

Managing multiple unmanned aerial vehicles from a 3D virtual environment

by

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TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	vi
ABSTRACT	vii
INTRODUCTION	1
Vision	3
Challenges	5
UAV Control Research	8
VR Aided Tele-operation	10
<i>Test Results</i>	12
Multiple UAV Control Research	14
Autonomous Strategies	15
<i>Current Research</i>	16
<i>Current Application</i>	17
<i>Advantages and Disadvantages</i>	17
High Autonomy Strategies	18
<i>Current Research</i>	19
<i>Current Application</i>	20
<i>Advantages and Disadvantages</i>	21
Mixed Autonomy Strategies	22
<i>Current Research</i>	22
<i>Current Application</i>	25
<i>Advantages and Disadvantages</i>	25
Command and Control Research	26
Research Objective	29
3D Battlefield Visualization	29
3D Interfaces for UAV Control	30
Determine Effectiveness of 3D Interface	31
SOFTWARE FOUNDATIONS	32
Command Driven Architecture	33
Commands	33
Command Loop	34
Clustering	36
Networking	37
Battlespace Research Platform	38
Statistical Performance Assessment	45
IMMERSIVE COMMAND AND CONTROL OF UAVS	49
Selection	50
Entity Billboard	54
Distance Lines	55

Radar	56
Path Visualization	58
Alert subsystem	61
Real time dynamic path alteration	63
Target Confirmation	66
Virtual Binoculars	68
Tablet Interface	71
RESULTS & DISCUSSION	73
Situational awareness in virtual environments	73
Demonstrations	75
Expert Feedback	77
CONCLUSION & FUTURE WORK	84
Future Work	86
APPENDIX A. PATH PLANNING ALGORITHMS	89
APPENDIX B. SURVEY INSTRUMENT	91
REFERENCES	97
ACKNOWLEDGEMENTS	102

LIST OF FIGURES

Figure 1. General System Model	11
Figure 2. Wire-frame Envelope	12
Figure 3. Skyview 3D Screenshot	27
Figure 4. Battlespace in the C4	28
Figure 5. Command Loop	36
Figure 6. Gamepad Interface Device	40
Figure 7. 2D Menu Interface	40
Figure 8. Strategic Mode	42
Figure 9. Strategic Mode Features	43
Figure 10. Tactical Mode	44
Figure 11. The C6 with Battlespace in it	44
Figure 12. Battlespace in the Babycave	45
Figure 13. Regression Plot	47
Figure 14. Selection Labeling in Application	51
Figure 15. Selection and Deselection Labels	53
Figure 16. Entity Billboard	54
Figure 17. Distance Lines Between Entities	56
Figure 18. 2D Radar	57
Figure 19. View corresponding to 2D radar above	57
Figure 20. UAV Path Representation	59
Figure 21. Highway in the Sky	60
Figure 22. UAV Alerts in Strategic Mode	62
Figure 23. Alternate UAV paths	64
Figure 24. Top down view of alternate paths	65
Figure 25. Highlight of chosen path	66
Figure 26. Ground Alert in strategic/tactical mode	67
Figure 27. Alert Information	68
Figure 28. NVIS binoculars	69
Figure 29. View from binoculars	70
Figure 30. Tablet Interface	72
Figure 31. IITSEC demo picture	76
Figure 32. Third Annual Human Factors in UAVs, Mesa, AZ	77

