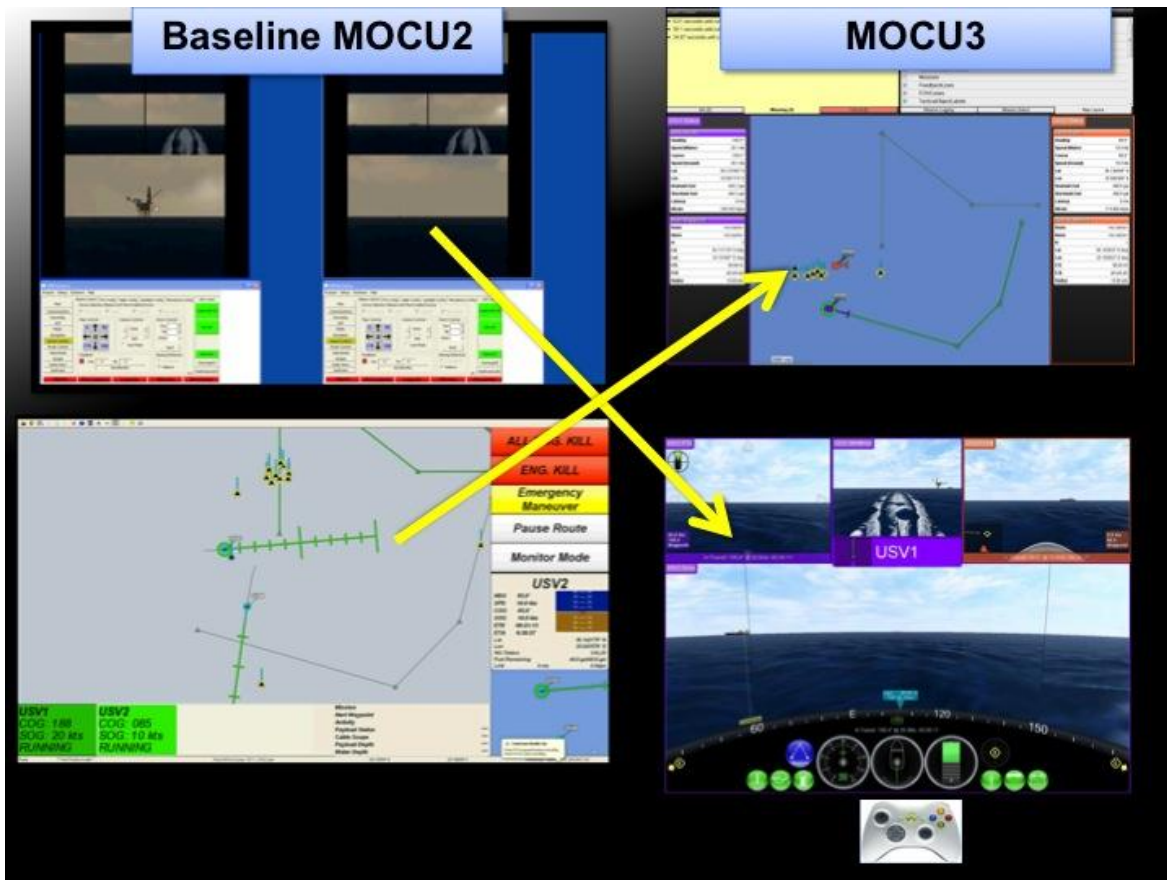


Figure 15. Replacement of Video and Map Information MOCU v2 to MOCU v3.



Figure 16. Rearrangement of Video Forward and Aft Video Feeds in MOCU v3.

The PTZ camera view was placed in the upper left portion of the lower display in MOCU v3 as shown in Figure 17. The PTZ, aft view, and forward view are all shown for the USV in primary control/view. The “secondary” USV shows the forward view in upper right (colored with orange border).

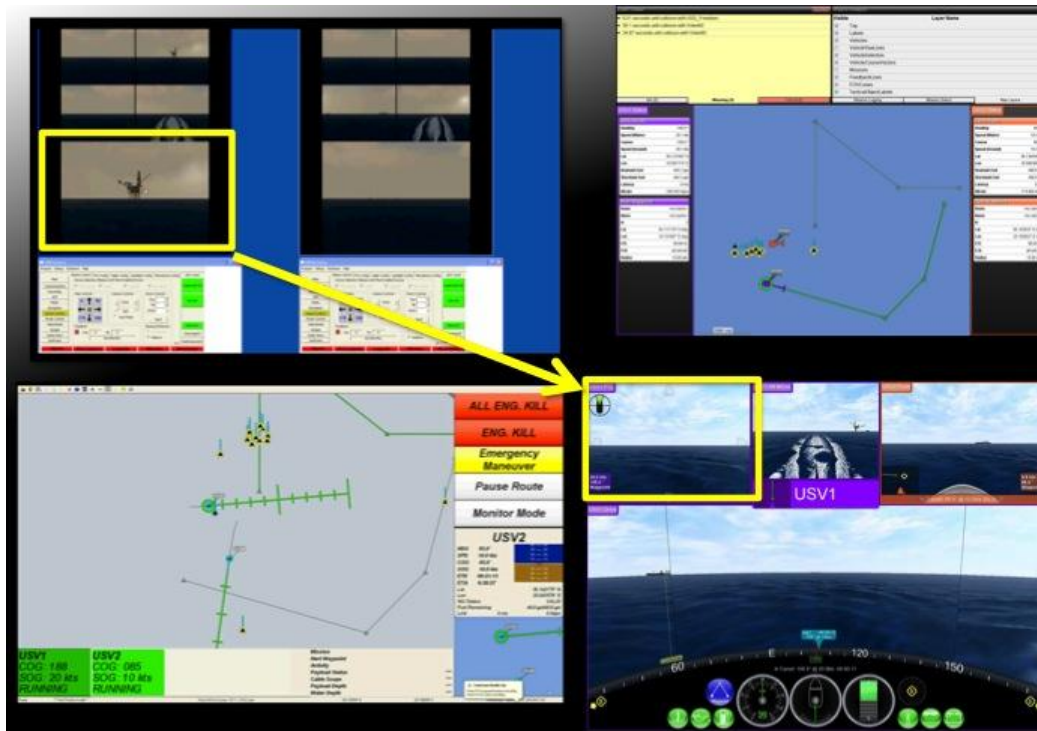


Figure 17. Relocation of PTZ Camera View in MOCU v3.

Further changes were made to the arrangement of the video windows following usability testing of v3. In v3.1, the secondary USV forward view was enlarged and the aft view was changed to toggle with the PTZ view. The ability to selectively hide the aft view was added based on feedback from

users that the constant movement and stream of the wake image in the aft view was distracting from other ongoing visual tasks. Figure 18 shows the v3.1 configuration.



Figure 18. Removal of Persistent Aft View Video and Enlarged Secondary USV Forward View in MOCU v3.1.

4.3.2 Alarms and Alerts

Alarms and alerts are used in the design to communicate equipment and mission status event changes to the operator. Figure 19 shows the location of the alarms in MOCU v2 and an example of a red flashing equipment alarm in the right side of the screen. Note, however, the inconsistent use of color coding with five buttons along the bottom of the screen also colored red during normal operations. In MOCU v3, the alarm indicators were distributed with an icon shown on PTZ view and also on the central control dashboard.



Figure 19. MOCU v2 Alarm Presentation (top) and MOCU v3 Alarm Graphics (bottom).

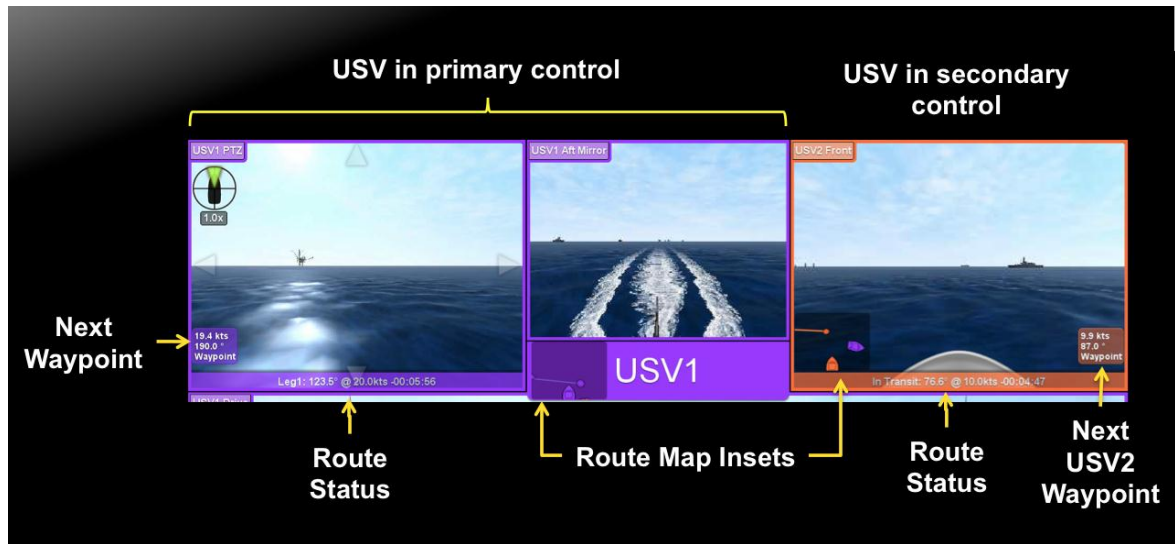
Results from usability testing for MOCU v3 indicated that a higher alerting cue saliency was required for the alarm information. A combination of increased visual cues and auditory information was added to the alarm indicators in v3.1. Figure 20 shows the visual changes to the alert indicators for v3.1. The visual alerting cue was increased in size to cover the entire section of the window and flashed on and off. Auditory messaging was also added to MOCU v3.1, alerting the operator to system alarms, changes in driving mode, waypoint approach, and potential collisions. A female voice was used for one USV and a male voice used for the other USV. An example auditory report is “USV One, high engine temperature” as shown in the figure, paired with the large flashing icon.



Figure 20. MOCU v3.1 Alert Presentation with Visual and Auditory Cues.

4.3.3 Route Status Information

MOCU v3 also included indicators for route status, including upcoming waypoints. Figure 21 shows the locations for USV1 and USV2 notices in video and dashboard locations. The map inserts are shown in the figure for each of the USVs. Route and waypoint information is shown on the lower part of the dashboard, with the next mission plan item shown on the bearing it occurs. The purpose of co-location of route information with video is to reduce the number of visual scan shifts typically done between the video and map displays. In MOCU v3.1, the route information was enlarged and displayed more prominently within the video area as shown in Figure 22. Auditory alerts were also added to inform the operator of the USV approaching each waypoint.



Waypoint to port off camera



Route plan leg on bearing 106.4

Figure 21. Route Waypoint Information in MOCU v3 shown on upper dashboard and along compass heading.



Route Insets Shown for USV 1 (purple) and USV 2 (orange).



Waypoint Countdown Indicator at 200 yds.

Waypoint Countdown Indicator at 100 yds.

Figure 22. Route Insets (top) and Waypoint Countdown Insets (bottom) for v3.1.

4.3.4 Contact Location and Video Integration

Information integration is a design attribute used to decrease visual workload and increase information transfer efficiency. Contact and collision avoidance is a critical mission task and situation awareness for surrounding contacts a critical decision-support need. Sensor-derived contacts shown on map in MOCU v2 were integrated with video displays in MOCU v3 as shown in Figure 23. The bearing and range of the contact is known from radar information and the corresponding contact information is shown on the contact bearing within the wrap-around video feeds display. Also, indicators are shown in the lower right and left of display for the number of tracks out of sight to port or starboard directions.