LIST OF TABLES

Table 1. Test Results	14
Table 2. Test Data	45
Table 3. Parameter Settings	63

ABSTRACT

One hundred and three years ago the aviation age began with the Wright brothers in Kittyhawk, North Carolina. It is well known that manned aviation has made tremendous progress over the decades that followed. Less familiar are the deep history and roots of unmanned aviation, which is often thought of as a recent phenomenon. Initially, modern unmanned aerial vehicles (UAVs) were instruments of war, and the challenge was to develop an unmanned system that could fly a preplanned route and return home. Once this level of autonomy was reached, it became clear that UAVs would have a considerable impact on future conflicts, but the possibilities extend beyond the practice of war and have potential to affect almost everyone's lives. This potential, however, will not be met with current interface technologies, which require a team of operators to control one UAV. New technologies must be created to reverse this ratio. One operator must be able to control multiple UAVs. To accomplish this goal, the operator must be able to manage the UAVs' flight paths and sensor feeds. The operator must also be able to maintain good situational awareness. This dissertation presents a 3D immersive ground control station capable of dynamic real-time path re-planning and in-context target confirmation as one possible solution to these challenges.

INTRODUCTION

Almost one hundred years ago, August 8th 1908, Wilbur Wright made the first official public demonstration of the Wright brother's flying machine. French aviation pioneers and onlookers, who months earlier had ridiculed the Wright brothers as frauds, lauded Wilbur's skills at being able to control his flight. This startling exhibition did not come out of nowhere. The Wright brothers were greatly inspired by the German aviation pioneer Otto Lilienthal who published a book *The Flight of Birds as a Model for the Art of Aviation* in 1890. Lilienthal's research notes on over 2,500 homemade glider flights formed a basis of knowledge for the Wright brothers to expand upon. The development of controllable manned flight ushered in a century of aviation innovations.

In the 21st century, the most remarkable innovations in this field will not be related to manned vehicles. Instead, this century will be marked by advancements in the control and management of unmanned aerial vehicles (UAVs). The concept of unmanned flight has been around for a lot longer than most people realize. The first unmanned vehicles capable of flight were kites. Invented around 2500 years ago in southeastern Asia, kites could be controlled through line of sight with a string. More modern UAV concepts didn't appear until the 19th Century when aviation pioneers such as Cayley and Du Temple built models to test their early concepts of flight. Nikola Tesla, famous for his contributions to electronics and the alternating current, boasted that he could build an unmanned aircraft that could be remote controlled as early as 1898. To back up his words, Tesla built the first remote controlled boat in 1898. He dubbed this new technology a "telautomaton"[30].

Unfortunately other projects attracted Tesla's interest and the remote controlled plane fell by the wayside.

After the Wright brothers' proved the concept of manned flight, other researchers became intent on creating autopilot systems to assist the human pilots. In 1916, Elmer Sperry built the first airplane capable of sustained flight without a human on board. Sperry's system of gyrostabilizers worked well, and research was conducted to make planes that could fly themselves to designated coordinates. The radio tracking technology was not mature enough, and the project was ultimately canceled in 1926 [30].

The concept of a remote controlled plane resurfaced in 1935 when Reginald Denny of the Radioplane Company revealed the Radioplane-1 (RP-1). The RP-1 could receive a radio signal and perform corresponding maneuvers such as up, down, left and right. These radio-controlled planes were used extensively in World War II as target drones. Serving as practice targets would be the UAVs' primary role until the next evolution when Radioplane added cameras to its RP-71 in 1955. These early UAVs still suffered from limited control capabilities, and accurate long distance control proved impossible for the technology of the time [30].

Still the Army and Air Force remained interested in the development of practical reconnaissance drones, and in 1964 the "modern" UAV came into existence with the creation of the AQM-34 Lightning Bug. In its inaugural mission, the Lightning Bug, flew a preprogrammed route over southeastern China and returned safely to a designated parachute drop point. Later versions of the Lightning Bug were equipped with a video camera that allowed for some in-flight adjustments to be made. The Lightning Bug saw extensive action in Vietnam completing 3,435 combat missions. Unfortunately over half of the 1,016 aircraft

used for these missions were lost [30]. Development continued after the Vietnam conflict, but the next real breakthrough came with the development of the Predator in 1993. The Predator truly ushered in the age of modern UAVs. The Predator was followed by even more technically advanced unmanned systems [30]. All of these UAVs have required multiple operators for one unmanned vehicle. The next step in the evolution of this field is for the operator to control not one UAV but multiple UAVs.