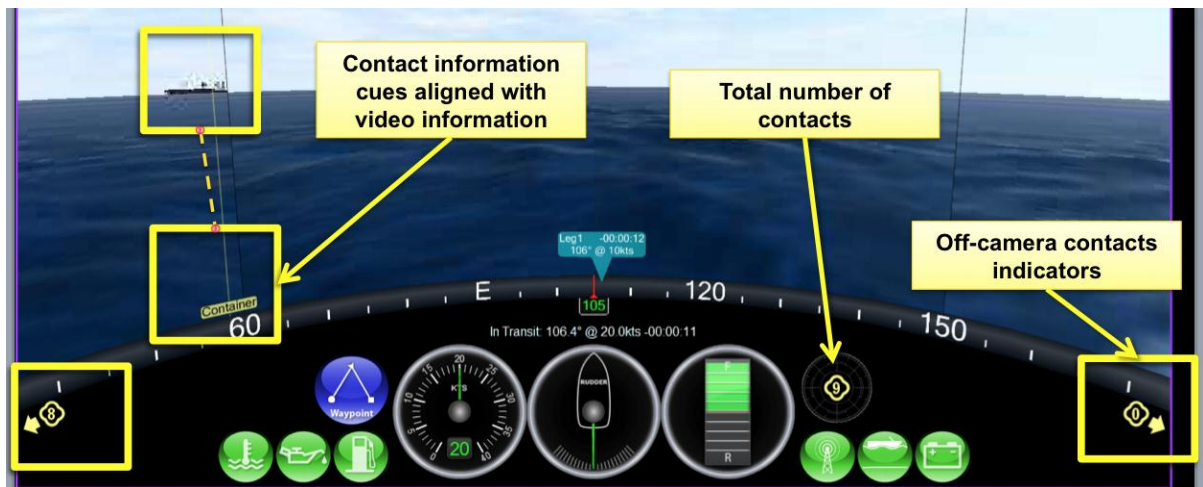


Figure 23. Contact Graphics Integrated with Video Information in MOCU v3.

4.3.5 USV Pan-Tilt-Zoom Display

MOCU v3 integrated on-screen camera controls with the camera being controlled. First, the PTZ camera could be controlled with on-screen arrows, as shown in Figure 24. The user could click and hold on the arrow controls to move the camera up, down, left, or right. A PTZ heading indicator was included in the design after observing users would leave the camera slewed to a port or starboard direction and later during camera re-use would think it was pointed straight ahead. The user could also use the camera joystick as described below. On the larger video displays looking port, starboard, and ahead, clicking and dragging the 360-degree camera tiled view rotates that view to port or starboard.

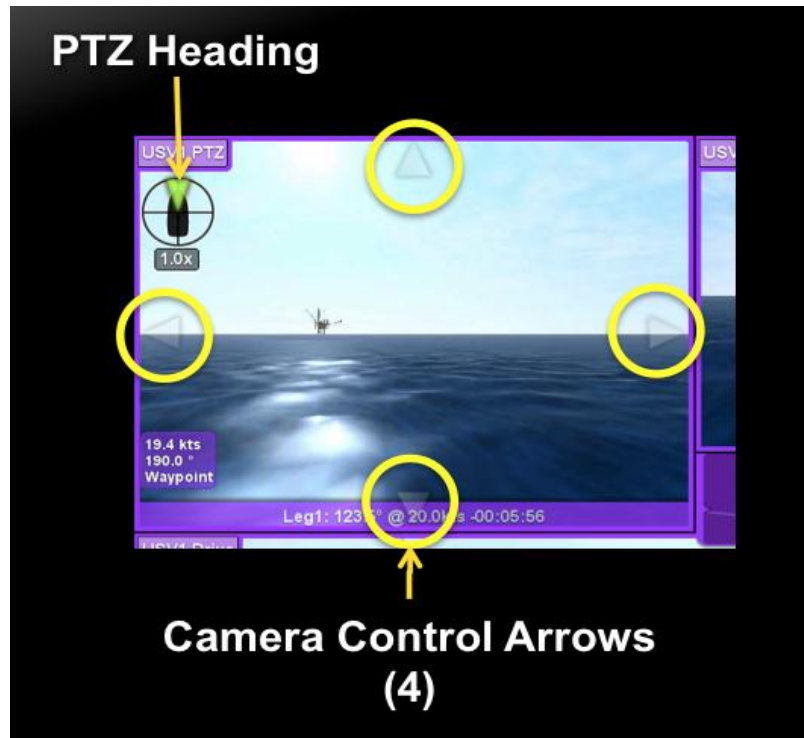


Figure 24. PTZ On-Screen Controls and Indicators.

4.3.6 Controller Interface

MOCU v2 required numerous and repeated point and click actions to conduct task sequences with the USV. For MOCU v3 and 3.1, an Xbox game controller was adopted and programmed to conduct many of the frequently repeated tasks conducted during a mission. Figure 25 shows the mapping of functions to the game controller interface.

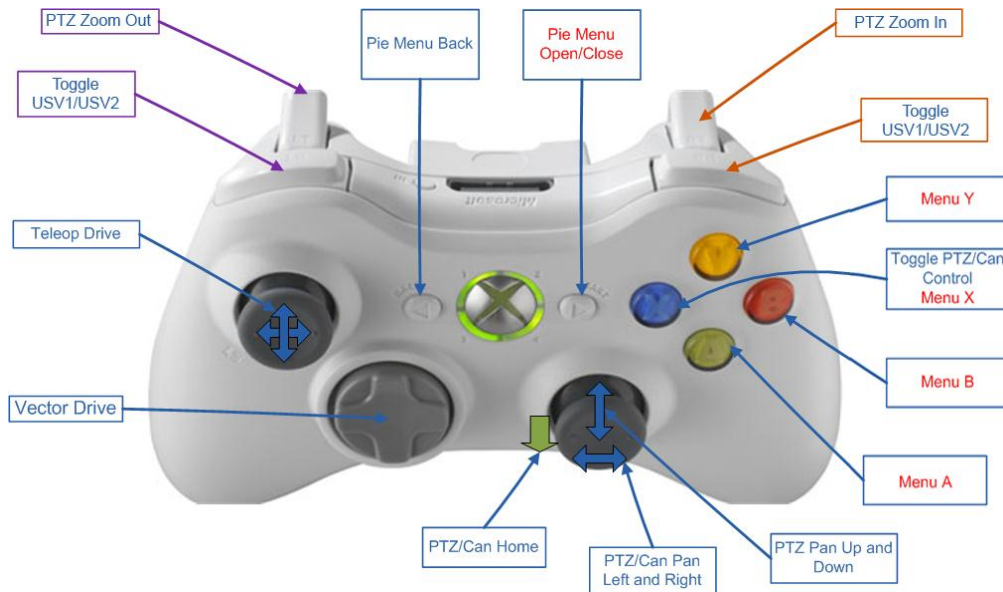


Figure 25. Functional Mapping with Game Controller User Interface.

Manual “driving” of the USV is performed in either Teleoperation Mode or Vector Mode. In MOCU v2, steering was performed by clicking on or dragging directional arrows. In MOCU v3 and 3.1, the left joystick and D Pad are used to control the direction of the vehicle in each of those modes. Movement of the left joystick immediately switches to Teleoperation Mode from either Vector or Waypoint Navigation. USV heading is then controlled by pushing the joystick in the direction of intended travel (forward, right, left, reverse). Speed is controlled by the distance the joystick is pushed from center position. As the joystick is pushed further in any direction, the speed increases. When the joystick is fully released, the USV stays in Teleoperation Mode but coasts to a stop. Vector Mode is activated via any movement of the D-Pad control, which switches the mode to Vector Mode from Teleoperation or Waypoint Navigation. The north and south nodes on the D-Pad control speed (north = increase, south = decrease). Each momentary button press increases or decreases speed by 1 knot. Speed will continue to increase or decrease if the button is held in the depressed position. Direction is controlled by the east-west nodes on the D-Pad. The west node changes USV direction to the left (port). The east node changes USV direction to the right (starboard). Each button press changes the direction by 1 degree. Direction will continue to change if the button is held in the depressed position.

For MOCU v3.1, several refinements were made to the driving controls and functionality based on observations from the usability testing. Movement of the left joystick now overrides the current drive mode and temporarily puts the USV in Teleoperation mode. This was done to provide the operator immediate, manual control in the event of an emergency situation. As the joystick is pushed further in the selected direction, speed increases. When the joystick is fully released, the USV will revert to the mode it was previously in (Vector or Navigation) unless Teleoperation mode has been deliberately selected by depressing the joystick (push down). Heading is still controlled by moving the joystick in the direction of intended travel (forward, right, and left), but the ability to put the USV into reverse via the joystick was eliminated. In MOCU v3.1, the operator must deliberately select reverse from the transmission options accessed through the Pie Menu. This was done to eliminate the possibility of inadvertently putting the USV into reverse as was observed during MOCU3 usability testing. The sensitivity of the joystick for teleoperation was also reduced in MOCU 3.1 based on feedback received after simulator testing. Controls for Vector Mode driving remained the same for MOCU v3.1 as in v3.0.

The right joystick is used to control the onboard PTZ camera and will direct the camera left, right, up, and down. Pushing down on the joystick automatically returns the camera to the home position. This feature was added to MOCU v3.1, along with a camera position icon, after observing several instances of subjects failing to return the camera to the home position after use and losing situational awareness with regard to the camera image they were observing. The trigger buttons are used to control the zoom feature of the PTZ camera.

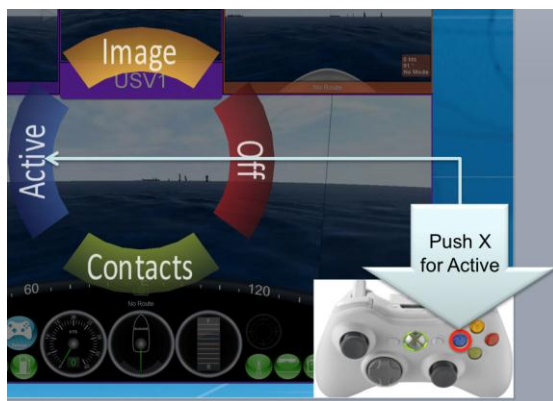
Many secondary controls are accessed via the Pie Menu that is opened and closed using the arrow buttons on the controller as shown in Figure 26. This approach allows the user to remember sequences by “feel and location” vs. conducting a visually focused cursor movement to a button or menu location during point and click. The user presses the Menu button and then A, B, X, or Y (green, red, blue, or yellow) depending on the desired menu selection. As shown in the figure, the user has selected “B” for Radar and “X” for Active, with the result shown on the radar graphic indicator.



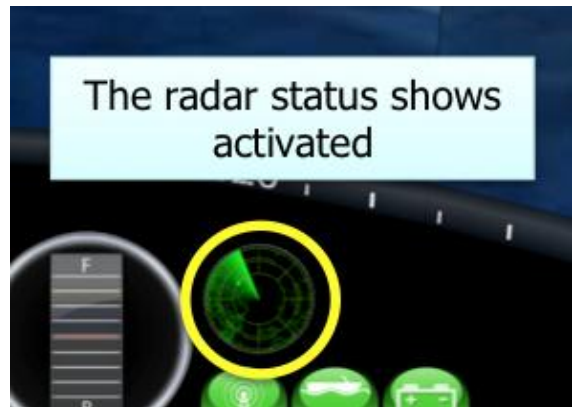
1. Press Pie Menu Button



2. Menu appears, press "B" for Radar



3. Press "X" for Active



4. Menu disappears and radar status is active

Figure 26. Typical Task Sequence with PopUp (Pie) Menu.

The Toggle USV controls shift the display focus as shown in Figure 27, with the primary focus USV being the subject of control manipulations from the controller. The secondary USV maintains a forward view camera while the primary USV has forward, PTZ, and rear views.



USV 1 in Primary Control (purple border)



USV 2 in primary control (orange border)

Figure 27. Shifting Primary Control between USV 1 and USV 2.

4.3.7 Procedure Re-Design

Procedure design affects usability and training. Complex and multi-step procedures inhibit efficiency of use and require a higher cognitive loading for memory. HCI procedures are also less efficient if they require constant hand-eye coordination such as point and click on display objects. If the objects are in a sequence that require movements from window to window or across screens, workload is further increased. Figure 28 shows a typical sequence for Baseline MOCU. Figure 29 contrasts this sequence with the MOCU v3 workflow.