Building on the previous work in the areas of UAV control, multiple UAV control and command and control, this dissertation presents the creation of a 3D immersive environment that provides many of the elements needed to control multiple UAVs. With a software foundation that is flexible, extensible and powerful, this environment contains interface innovations that grant new and effective control capabilities, providing a state-of-the-art platform for researching the benefits of 3D immersive command and control of UAVs. This environment shows promise in helping a single operator control multiple unmanned aerial vehicles.

Vision

In the future unmanned aerial vehicles will grow in capability and play a significant role in most of our daily lives. They will vary in size from vehicles as small as an insect to vehicles the size of a passenger aircraft. UAVs of the near future will participate in commercial endeavors, provide valuable public service and play a vital role in the armed forces. As the technology progresses large swarms of UAVs could be used to solve both military and commercial problems [24][23][30][49].

Presently, there is ongoing research by the Federal Aviation Administration (FAA) on the integration of unmanned vehicles in civilian airspace. Shipping companies such as Federal Express and UPS are looking into technologies that will allow one pilot to fly multiple freight aircraft. Considering the labor troubles that most major airlines have experienced lately, this type of technology could have a considerable impact on how people fly. By the year 2015 commercial aircraft could be flying without pilots [50][30]. UAVs also show potential in public service. One border patrol agent could effectively monitor hundreds of miles of a border through the use of multiple UAVs, and search and rescue operations could expand the amount of area that each team member would be able to cover [40].

The United States Department of Defense (DOD) is already invested in expanding the role of UAVs. In fact, it is the DOD's hope that by 2015 UAVs will make up at least 25% of all military aircraft [31]. However, the DOD realizes that this expansion cannot happen with current generation interfaces, which require several operators to control one vehicle. Because the DOD views UAVs as future force multipliers, its road map calls for a single operator controlling multiple UAVs.

Initially, UAVs will take on missions that are commonly referred to as the dull and the dangerous. But as their capabilities expand, their roles will increase in breadth and depth. For example, current generation UAVs are used primarily for reconnaissance, but future UAVs are envisioned as strike aircraft responsible for destroying high-risk high-priority targets. Additionally UAVs can hover over areas for longer periods of time than human pilots can without suffering the effects of fatigue. Such hovering craft would provide additional agents to bring to bear on a target if a window of opportunity opened for an attack.

The next step beyond one operator controlling a small number of UAVs is one operator monitoring a large swarm of them. These swarms could have many potential applications. Swarms of UAVs, the size of bees [48] and powered by the sun, could serve as a guard against unwanted pests in a farmer's fields. These solar powered UAVs could also serve as a non-invasive way of monitoring the behavior of wildlife. The Amazon rain forest holds many mysteries that perhaps could be investigated by the use of a swarm of unmanned vehicles.

The military also sees an application for a large swarm of UAVs. Swarms could be used as means of gathering even more thorough reconnaissance about a particular area. With a small number of UAVs, each one is responsible for monitoring a couple hundred square miles. With a swarm that same area could be covered by hundreds of UAVs. In addition, swarms provide the benefit of redundancy. If one of the UAVs is lost another UAV within the swarm can compensate. This means that higher risk targets can be monitored without the fear of losing the one UAV responsible for that area. It also means that an unexpected mechanical failure of one of the UAVs will not change the dynamics of a critical mission.

Challenges

UAVs have the potential to change the field of aviation, but, in order for this potential to be realized, significant advances in current control technologies must arise. Just as early aviation pioneers struggled with the development of aerodynamic control systems that would enable one man to control speed, pitch, yaw and roll simultaneously, modern researchers must develop means for one operator, or a small team of operators, to manipulate the navigation systems, mission objectives and sensors of multiple UAVs. These tasks are

further complicated by the two dimensional nature of current multiple UAV interfaces. Few people foresaw the impact that Wilbur Wright's controlled flight would have on the world, and it is unlikely that even those researching UAV control will be able to anticipate the impact that an effective multiple UAV control interface will have on the future.