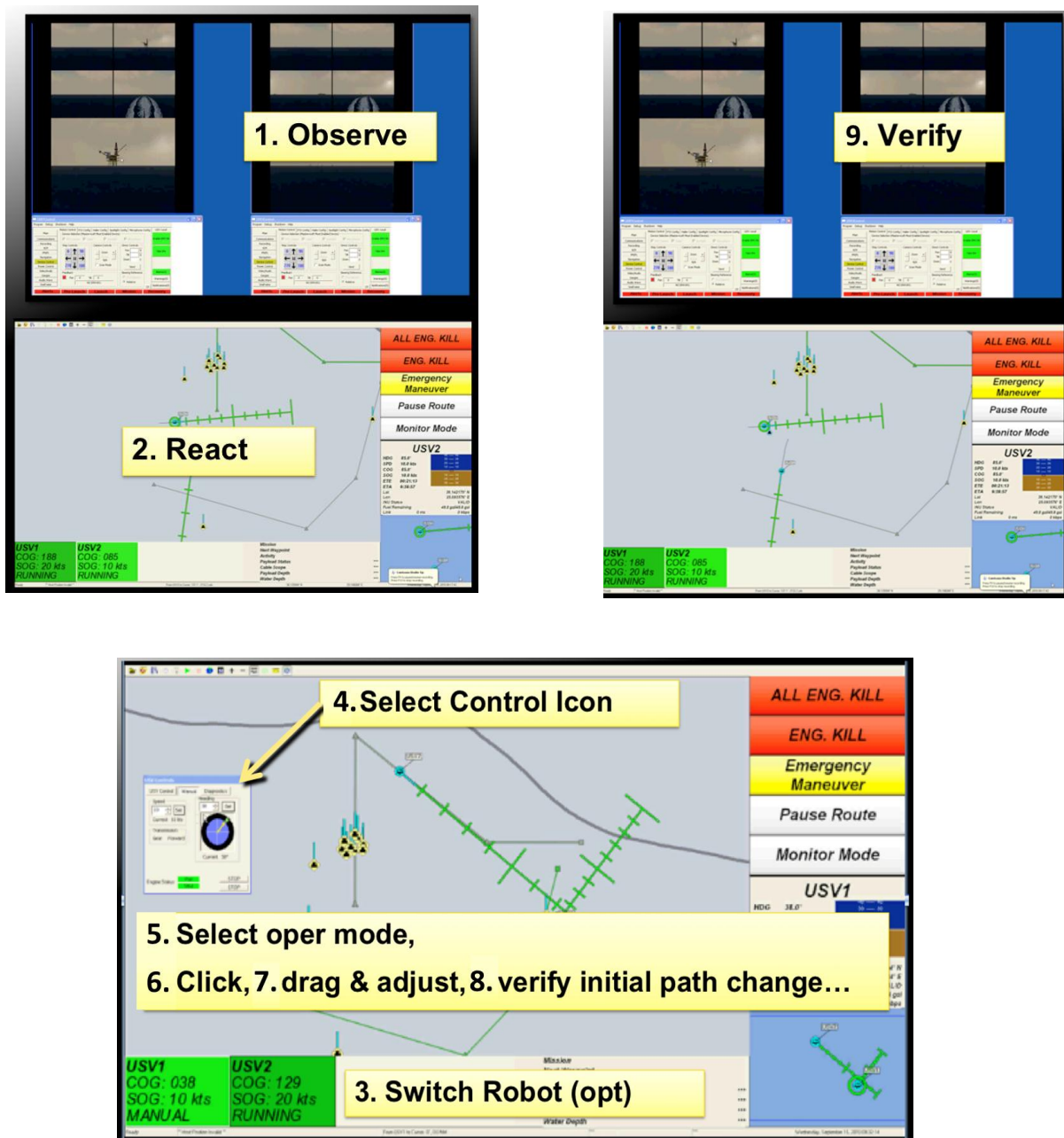


Figure 28. Baseline MOCU Task Procedure Sequence.

First, viewing the video screens the user sees something on video that requires an action controlling the USV. The procedure design requires that attention is then shifted to the lower screen where several point and click actions are needed (as shown in steps 3 through 8 in the sequence). Next, attention shifts to the upper screen to verify visually that the change is taking place. The sequence is cumbersome and requires significant reaction time to complete once a visual cue prompts the sequence.

In comparison, as shown in Figure 29 for MOCU v3, the user first views the visual item as in MOCU baseline; however, the forward views (e.g., for detecting possible collisions) are located on the primary lower display. The need to shift between displays is eliminated. Next, the user does not need to point and click on menus or controls on the screen to make an evasive maneuver. The controller provides hands-on control options while the visual focus can remain on the primary video windows. This allows for a continuous focus on critical visual information. Thus, “React” requires only a single control action on the hand-held controller. Observe and Verify become seamless and “React” requires no visual workload.

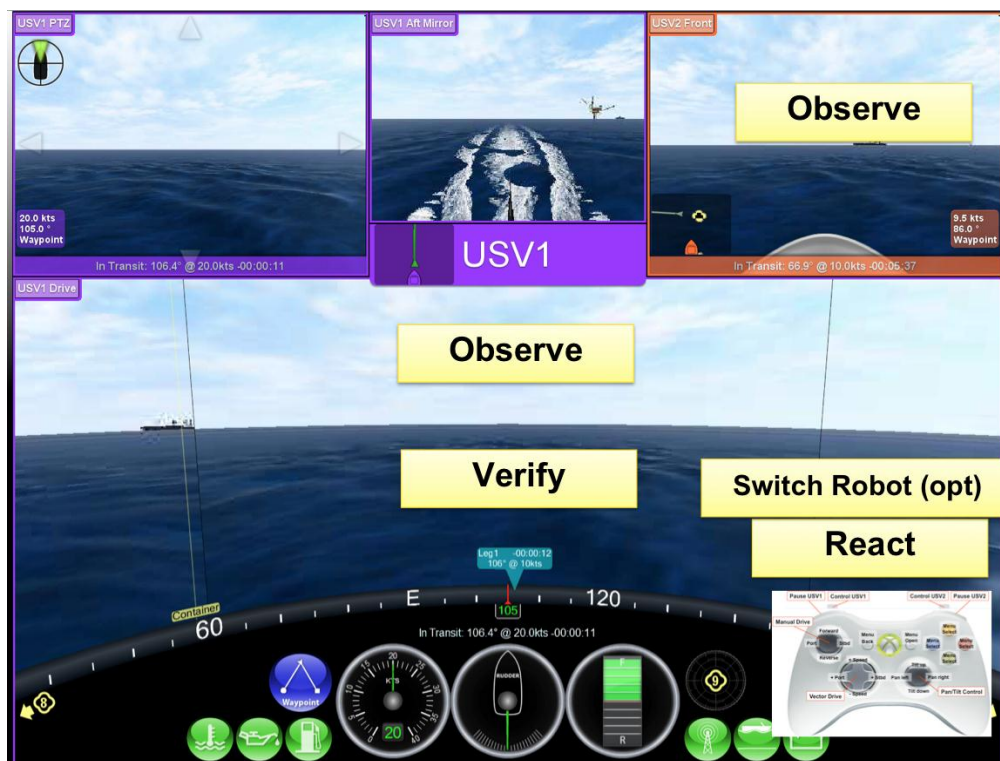


Figure 29. MOCU v3 Procedure Sequence Example.

4.3.8 Vehicle and Mission Status

For MOCU v3 and 3.1, windows were also added to the map (upper) display showing summary vehicle status information displayed on either side of the map, and mission status and analysis information, displayed above the map. Figure 30 shows the additional windows added to the map display. For purposes of the simulator usability testing described later, the Event Viewer and Mission Analysis windows were not active.

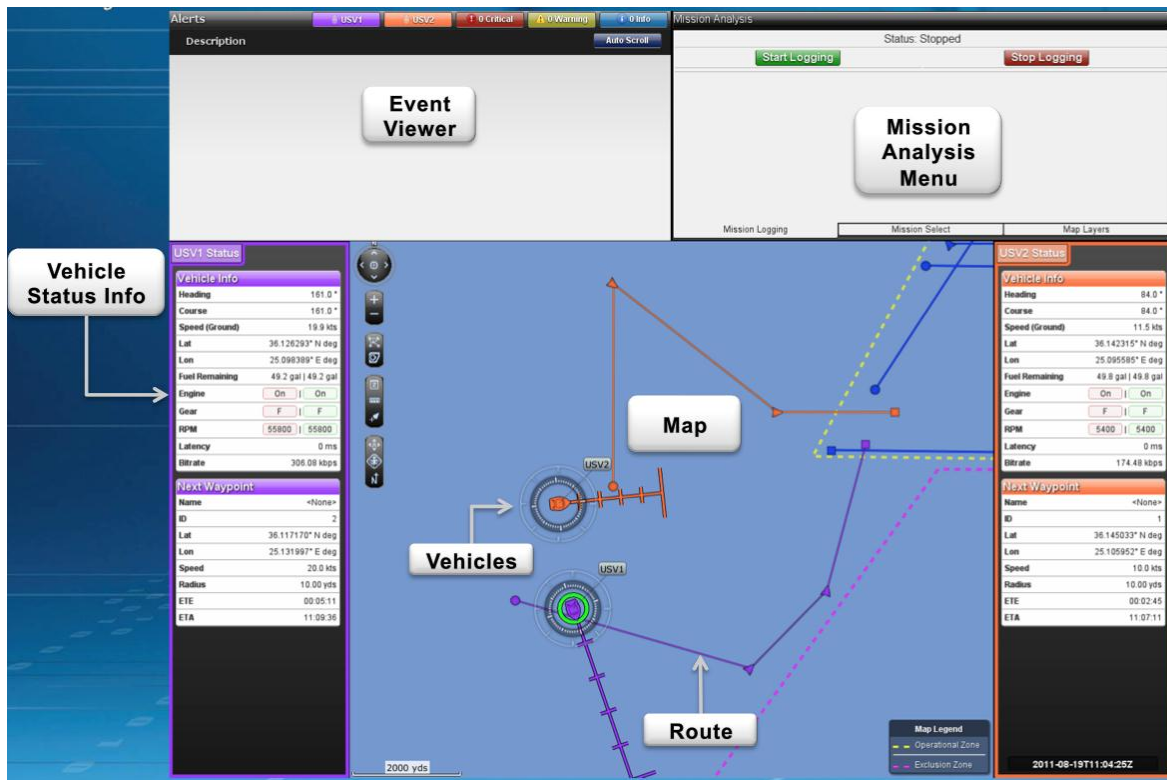


Figure 30. Upper Display Showing Vehicle and Mission Status.

5. HCI USABILITY TESTING

Following completion of the USV simulator that included the integration of simulated video into MOCU, a series of usability tests were conducted in which Navy operators performed USV operations during a simulated mission scenario. Performance was measured for operation of one USV as well as operation of two USVs. The results were used to derive conclusions about the design and recommendations for changes to be included in subsequent design iterations. Details of the simulator usability testing procedures and results are provided in the following section.

5.1 PURPOSE AND SCOPE

The purpose of the usability testing described here was to guide development of HCI enhancements to the MOCU design and to empirically evaluate operator performance using the new HCI designs against baseline versions. HCI evaluation was accomplished through collecting performance measures indicative of workload and situational awareness while conducting simulated missions in which USVs were deployed on a simulated mission. The study consisted of four phases of usability evaluation, corresponding to delivery of successive versions of the MOCU interface. Performance data and user feedback collected during each phase were used to guide HCI enhancements that were integrated into each subsequent MOCU version as previously described.

The focus of the initial testing (Phase I) was to establish a baseline level of performance for operating both a single USV and two USVs using the current interface and to determine whether the addition of a second USV would adversely affect operator performance. For operation of two USVs, only minimal revisions were made to the existing interface to allow for dual vehicle control. In essence, this constituted a side-by-side replication of the system status displays and video camera windows currently displayed for a single USV on one monitor and incorporation of the second USV on the overall Digital Navigation Chart (DNC) displayed on the second monitor. Based on conversations with USV subject matter experts (SMEs), this interface design was representative of the configuration that could be anticipated if operators were required to control two USVs “tomorrow.” Phase II of the study measured operator performance using the initial prototype interface design concepts incorporated into MOCU v3 compared to the Baseline MOCU interface. Phase III evaluated additional refinements incorporated in the MOCU v3.1 HCI design. Phase IV then evaluated the impact of HCI improvements made over the course of the project in controlling a single USV, comparing the Baseline HCI to a single USV version of the MOCU v3.1 interface.