Automation will be a critical component to this technology. A human operator will not be able to directly teleoperate multiple UAVs at the same time but complete autonomy is not yet a feasible or even desirable option [2][9]. While artificial intelligence and automation can accomplish some very sophisticated tasks in both the civilian and military world, it comes down to an issue of trust. Automated systems make mistakes. The FAA is not prepared to allow unmonitored vehicles to fly through the crowded U.S. airspace while the U.S. military is not prepared to let armed UAVs make firing decisions on their own. The FAA does not want to be held responsible when a unmonitored aircraft crashes into a passenger jet. The military does not want to be held responsible when a machine accidentally targets a civilian or friendly. UAV control systems need to use a blend of autonomous and human directed behavior as the UAV operator transitions from pilot to manager.

Modern UAVs have a sophisticated flight control system that allows them to fly paths on their own. Boeing's X-45 and the Air Force's GlobalHawk can currently fly between a set of specified waypoints without human intervention. These UAVs are controlled by the manipulation of their waypoints. This capability forms the basis of an automated navigation system that needs human oversight. There are three requirements inherent in this automated system: the human operator must be able to visualize the UAV's path, verify its suitability and correct it if necessary. When errors occur in this automated system human intervention is

required; however, the acts of verification and correction become difficult, if not impossible, if the operator cannot easily visualize the path of the vehicle. Current 2D interfaces effectively convey the longitude and latitude of the UAV, but they are limited in their ability to convey altitude. This limitation can be overcome with the implementation of a 3D interface.

Mission management is another critical component of multiple UAV control. This is especially true in the military's experience with UAVs. All aerial military operations start with a basic mission plan also known as an air tasking order (ATO). The ATO is often developed by a weapon's director several days prior to mission execution and contains objectives that need to be met. These objectives can include targets to be destroyed, reconnaissance pictures to be taken and operational areas to avoid. However, due to the datedness of these mission plans and the unpredictability of war, situations often arise that were not anticipated in the original plan. Those executing the mission plan must be capable of dealing with these unexpected events. Training, experience and initiative help pilots respond to these challenges. Semi-autonomous unmanned aircraft do not have the pilot's capacity to learn from training or to draw upon past experience. For this reason, human operators must be capable of providing this expertise and supervision to every unmanned vehicle under their control. The UAV operator must have good situational awareness to accomplish this task. In current 2D UAV interfaces operators must construct this awareness from completely exocentric data. A 3D interface can provide both an exocentric view and an egocentric view, increasing the operator's situational awareness.

Additionally, in a system where a single operator controls many UAVs, that operator will need to be able to handle a wide variety of information feeds and sensors. The most

useful and prevalent of these information sources will be the video feeds and still pictures. Video feeds provide motion capture, which can be important, but the resolution is typically fairly low. Still picture provides higher resolution imagery that may help distinguish subtle features. Using current interfaces, an operator must mentally place the imagery in the overall context of the battlefield. The 3D interfaces presented in this dissertation offer the ability to place the imagery within the context of a 3D virtual environment.

One last concern that is held by both civilian and military operators alike is the concept of shared fate. Catastrophic errors or enemy threats facing the vehicle directly affect the life of the pilot. This shared fate prompts certain survival skills and instincts that are not always present with remote operators whose fate is not shared with the vehicle. 2D interfaces do nothing to convey to the operator the sense that they are present inside the vehicle. A 3D interface can enhance the operator's sense of presence by placing them within a virtual environment that closely resembles the operating environment of the UAV.

UAV Control Research

The U.S. Armed Forces' interest in unmanned systems, primarily as reconnaissance tools, and the considerable research effort invested in them have resulted in several unmanned aircraft that are in active use today. These include the Army's Shadow and Hunter, the Air Force's Predator and GlobalHawk and the Navy's Pioneer. These UAVs have seen prolific use in current military operations. Each UAV is piloted by a ground control station that is usually in reasonable proximity to the UAV's operational environment with the exception of the Predator. These ground control stations are often not connected to

mission control where the ATOs are issued. This disparity has caused conflicts with manned operations through the lack of a centralized control station.