5.2 PARTICIPANTS

Over the course of the project, 32 Navy enlisted personnel participated in simulator usability testing sessions. Distribution of subjects to experimental conditions was as follows:

- 2 USVs, Baseline HCI – 6 Participants
- 2 USVs, MOCU v3 HCI – 8 Participants
- 2 USVs, MOCU v3.1 – 10 Participants
- 1 USV, Baseline HCI – 4 Participants
- 1 USV, MOCU v3.1 HCI – 4 Participants

Most participants were assigned to one of the two mission package detachments that had been designated to operate USVs when they are deployed aboard USS *Freedom* (LCS 1). Ten were Sonar Technicians from the ASW detachment and 17 were Minemen from the MCM detachments. All participants were stationed in San Diego. Twenty participants had actual USV driving experience, but due to the newness of the position, less than half the participants had more than 10 hours, and

only four had operated a USV within the past 6 months. All participants had at least some small boat driving experience. Additional participants were involved in pilot testing that preceded formal usability testing phase to validate the mission scenario and refine the test protocol, including two Sonar Technicians with significant USV experience who assisted in validating the realism of the scenario. Participant demographics are shown in Figure 31.

Subject Number	Years Service	Job Specialty	Years in Rate	USV Hours	Simulator Hours	Recent USV Experience
1	13	STG	> 5	> 20	1-5	Yes
2	8	MN	1-2	> 20	> 20	No
3	8	STG	0	0	0	No
4	8	MN	2-5	5-10	10-20	No
5	10	STG	> 5	0	0	No
6	14	MN	> 5	5-10	5-10	No
7	7	STG	1-2	< 5	10-20	No
8	14	MN	>5	0	0	No
9	14	MN	>5	>20	>20	No
10	11	STG	>5	>20	0	No
11	11	STG	> 5	>20	<5	No
12	12	STG	> 5	>20	>20	No
13	16	MN	>5	5-10	<5	No
14	13	STG	>5	10-20	>20	No
15	13	MN	>5	<5	<5	No
16	11	MN	>5	<5	<5	No
17	12	MN	>5	0	<5	No
18	8	BM	0	0	0	No
19	12	MN	>5	<5	<5	Yes
20	4	MN	>5	<5	<5	No
21	16	SK/DV	>5	>20	<5	No
22	15	Cox	0	0	0	No
23	9	FC	0	0	<5	No
24	10	EngO	<1	0	0	No
25	8	STG	>5	0	0	No
26	7	STG	>5	0	0	No
27	8	MN	1-2	10-20	5-10	No
28	7	MN	>5	0	0	No
29	8	MN	1-2	10-20	5-10	Yes
30	15	MN	1-2	5-10	5-10	Yes
31	10	MN	3-5	10-20	10-20	No
32	12	MN	3-5	0	2-5	No

Figure 31. Subject Demographics.

5.3 METHODOLOGY AND TEST PROCEDURES

5.3.1 Mission Scenario

The usability testing consisted of each participant performing the role of USV operator in a simulated ASW mission scenario. The scenario required them to respond to a series of pre-determined conditions and events as they transited the USVs from the LCS host ship to the mission operations area. The scenario was designed to elicit performance of critical tasks derived from previous SME interviews, ranging from making routine reports to taking emergency actions to avoid collision with other vessels in the immediate area. The test scenario ran on a PC-based simulation program developed by SSC Pacific's Unmanned Systems Group that incorporated video graphics from a customized nautical gaming simulator with the MOCU-based user interface displays and controls. Although not all MOCU functionality was available in the simulation, feedback from the participants regarding the level of fidelity was quite positive. The scenario script is provided in Appendix A.

5.3.2 Performance Measures and Data Collection

For each critical event (CE) in the scenario requiring an operator response, an expected course of action (COA) was defined along with criteria for successful completion. These COAs constituted the decision support focus for performance metrics on speed and accuracy, and were listed next to each initiating event on the facilitator's scenario script that also served as the data collection form. As the scenario progressed, the facilitator noted whether the participant executed the correct course of action for the CE. In some cases, the response was time dependent and had to be performed within a specified window to be considered a correct response. The facilitator also recorded any comments made by the participant or observations made that provided additional context to the COA selected by the user for each event.

5.3.3 Participant Welcome and Background Questionnaire

Upon arriving at the site, participants were greeted by the researchers and thanked for their participation. The researchers presented an overview of the project explaining the purpose of the study and the participant's role. Participants were told that the objective of the study was to evaluate the user interface and was not a test of his or her skills. Each participant was assured of the confidentiality of the results and that their participation was strictly voluntary. After agreeing to continue their involvement in study and signing the Voluntary Consent form (Appendix B), each participant completed a brief Background Questionnaire designed to obtain information regarding the participants' overall military service experience as well as experience specific to USV operations. The Background Questionnaire is provided in Appendix C.

5.3.4 MOCU Orientation and Practice

Although most participants in the formal usability study were assigned to mission package detachments that were expected to deploy USVs, a significant number of individuals had only been recently assigned and had not yet operated a USV. Also, there are some minor differences between the MOCU interface for the ASW and MCM mission packages. To ensure that all participants had a basic understanding of the specific MOCU interface used in the study, a brief (approximately 30-minute) training session with hands-on guided practice was conducted prior to the actual test. The training also addressed differences between the simulator and the actual system. An outline of the training protocol is provided in Appendix D.

5.3.5 Usability Testing

Upon completion of the training and practice session, the facilitator read the mission briefing to each participant that described the nature of the mission as well as the communications protocol between the facilitator, who played the role of the Mission Supervisor, and the participant, who performed the role of the USV operator (See Appendix E). The briefing also included instructions calling for the USV operator to make periodic reports to the Mission Supervisor throughout the course of the mission, including waypoint achievement and sighting of any contacts along the route.. After answering any questions the participants had, the mission was initiated by the facilitator directing the USV operator to “Take control of USV 1,” followed by instructions to “activate radar and proceed to the first waypoint in vector mode.” A second researcher located out of sight from the participants acted as the simulator operator, controlling the timing of initiating events such as alarm activation and directing other boat traffic. Figure 32 shows a subject seated at the workstation during usability testing.



Figure 32. Subject at MOCU Simulation Workstation.

5.3.6 Exit Survey and Debrief

On completion of the testing, participants were asked to complete an Exit Survey that asked questions designed to elicit subjective feedback as to how well the interface supported the operator in performing the mission. The participants were asked to agree or disagree with a series of statements about MOCU's effectiveness and intuitiveness for navigation and control tasks. A 5-point Likert-

style rating scale was used to measure participants' responses, with the scale ranging from 1, "Strongly Disagree," to 5, "Strongly Agree." Open-ended questions were also included asking for participants suggestions on improving various aspects of the interface. This was followed by a debrief session in which the facilitator was able to gain further understanding of certain actions taken (or not taken) by the participant USV operators. The Exit Survey is provided in Appendix F.

5.4 RESULTS

5.4.1 Data Analysis

For each experimental condition, pass/fail performance on critical tasks was determined based on the subject's course of action during the mission scenario. For data analysis and description purposes, related critical tasks were grouped into the following five task domains: USV System Control, Waypoint Reporting, Contact Reporting, Collision Avoidance, and System Alarm Response. Each task domain was made up of six to eight related or recurring tasks constituting N trial opportunities for pass/fail data points for each subject. Pair-wise comparisons were made within each task domain and for the total tasks between: MOCU v1 and MOCU v2 (Phase I), MOCU v2 and MOCU3 (Phase II), MOCU v3 and MOCU v3.1 (Phase III), and MOCU v1 and MOCU v3.1 for a single USV only (Phase IV). For each condition, the number of passes and fails for N trials were computed and used to generate a probability of success and a probability of failure. Given the total number of trials for each task domain, p and q were used to generate an expected number of passes and failures for the comparative condition. The expected number of pass/fails were then compared to the obtained number of pass/fails for that condition.

In order to test whether the obtained number of pass/fails were significantly different than the expected number of pass/fails, three statistical tests were carried out. A χ^2 test was first computed. In cases where there are only two outcomes, it can be shown that $\chi^2 = z^2$ and that:

$$z^2 = \chi^2 = \frac{(f_{e1} - f_{o1})^2}{f_{e1}} + \frac{(f_{e2} - f_{o2})^2}{f_{e2}}$$

Taking the square root then generated a z-score for each trial. The z-score in this two alternative outcome is an approximation of the binomial distribution. A Yates correction was then applied, giving the following equation:

$$\chi^2 = \left[\left(\left| \frac{f_{e1} - f_{o1}}{f_{e1}} - .5 \right| \right)^2 / f_{e1} + \left(\left| \frac{f_{e2} - f_{o2}}{f_{e2}} - .5 \right| \right)^2 / f_{e2} \right]$$

Lastly, given the p and q for each task domain within each version of MOCU, the probability of obtaining the observed number of passes and failures in each comparative MOCU condition of MOCU was computed with the binomial distribution.

5.4.2 Phase I – One USV vs. Two USVs with Baseline HCI

In Phase 1, subjects controlled either one USV or two USVs using the Baseline MOCU HCI in both conditions. The results of the Phase 1 Baseline testing are shown in Figure 33. Data analysis showed a significantly lower percentage of correct responses across each task domain for participants operating two USVs rather than a single USV. Of notable concern was the dramatic decrease in performance for Alarm Response tasks when operating two USVs (38% correct response rate with two USVs) and for Collision Avoidance tasks (only 50% correct response rate). The overall (combined) performance score for two USVs was also significantly lower than the overall score for single USV operations.

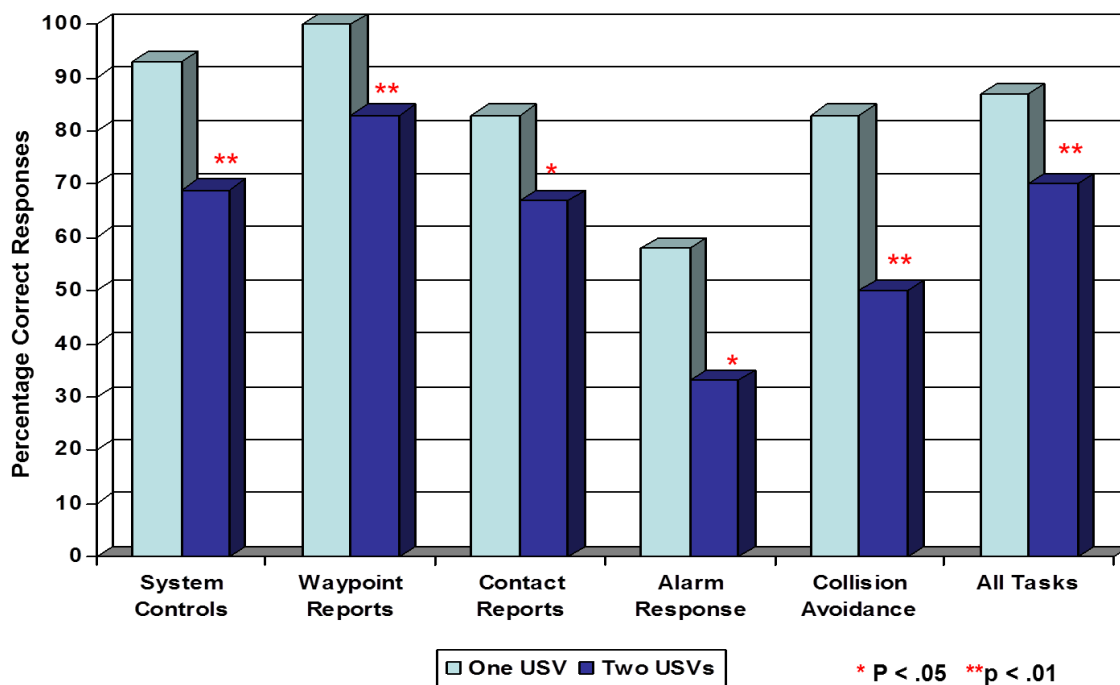


Figure 33. Percent Correct Responses Controlling One USV vs. Two USVs Using Baseline MOCU.