Additionally, each ground control station requires a team of operators in order to function with a reasonable level of safety and effectiveness. Despite successful military operations, incident data suggests that current UAV interfaces are not as robust as desired [17][51]. Indeed, a fair number of UAVs have been lost due to human factors related issues [17]. These interface issues include, loss of situational awareness, poor interface design and crew miscommunication. Researchers have proposed various interface improvements [11][4][18].

Ruff et al experimented with voice as an alternative to some of the manual button presses used in the Predator ground control station [4]. They found that voice manipulation provided a more pleasant operating experience for the human's controlling the UAV while at the same time increasing operator performance. They reasoned that the human operators could invest more attention towards understanding the UAV's environment rather than manipulating the UAV's interface.

Quigley et al experimented with a wide variety of user interfaces that controlled a small fixed-wing UAV. The capabilities of this UAV generally resembled the capabilities of the Army's Shadow or Hunter. The authors' initial experimentation revealed some promising interface methods. One of these methods was direct manipulation. Using direct manipulation the user could alter a simple graphical representation of the UAV's vital statistics (heading, roll, speed, altitude) to steer the real UAV. Another method that demonstrated promising results was joystick control. Joystick control used a more advanced graphical representation of the UAV that was changed by user input. Lastly, Quigley et al

tested a physical icon interface. With the same graphical representation used in joystick control, the operator could manipulate the heading and roll of the physical model, which would then change the behavior of the UAV.

These interface improvements could help in the operation of a single UAV. While advances in automated flight control and the presence of multiple UAVs make the interface issues of controlling one UAV less important, the primary lesson learned from operating a single UAV remains: intelligent interface design is crucial.

VR Aided Teleoperation

In 2002, the author began work on a new teleoperation control system, combining vehicle dynamics simulation, position and orientation tracking and a virtual reality representation of the operational environment to create a vehicle control station that provides superior situational awareness and vehicle control in the presence of signal lag [28][29]. The primary goal of this system was to develop an interface that was easier on the operator. Instead of requiring the operator to do mental gymnastics to compensate for lag, the control system made it so that the operator could drive as if lag were not an issue. The primary components of this new VR aided teleoperation system are shown in Figure 1.

Using an appropriate control interface, the VR-aided teleoperator controlled the vehicle from a virtual environment displayed by the image generator. The operator's commands were sent to a dynamics simulation that used these inputs to predict the dynamic state of the virtual vehicle. The dynamic state included information such as position, velocity, acceleration and heading. The state created by the dynamics engine was a

simulated state, used to both position the virtual vehicle and provide a desired path for the teleoperated vehicle.

As the teleoperated vehicle received these simulated states they were synchronized to account for the lag and jitter generated by the communications delay. The vehicle used these synchronized simulated states as a series of goal states. A simulation run locally on the vehicle determined the inputs required to get the vehicle to approach the simulated state from its current state. Of course, to calculate these inputs, the current state of the vehicle had to be determined. A tracking system or observer provided this state information. The tracking system was responsible for reporting the vehicle's state information to the operator and the vehicle. The operator used the reported vehicle position, corrected for lag and subsequent vehicle control, to visualize the likely future position of the vehicle. As shown in Figure 2 below, this predicted position was depicted graphically as a wire-frame box surrounding the virtual vehicle that grew and shrunk with the difference between the simulated state and the vehicle's predicted state. This wire-frame envelope allowed operators to adjust their control to obtain higher fidelity with the remote vehicle, closing the loop between the human and the computer controlling the remote vehicle.