5.4.3 Phase II – Baseline MOCU vs. MOCU v3 (Two USVs)

Phase II evaluated subject performance while controlling two USVs, comparing the baseline HCI to the first version of the advanced prototype HCI (MOCU v3). The results of Phase II testing are shown in Figure 34. For three of five task domains, subjects demonstrated a significant performance improvement using the MOCU v3 interface over the Baseline HCI. The overall performance score was also significantly higher for the MOCU v3 users. The most notable improvements were noted for Alarm Response tasks (66% correct vs. 33%) and Collision Avoidance tasks (84% correct vs. 50%). Slight but insignificant improvements were noted for Waypoint and Contact Reporting Tasks. In follow-up interviews, several participants indicated that “in the real world” they do not routinely provide waypoint reports or report contacts that have been identified and do not pose a potential threat. Therefore there may have been some selective under-reporting during the scenario due to carryover from previous experience.

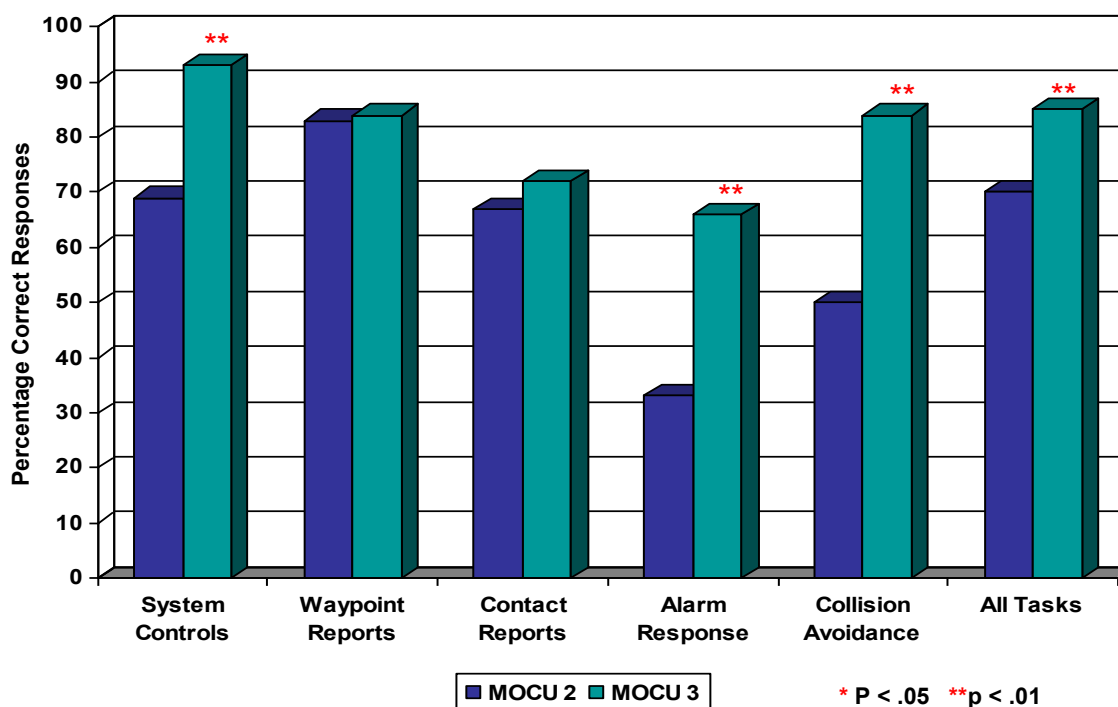


Figure 34. Percent Correct Responses Controlling Two USVs Using Baseline MOCU vs. MOCU v3.

5.4.4 Phase III - MOCU v3 vs. MOCU v3.1 (Two USVs)

Phase III testing was conducted to evaluate the effects of the enhancements introduced in MOCU 3.1 vs the initial prototype HCI (MOCU v3). The results of Phase III testing are shown in Figure 35. Data analysis confirmed a significant increase in the percentage of correct responses for participants using the MOCU v3.1 interface vs. participants using the MOCU v3 interface across three of five task domains and for all tasks combined. The most significant increase in correct responses was

observed for Alarm Response tasks, (95% correct vs. 63%) likely due to the addition of audio alerts announcing changes in alarm status. A slight but not statistically significant decrease in Collision Avoidance accuracy was noted.

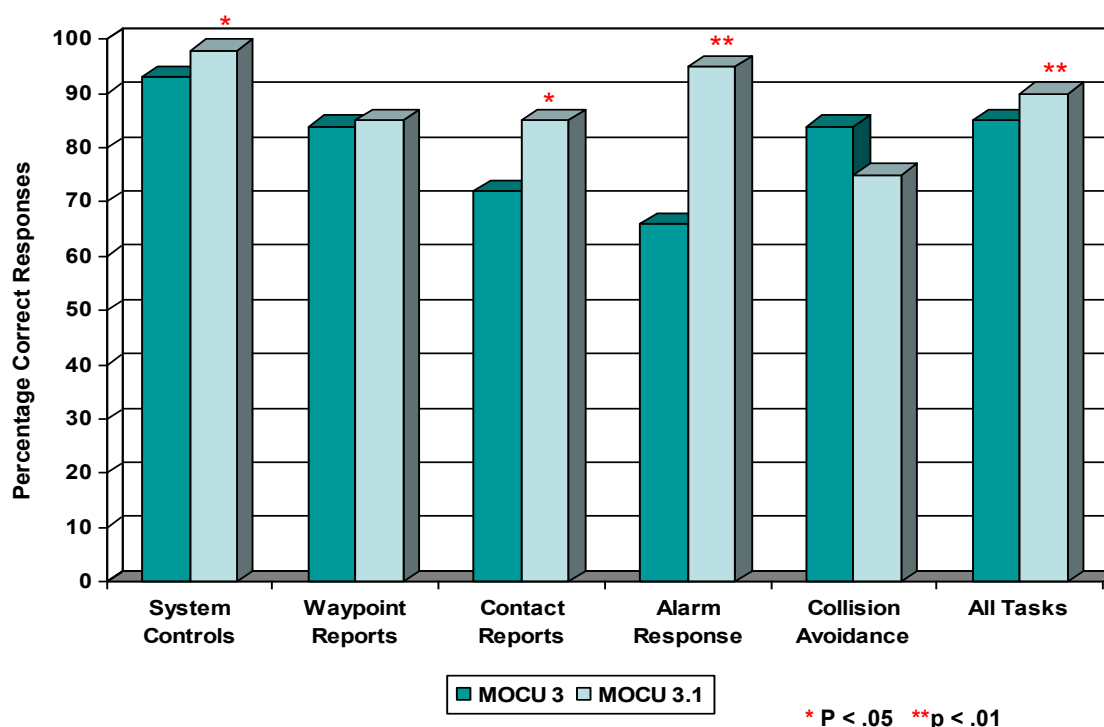


Figure 35. Percent Correct Responses Controlling Two USVs Using MOCU v3 vs. MOCU v3.1.

5.4.5 Phase IV - Baseline MOCU vs. MOCU v3.1 (One USV)

The Phase IV study was conducted to evaluate the impact of HCI improvements made over the course of the project in controlling a single USV. Although the overall purpose of the ONR FNC was to investigate HCI improvements to support multiple USV operations, implementing design improvements for single USV operations would be a logical “first step” in the transition process. Therefore, the research team (with support from NAVSEA) felt it important to validate the prototype design in a single USV environment as well. The results of Phase IV testing are shown in Figure 36. Although performance improvement was observed across all task domains for participants using the MOCU v3.1 interface (except for Waypoint Reporting which was already maxed at 100%), the results were statistically significant only for Alarm Response tasks and combined tasks due to the relatively small number of participants in this phase (8 total). As noted in the analysis of the Phase III results, the significant improvement in performance observed for Alarm Response tasks is attributed to the addition of audio messaging used to alert the operator to changes in alarm status.

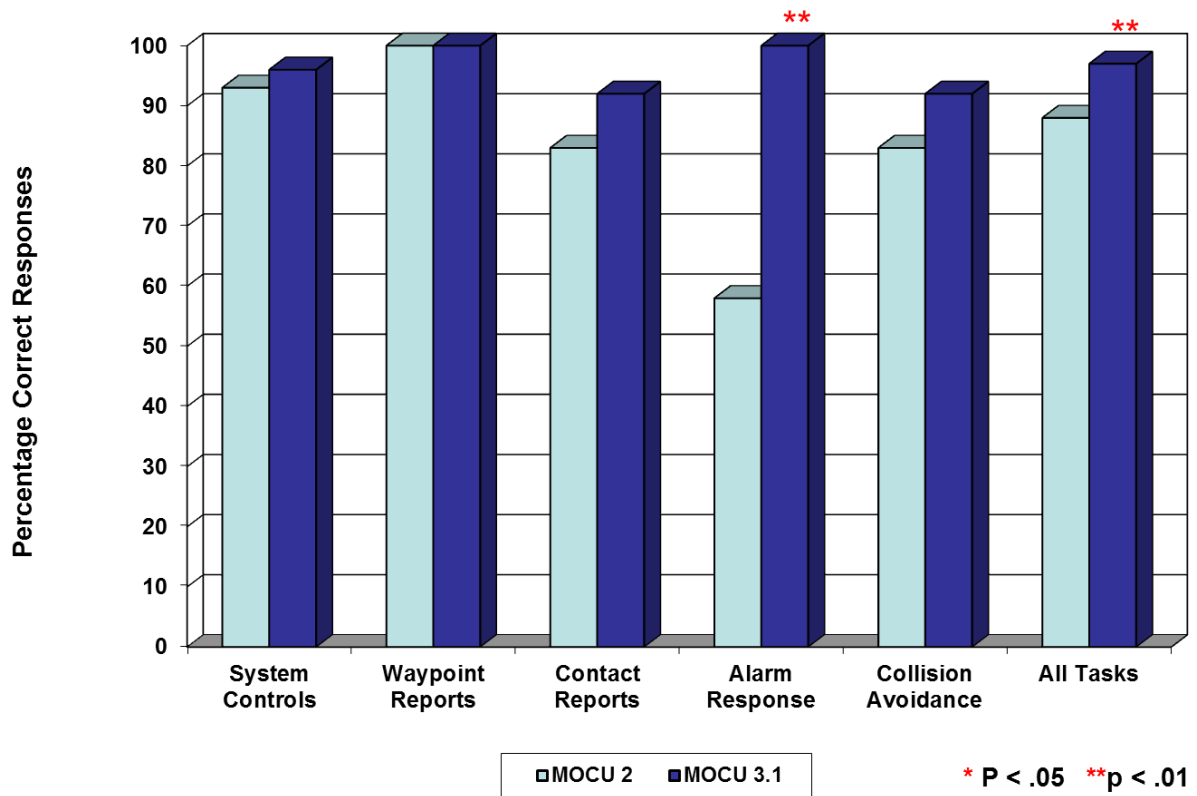


Figure 36. Percent Correct Responses Controlling One USV Using Baseline MOCU vs. MOCU v3.1.

5.4.6 Summary Comparison across All MOCU Versions

Results are shown in Figure 37 for each of the major scenario critical tasks and events, across all the MOCU versions. For all operational tasks, MOCU v3.1 was significantly improved from v3.0 ($p = .01$) and from Baseline MOCU. USV System Control tasks showed significant improvement ($p = .05$) from v3.0 and from Baseline ($p = .01$). Contact reporting, a secondary workload measure verbal report task, improved significantly ($p = .05$) in v3.1 from v3.0. v3.1 was significantly better than Baseline MOCU. Collision avoidance was unchanged from v3.0 to v3.1, with both versions significantly improved from MOCU baseline ($p = .01$). Alarm response improved significantly from v3.0 to v3.1 ($p = .01$) and improved from Baseline MOCU ($p = .01$). Analysis of collisions separated them into easy and hard problem groups. Results indicated that difficult collision problems, which contained no radar or sensor detection cues, still caused problems for operators with a 50% miss rate in v3.1. In comparison, easier problems where visual and sensor information was available in parallel with video information, produced a 100% accuracy rate in v3.1.

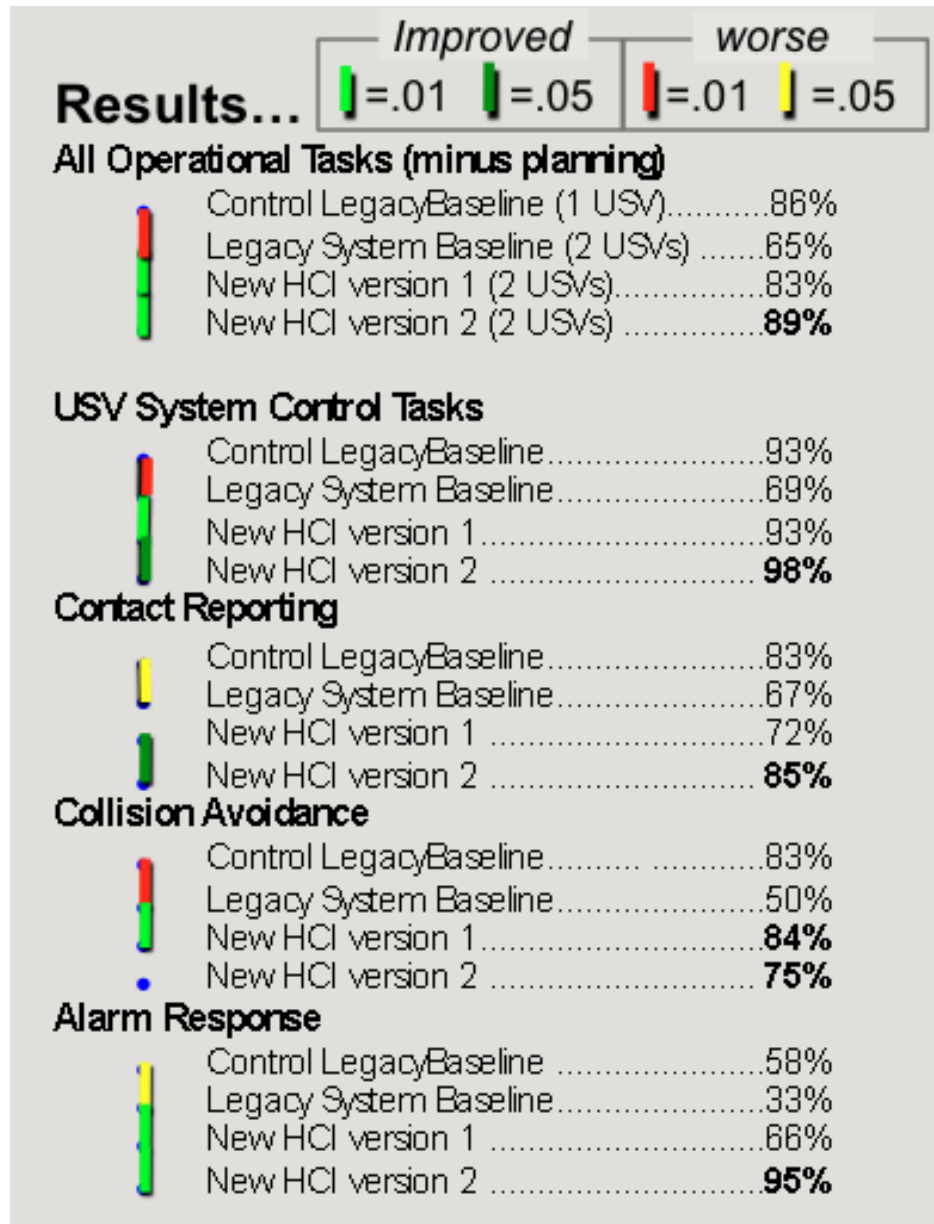


Figure 37. Comparison of Accuracy Rates across All MOCU Versions.

5.4.7 Results of Exit Survey

The results of the exit survey administered at the conclusion of each testing session indicated a strong user preference for the advanced interface when controlling two USVs. Figure 38 shows percentage of positive and negative participant responses between the Baseline MOCU and MOCU v3.1, the final prototype HCI for two USVs.

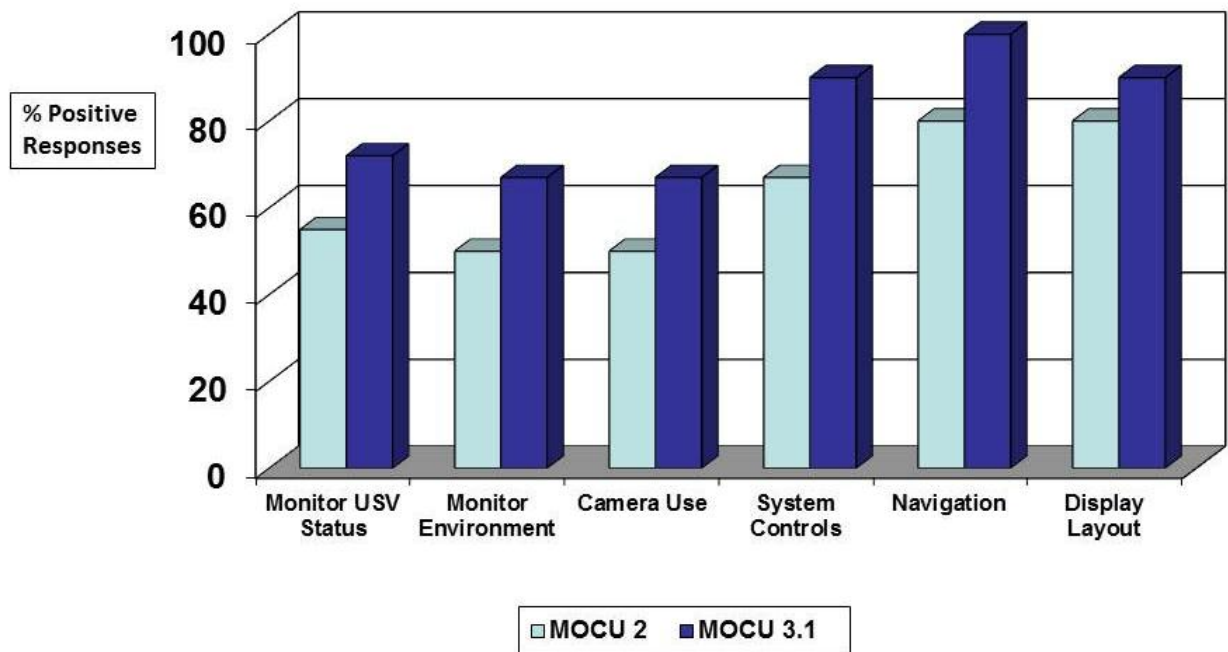


Figure 38. Participant Responses Controlling Two USVs Using MOCU v2 vs. MOCU v3.1.

5.4.8 Technology Transition Exit Criteria

The following exit criteria were listed in the TTA² and reported to NAVSEA at the conclusion of the FNC program, (t) = Minimum Threshold, (o) = Objective.

1. *Objective:* Continuous operation of two vehicles: one mission suspension under highest workload (t); all workload conditions (o).
Result: Users were able to operate two vehicles simultaneously with no mission suspension required and under all imposed test workload conditions. Objective met.
2. *Objective:* Correct object interpretation : >90% (t) with suspension of multiple streams due to reduced image quality; >99% with multiple video streams with time-sharing of tasks.
Result: Budget limited the ability to test with live USVs and broadcast video; however, simulated results indicated that the improved video arrangement and tiling significantly reduced errors in object detection and interpretation. 100% accuracy achieved with full sensors. 89% overall with simulated degraded radar sensors. Objective met with fully operational sensors. With degraded sensors threshold nearly met.
3. *Objective:* Training hours required for operator success: <5 (t); <2 (o) hrs.

² Technology Transition Agreement, Office of Naval Research, Maritime Warfare Branch N863 and LCS Mission Modules Office (PMS-420) PEO Littoral and Mine Warfare, June 30th, 2008.

Result: Training was successful in far less than 2 hours; usually, approx. 15 min. of training was sufficient for acceptable performance. Objective met.

4. *Objective:* Operator SA for Key Mission components: 80% (t); 95% (o).

Result: Situation Awareness as measured by mission progress through waypoints, surrounding contacts, USV status and response to status alarms and changes was significantly improved. All exceeded minimum threshold of 80% accuracy with 89% overall accuracy for all tasks. Objective met.

5. *Objective:* Operator awareness: react to verbal instructions (t); adaptive proactive reaction (o).

Result: Users were 100% able to react to verbal instructions during experiments from a role-play of the officer in charge of USV operations. Users responded to command requests and provided verbal reports as required during testing. Users also were able to enact proactive responses to emergency situations as they developed. Objective met.

6. VISUAL PERFORMANCE MODEL

In addition to the work described in previous sections, a model of human visual detection performance against small objects on the horizon was developed to support automated human visual attention management for command and control of multiple autonomous or semi-autonomous robots by a single operator. An eye-tracker system was used to collect data in a human visual detection task utilizing a single-pixel high-contrast target on a simulated horizon (1280 pixels). Initial results indicate near perfect detection performance was achieved using on average 18 fixations (eye-movements), each with an average duration of 296 seconds. This corresponds to an average of 5.3 seconds per trial (24 trials). This result was used to calculate an observed fovea diameter of 1.66 degrees (67.3 pixel field of view). These results are consistent with a simple detection model that assumes a target is detected if it is foveated. This initial experiment and results were presented at the May 2010 Visual Sciences Society Symposium. The abstract was published in the *Journal of Vision*. (Ahumada, 2010, 2011).

6.1 RATIONALE FOR EMBEDDED VISUAL MODELS

The operation of multiple semi-autonomous vehicles will require operator attention shifts between robots. Attention can be guided by visual and auditory cues; however, these cues must be appropriately used within the context of the robot state and mission status. The robots will not contain obstacle avoidance hardware or software requiring visual supervision and operator attention. The conditions that are worrisome include the floating oil drum or wood palette not detectable by radar, that can damage or sink the robot, and that is only detectable by visual methods through video cameras. Another dangerous condition involves local small craft that might be difficult for radar detection. A simple method to guide attention would be to consider the kinematics of the robot (course and speed), known obstacles (digital charts), and local ship radar contact picture, and to provide simple timing cues to drive attention allocation. Tying alerts to this simple model would likely become annoying and result in operator intervention to circumvent embedded cues. An alternate method would be to also add consideration of visual conditions embedded in a human performance model that would adjust the attention cues according to robot operating conditions. This method would allow alternate cue intervals, depending on visual conditions. The result would be embedded cues for attention that are tied to robot conditions and human visual performance within the operational environment.

6.2 VISUAL PERFORMANCE MODEL DEVELOPMENT

Computational models predicting the distribution of the time to detection of small targets on a display are being developed to improve workstation designs. Search models usually contain bottom-up processes, like a saliency map, and top-down processes, like a priori distributions over the possible locations to be searched. A case that needs neither of these features is the detection of target near an empty horizon. Initial models have incorporated a saccade-distance penalty and inhibition-of-return with a temporal decay. For very small, but high-contrast targets, using the simple detection model that the target is detected if it is foveated is sufficient. For low-contrast signals, a standard observer detection model with masking by the horizon edge is required. Testing to determine parameter values for this model was conducted in FY 10.

6.2.1 Simple Search Model

- Select fixation position at random.
- Is target in fovea? If yes, end search. If no, go to 1.

- Search task: Detect a small target on a simulated horizon in a uniform sky above a uniform ocean.

6.2.2 Underlying Assumptions

- The luminance difference of the target pixel is such that it will be detected with $p = 1.0$ if it is fixated.
- The visual search is memoryless, i.e., a previously visited fixation point may be returned to.

6.2.3 Stimuli

- Screen distance: 69 cm Image width: 38 cm
- Image size in pixels: 1280 x 1024 (W x H)
- Sky y pixel range: 0–509
- Sky RGB color: 0 128 255 \Rightarrow 45.4 cd/m²
- Target, ocean: 0 0 128 \Rightarrow 6.62 cd/m²
- Target pixel size: 1 x 1
- Target y position: 509
- Target x positions: $i \cdot 100$, $i=1,12$
- Blank screen fixation cross, x y: 512 384
- (Samsung Syncmaster 910T LCD monitor)

An approximation of an actual test stimulus is provided in Figure 39. Note that the size of the target relative to the ocean and sky is much greater than the proportional size of the one-pixel target in the actual simulated scene.



Figure 39. Approximate Appearance of a Test Stimulus for Target on Horizon.

6.2.4 Methods

Eye positions were recorded at 250 Hz by an SR Research Eyelink II head-mounted tracker. The experiment was controlled by an SR Research Experiment Builder program. There were three test runs of 12 trials. Before each three-trial group a recalibration was performed. Each test included all 12 positions in a random order. The sequence of fixations was extracted by an SR Research Data Viewer program. The data from the first test run was discarded.

6.2.5 Preliminary Findings

Detection of a single pixel on a simulated horizon (1280 pixels) requires on average 18 fixations (eye-movements), each with an average duration of 296 seconds. This corresponds to an average of 5.3 seconds per trial (24 trials). This result was used to calculate an observed fovea diameter of 1.66 degrees (0.024652 deg/pix, fovea = 67.3 pixel field of view).

6.2.6 Discussion

The above assumptions are clearly violated by the data, but relaxing the assumptions in meaningful ways, e.g., assuming $P = .75$ and the search is not memoryless, changes the estimate of the fovea diameter by a factor close to 1.0 so the estimate from the data is very reasonable. If the fovea diameter is relatively constant, then detection time is simply the ratio of the estimated fovea diameter to the size of the area being searched times the duration of a fixation.

In terms of automated visual attention management, an unobtrusively eye-tracked operator can be alerted when the expected time to detect is passed so that he or she can safely shift visual attention to another task. A higher-level decision support system could also calculate risk levels for shifting/resuming visual search based on the simple detection model and situational variables such as speed, visibility, and target contrast models.

Next steps include obtaining more detection data in order to validate the fovea diameter estimate and evaluate effects due to non-random search and the assumption of a target luminance detection threshold. Note that the initial data did not include any false alarms. However, data just recently collected and not reported here indicate false alarms are possible even with high-contrast targets. In this case and especially when low contrast targets are present, the assumption of a target luminance detection threshold must be dropped and the detection model modified to include a false-alarm parameter. This more complicated model can be investigated using the test paradigm reported here by utilizing low-contrast targets, i.e., a target pixel having a luminance value closer to that of the simulated sky.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 ASSESSMENT OF BASELINE MOCU

The results of the study clearly indicate that the Baseline MOCU does not support safe operation of multiple vehicles by a single operator. When participants were tasked with controlling two USVs simultaneously in a simulated mission, overall performance on operational tasks dropped from 86% correct course of action (COA) responses to 65% correct COA responses. Significant drops in performance were seen across all task domains. Of particular concern though was the performance drop-off observed in participants' responses to potential collision situations where correct COA response rates dropped from 83% to only 50%. Also of notable concern was the diminished rate of correct responses to system alarms. Using the baseline HCI, correct response rate was only 58% for a single USV and dropped to a disturbing 33% correct COA when operating two USVs.

7.2 ASSESSMENT OF ENHANCED MOCU

The significant improvements in operator performance that were observed after implementing the enhanced MOCU v3.1 interface indicates the potential for successful operation of multi-USV operations with HCI visual, auditory, and control enhancements. Performance improved across all major task COA categories; however, collision avoidance still contained a level of operational risk. The most difficult tasks involved avoidance of contacts with no detection or radar information, relying only on human vision and manual reaction to a pending collision. Even though all participants were warned during the mock mission briefing that radar was unreliable on one USV, requiring diligent monitoring of video cameras, many participants failed to adequately monitor the forward view video window for extended periods of time when other distracting activities (such as system alarms) were taking place. Using the baseline interface (MOCU v2) when controlling two USVs, participants were five times more likely to collide with a vessel that did not appear on radar. With the MOCU v3.1 interface, collisions with vessels not displayed on radar were twice as likely as those with sensor information available. Two participants actually reported seeing the obstacle vessel in the video window prior to collision but because they did not have a radar image to confirm, they were not sure of the impending threat and took no action to avoid collision. These findings indicate a very narrow window of opportunity that the operator attention can stray from direct USV video monitoring without the added assistance of reliable radar or other collision avoidance obstacle detection alarms.

Thus, USV system functions for obstacle avoidance – missing in this simulation – may be critical in supporting multi-USV operations, including improved sensor capability to detect and warn of potential collisions. Although the HCI enhancements implemented assistance to operators' ability to monitor video displays, the lack of an active warning system leaves the USV vulnerable to collisions with undetected objects, particularly during periods of heavy workload (alarms or other visual distractions across multiple USVs).

7.3 ASSESSMENT OF GAME CONTROLLER INPUT DEVICE

User performance while using the game controller indicates that game-type controllers represent a trainable and effective option to control a USV across manual-vector-waypoint operational modes. The addition of the game type controller was seen as an integral component of the overall MOCU v3.1 interface package. As indicated during post-test discussions, a high percentage of the participants engage in video games on a regular basis and were already familiar with the basic operation of the X-box type controller. We suspect that this is not atypical of the enlisted Navy population in general. Because the USV functions were mapped to the controller following "standard

gaming conventions” where possible, the button and joystick assignments made intuitive sense to the participants who were able to learn to drive the USV in relatively short order. Although a controller mapping diagram was provided during training and available to participants throughout the scenario, researchers rarely observed participants needing to consult the diagram. In most cases, participants operated the controller by feel and rarely had to visually site the buttons or joystick in order to execute a command. This ability to “drive by feel” then afforded significantly more visual attention resources to monitoring the map, video windows, and status indicators. While the MOCU v3.1 interface still relies on menus for execution of some lower order tasks, menus are called up and options prosecuted through an easy-to-use button configuration on the controller that is similar to menu strategies found in many video games. This is in contrast to the multilayered pull-down menus in the baseline HCI that required participants to control and visually monitor the location of an onscreen cursor to make selections.

7.4 IMPLICATIONS FOR SINGLE USV OPERATION

The Phase IV study conducted as a follow-on effort to the multiple USV work indicates that the HCI enhancements made to support multiple USV operation had a significant (positive) effect in controlling a single USV. While some improvements were noted across all task domains, the highly significant improvement in response to alarm indications was noteworthy. Since current plans call for developing a redesigned USV to support MCM operations onboard the LCS, in a single USV configuration, these results have an immediate impact on near-term LCS HCI design.

7.5 EASE OF USE AND TRAINING IMPLICATIONS

The USV mission simulator proved to be a valuable tool for evaluating the potential of the HCI products from this project related to positive training impact. The simulation used for these studies has potential for being an easy-to-use training method allowing users to gain experience in USV operations in a cost-effective manner. The short time period to train and familiarize users with the operations of MOCU indicates an easy transition from Baseline MOCU or an efficient introduction for a novice operator. These interface design properties should also be considered for other human-robotic interfaces on LCS.

7.6 RECOMMENDATION FOR FURTHER TESTING

The current set of studies had limitations with respect to validity of results. First, the laboratory simulation estimated the results of live video, radar, and other sensors. The degree of difference between the real operational sensors and the simulation could affect results in a positive or negative manner. For example, the HCI “windshield” view was created by “stitching” together video images from four discrete cameras into one continuous panoramic view. While this feature was well received by the subjects using simulated video, trials with real video feeds from the actual USV cameras should be performed to determine the effects of distortion or blind spots created at the seams where the images meet. Second, the simulation of a USV with no active radar stressed the range of system performance from all systems working toward a degraded state. In reality, tactics and operations could reduce the effects of degraded radar, e.g., the degraded USV could follow the fully operational one, or a mandated reduced speed or other cautionary methods could be employed. In reality, the mission could be postponed for sensor repairs depending on urgency or another robot inserted. Obstacle detection systems could be incorporated, but increase the cost of the USV platform. This cost must be weighed against the risk of collision and need to collect mission data under all circumstances of environmental clutter. Thus, further tests of operational results with operational USVs on the water would increase the validity of HCI design decisions made during this ONR project.

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APPENDIX A. SCENARIO SCRIPT

Participant # _____	Date _____							
USV One				USV Two				Observations / Comments
Simulation Event	Expected COA	Yes	No	Simulation Event	Expected COA	Yes	No	
MS "Take control of USV1"	Selects correct USV.							
MS "Activate radar and display contacts for USV1"	Selects: Activate, Display. Contacts up by WP1.							
MS "In vector mode, set course to WP1, 20 knts."	Sets correct heading, speed.							
MS "At WP1 check with MS to execute route."								
USV 1 reaches WP1.	Reports WP1 to MS.							
MS " Select and execute Southern Route for USV 1 in waypoint mode."	Correct Rte executed.							
USV 1 heads to WP2.				MS - "Take control of USV 2 ".	Selects correct USV.			
USV 1 continues to WP2.				MS - In vector mode, set course to WP1, 20 knts	Sets correct heading, speed.			
USV passes oil rig on SB.	Oil rig reported to MS.			MS "At WP1 check with MS to execute route."				
MS "Use PTZ to inspect oil rig for adversaries".	Able to use PTZ.			USV 2 reaches WP1, heads to WP2.	Reports WP1 to MS.			
USV 1 continues to WP2.				MS Select and execute Northern route for USV2.	Executes correct route.			
USV 1 continues to WP2.				USV 2 heads to WP2.				
USV 1 continues to WP2.				Sailboat traffic in display / radar.	Traffic reported to MS.			
Temp alarm light flashes red.	Reports alarm within 10 secs.			MS "Change to vector mode, reduce speed to 10 kts."	Vector mode selected. Speed set at 10 kts.			
MS "USV1 has high temp alarm. Shut down both engines."	Selects: Stop Engines.			Operator continues in vector mode.	Avoids hitting sailboats.			

Alarm light clears, MS "Restart engines & resume route."	Reports alarm clear within 10 secs. Resumes route.			MS "When USV 2 is clear of traffic, resume route."	Resumes waypoint mode AFTER clear of sailboat traffic.			
USV1 continues to WP2.				USV2 continues to WP2.				
Temp. alarm flashes again.	Reports alarm to MS within 10 secs.			USV2 continues to WP2.				
MS "Pause route and put engines in neutral to allow alarm to clear."	Selects pause, neutral.			USV2 reaches WP2, heads to WP3.	Reports WP2 to MS.			
Alarm light goes off.	Reports alarm clear within 10 secs.			USV2 continues to WP3.				
MS "Resume Waypoint Route on USV1".	Places in forward. Resumes route.							
USV 1 reaches WP2, heads to WP3.	Reports WP2 to MS.			2 boats in collision path.	Executes Emergency Maneuver in time.			
USV1 continues to WP3.				USV2 reaches WP3, heads to WP4.	Reports WP3 to MS			
USV1 continues to WP3.				USV2 continues to WP4.				
USV1 continues to WP3.				Boat approaches head on collision.	Executes Emergency Maneuver in time.			
USV1 reaches WP3, heads to WP4.	Reports WP3 to MS.			USV2 continues to WP4.				
Container ship in direct path of new heading.	Reports contact to MS.			USV2 continues to WP4.				
MS: Monitor movement of contact. Switch to vector mode and adjust course as necessary.	Avoids exclusion zone.			USV2 continues to WP4.				
USV continues to WP4.				Pursuit boat approaches from aft port.	Reports correct location of pursuit boat before passing.			
USV reaches WP4 (Mission Area).	Reports WP4 to MS.			USV reaches WP4 (Mission Area).	Reports WP4.			

APPENDIX B. VOLUNTARY CONSENT FORM

INFORMED CONSENT

Protocol Title: “Evaluation of the Advanced Multi-robot Operator Control Unit (MOCU) human-interface for controlling multiple Unmanned Surface Vehicles”

Principal Investigator: Dr. Glenn Osga

Associated Investigator: Mike McWilliams

Protocol Number:

INTRODUCTION

You are invited to participate in a research project being sponsored by the Office of Naval Research (ONR) and SPAWAR System Center Pacific. Your participation in this study is voluntary; therefore, you may withdraw from the experiment at any time. Please read the information below and feel free to ask question before deciding whether to participate.

PURPOSE OF RESEARCH

The purpose of the study is to evaluate variations in configuration of the USV control unit.

DURATION OF STUDY INVOLVEMENT

Your participation in this study should last no longer than 90 minutes.

PROCEDURES

The following activities will be conducted as part of this study participation:

1. Meet the researchers and be briefed on the purpose of the study. Estimated time - 5 minutes.
2. If agreed to participate, read and sign this Informed Consent Document. The researchers will answer any questions or concerns you may have at this time. Estimated time - 5 minutes.
3. Complete the Background Survey. Estimated time - 10 minutes.
4. Familiarization session with the USV controller. Estimated time - 15 minutes.
5. Mission briefing will be provided to each participant. Questions about the mission can be asked at this time. Estimated time - 10 minutes.
6. Perform the simulated mission scenario. An observer will record data on a number of mission performance parameters. Estimated time - 30 minutes.
7. Complete the Exit survey. Estimated time - 10 minutes.
8. Researchers thank participants for their collaboration. Estimated time - 5 minutes.

“This is revision # of _____. Approved _____. This document may NOT be used after _____.”

1

RISK AND DISCOMFORT

There is no physical or psychological risk associated with participation on this study.

POTENTIAL BENEFITS

The information obtained from this study will provide the basis for evaluating different versions of the USV control unit. The benefit of your participation in this study is the opportunity to contribute to the evaluation of future improvement in the control unit that could make your tasks easier in future mission deployments.

ALTERNATIVES TO PARTICIPATION

An alternative to participation in this study is to not participate in the study.

VOLUNTARY PARTICIPATION AND WITHDRAWAL

By volunteering for this study you have agreed to provide honest and ethical responses and perform to the best of your ability through the study. Failure to follow directions and procedures may result in invalid test data and be cause for your dismissal from the research study. Dismissal from the research project will involve no reproach, prejudice or jeopardy to your job or status.

CONFIDENTIALITY

Prior to the collection of any data, your name will be assigned a number. That number will be the only identifier used when referring to your data. No one other than the study investigators will have access to individual data sets. Only data summarizing across all individual data sets will be included in any subsequent report. All data and personal information regarding your participation as well as that of other subjects will remain confidential with the appropriate safeguards and stored by the Principal Investigator in accordance with the Privacy Act of the Government of the United States.

CONTACT INFORMATION

For inquires after the study has been completed, please contact the Principal Investigator, Dr. Glenn Osga, SSC Pacific at (619) 553-4644 or by email at glenn.osga@navy.mil. For questions about your rights as a volunteer participant or any problem related to protection of research volunteers, please contact the Chair of the SSC Pacific Institutional Review Board (IRB), Dr. Jerry Kaiwi, at (619) 553-9220.

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SIGNATURE OF RESEARCH SUBJECT

I have read the Privacy Act Statement, this voluntary consent form and the approval letter for this study issued by the SSC Pacific Commanding Officer. I have been given the opportunity to discuss any questions or concerns that I might have with the researchers and had all my questions answered to my satisfaction.

Participant's Printed Name

Participant's Signature

Date

Investigator

Date

"This is revision # of _____. Approved _____. This document may NOT be used after _____."

3

PRIVACY ACT STATEMENT

To be read by all voluntary Human Subjects prior to signing the Informed Consent Document

Authority. SECNAVINST 5211.5E, Department of the Navy Privacy Act (PA) Program, 10(a) Page 12, 10(d) Page 13 of 28 December 2005

Purpose. Human performance data and other research information will be collected in an experimental project entitled "Evaluation of the Advanced Multi-robot Operator Control Unit (MOCU) human-interface for controlling multiple Unmanned Surface Vehicles".

Routine Uses. The Departments of the Navy and Defense, and other U.S. Government agencies will use the resulting research data for analyses and reports. Use of the information obtained may be granted to non-Government agencies following the provisions of the Freedom of Information Act or contracts and agreements. I voluntarily agree to its disclosure to agencies or individuals identified above and I have been informed that failure to agree to this disclosure may make the research less useful. The "Blanket Routine Uses" that appear at the beginning of the Department of the Navy's compilation of data bases also apply to this system.

Voluntary Disclosure. Participation in this study and provision of information is voluntary. However, failure to provide requested information may invalidate test data and/or test procedures and could therefore result in removal from the project. Dismissal from the research project will involve no reproach, prejudice or jeopardy to my job or status.

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APPENDIX C. BACKGROUND QUESTIONNAIRE

Demographic and Experience Questionnaire

Branch of Service _____

Occupational Specialty _____

Years of Service _____

Rank/Rate _____

1. How many years of experience do you have in the area of ASW or MCM?

- ☐ None
- ☐ Less than 1 year
- ☐ 1-2 years
- ☐ 2-5 years
- ☐ More than 5 years

2. How many hours of USV operational experience do you have?

- ☐ None
- ☐ Less than 2 hours
- ☐ 2-5 hours
- ☐ 5-10 hours
- ☐ More than 10 hours

3. How many hours of USV simulator experience do you have?

- ☐ None
- ☐ 1-2 times
- ☐ 3-4 times
- ☐ 5-6 times
- ☐ 7 times or more

4. Have you operated a USV during the past 6 months?

- ☐ Yes
- ☐ No

APPENDIX D. TRAINING PROTOCOL

Welcome Participants

- Discuss purpose of the study – to capture data for improving the user interface.
- Discuss the nature of participation – conduct a simulated ASW mission.
- Assure it is not a test of his / her skills.
- Ensure confidentiality and have participants read the Informed Consent Document (including Privacy Act Statement) and sign the ICD if they agree to participate.
- Have Participants Complete Background Survey.

Review Upper Monitor Screen (Map and Status)

- **DNC (Use mouse to zoom in / out)**
 - Boat icons, inc compass rose and speed header
 - North / South routes / WP markers
 - Operations area and Exclusion Zone
- **Vehicle Status Information (color coding)**
- **Mission Analysis / Event Viewer not active**

Review Lower Monitor Screen (Video and Dashboard)

- **Video Window Layout**
 - Main Windshield (Stitched video)
 - PTZ, Aft View, Forward view of Other USV
- **Speed / Rudder Position / Throttle & Gear**
- **Waypoint previews**
- **Control Mode and Radar Status**
- **Alarm Icons and Alerts**

Walkthrough Controller Mapping

- **Taking / Switching Control of USVs (note screen changes)**
- **Using the Camera Controls**
 - Toggle PTZ to Camera Can (note camera arrows)
 - Pan / Tilt , Zoom / Home
- **Driving in Vector Mode**
 - Steering
 - Speed Set
- **Manual Mode Override (Teleop)**
 - Steering /Speed
 - Pull back for idle speed
- **Driving in Waypoint Mode**
 - Executing Routes
 - Pause / Resume
- **Other Pie Menu Functions**
 - Enabling Radar - Active / Contacts
 - Starting / Stopping Engines
 - Transmission gear select / idle

Download and Run Practice Scenario

APPENDIX E. MISSION BRIEFING

2 Boats:

This mission involves deployment of 2 USVs from the Littoral Combat Ship, USS Freedom in the Aegean Sea off the coast of Greece. We will be conducting ASW operations using bi-static sonar surveillance techniques. For this scenario we will be transiting the USVs to the mission area but will not be running search tracks. You will act as the operator, controlling and monitoring both USVs as they transit to the mission area and I will act as the mission supervisor. The USV routes have been reviewed and entered into MOCU and are ready to be executed. Both USVs have already been launched, systems have been checked out and are ready to have you take control. At the direction of the mission supervisor, you will take control of USV 1 and drive the USV away from the LCS in vector mode toward Waypoint 1. When USV 1 reaches Waypoint 1 (WP1), request permission from the Mission Supervisor to execute the route in auto mode. After USV 1 has reached WP1, directions will be given to take control of USV 2. You will then drive USV 2 to Waypoint 1 for its route and again request permission to execute the USV 2 route. For this mission, the radar on USV 2 is inoperable. Radar from the host ship provides coverage up to WP 2 but from there on there is no reliable radar for USV2 so be extra vigilant in monitoring your video cameras.

1 Boat:

This mission involves deployment of 2 USVs from the Littoral Combat Ship, USS Freedom in the Aegean Sea off the coast of Greece. We will be conducting ASW operations using bi-static sonar surveillance techniques. For this scenario you will be transiting one of the USVs to the mission area but will not be running search tracks. You will act as the operator, controlling and monitoring the USV as it transits to the mission area and I will act as the mission supervisor. The USV route has been reviewed and entered into MOCU and is ready to be executed. The USV has already been launched, systems have been checked out and is ready to have you take control. At the direction of the mission supervisor, you will take control of the USV and drive away from the LCS in vector mode toward Waypoint 1. When the USV reaches Waypoint 1 (WP1), request permission from the Mission Supervisor to execute the route in auto mode. For this mission, the radar on the USV may not be operating properly. Radar from the host ship provides coverage up to WP 2 but from there on there is no reliable radar for so be extra vigilant in monitoring your video cameras.

You will need to make several reports to the MS during the mission:

- As each waypoint is reached, report the WP reached and the new heading and speed for the next track.
- Report all contacts observed along the route and whether they present a potential collision hazard that may require change of course.
- If there are any immediate collision hazards, use the emergency maneuver control to avert contact. Report these as conditions allow.
- Report any system problems to MS, including alarms and cautions.

APPENDIX F. EXIT SURVEY

Exit Survey

1. I found it easy to use for monitor the status of each USV separately.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

2. I had difficulty monitoring the status of both USVs at the same time.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

3. I found it easy to assess the immediate environment using the USV cameras.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

4. I had difficulty keeping track of the USV camera orientation (direction of view).

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

5. I found it was easy to MANUALLY set and maintain the desired speed of the USVs.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

6. I found it was easy to MANUALLY set and maintain the desired course heading of the USVs.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

7. I found the interface provided the necessary visual information for orientation while navigating and performing mission tasks.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

8. I had difficulty locating necessary information on the display to perform mission tasks.

☐ Strongly Disagree

☐ Disagree

☐ Neutral

☐ Agree

☐ Strongly Agree

Comments _____

8. The most difficult part of controlling two USVs is:

9. If I could change one thing about the system status displays it would be:

10. If I could change one thing about the camera displays it would be:

11. If I could change one thing about the digital chart displays it would be:

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14. ABSTRACT This report describes a multiyear research effort conducted by SPAWAR Systems Center Pacific (SSC Pacific) investigating Human-Computer Interface (HCI) issues associated with operating unmanned surface vehicles (USVs). An iterative user-design process was used that resulted in the development of an enhanced HCI design. The primary focus of this effort was to investigate improvements to the baseline HCI design of the SPAWAR Multi-Operator Control Unit (MOCU) software to support simultaneous operation of multiple USVs by a single operator. A number of significant design enhancements were made to the baseline HCI as it was adapted to support multiple USVs. The enhancements included integrated visualization of video and graphics combined with multi-modal input and output using synthetic speech output and game-controller input. Significant gains in performance times and error reduction were found with the enhanced design. Following the ONR effort, Naval Sea Systems Command (NAVSEA) LCS Mission Modules Program Office (PMS 420) supported the development of a prototype HCI design for operation of a single USV. While overall results of simulator-based usability evaluations indicate improved operator performance, the researchers conclude that improvements in on-board sensor capabilities and obstacle avoidance systems may still be necessary to safely support simultaneous operation multiple USVs in cluttered, complex transit environments.					
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