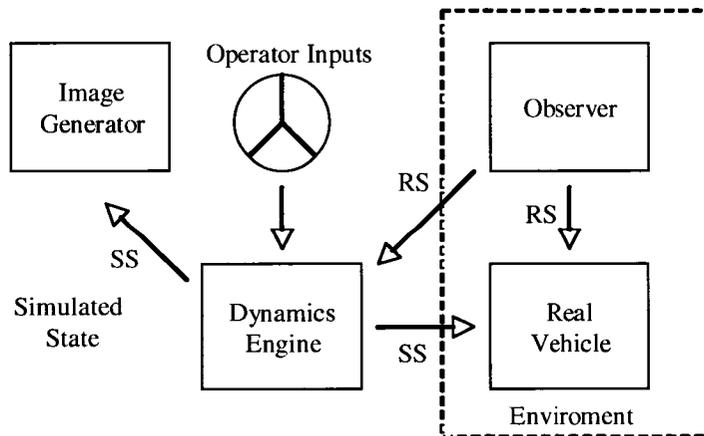


Figure 1. General System Model

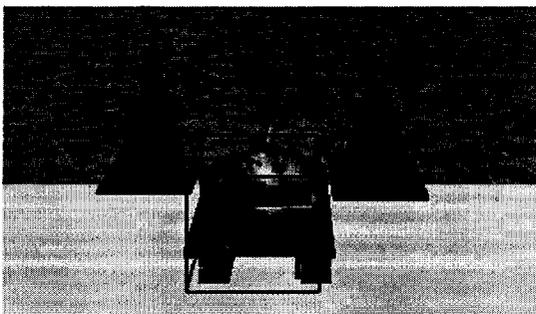


Figure 2. Wire-frame Envelope

Test Results

To assess the merit of these ideas, the research team implemented a test version of the VR-Aided teleoperation system described above, using a remote controlled model tank.

Wiring the tank controller to a circuit board, made it possible to use a computer to control the vehicle. By measuring the tank's response to inputs from the controller, it was possible to model the vehicle's dynamics. This simulation model could closely predict the response of the tank to a given input. The computer running this simulation (the dynamics engine) was a Dell PC attached to a Microsoft Sidewinder steering wheel. The dynamics engine used the tank simulation to generate the simulated states and send them to the laptop controlling the tank (Figure 1).

The observer, an optical tracking system, looked for two 3" cardboard squares, one red and one blue, which were placed on the top of the front and rear of the tank, respectively. A web cam situated at a fixed location above the operational environment used an image-processing algorithm to find these blue and red markers. Camera calibration enabled conversion of marker pixel location to a real-world location. Incorporating the fixed distance between the vehicle markers and the center of the tank, the system could determine both the tank's position and heading. Further, by storing the tank's previous position and orientation,

the system could provide a first order approximation of the tank's linear and angular velocity. This information comprised the real vehicle state required by the vehicle and the dynamics engine (Figure 1). The image generator was an SGI RealityEngine2, and it used simulated and real vehicle states to generate a model of the tank in the virtual world. VRAC's C6 virtual world display device is a 10'x10'x10' room where each wall is capable of displaying a rear projected stereo image in which the user is immersed. The dynamics PC and steering wheel were setup in the C6 to place the operator within the virtual representation of the operating environment.

All of the components of the test system were connected on the same low latency network. To simulate the signal delay present in a real control situation, each command sent between the operator and the vehicle was delayed before transmission. Of course, constant signal delay is not sufficient to model real world behavior. To simulate variable signal delay, random $\pm 10\%$ perturbations in the delay times were introduced. To manage the changing signal delay times, operator commands to the vehicle were buffered at the vehicle to ensure that they could be properly spaced in time. This type of packet buffering is a common technique in distributed systems such as streaming video. Ensuring that the commands reach the vehicle within the expected timeframe helped the vehicle follow the path laid out by the operator.

In the system test, the tank was piloted through a course of cone gates using three methods: direct control, camera-aided teleoperation and virtual teleoperation. The average course completion time and number of gates navigated was recorded for each method. Because direct control does not suffer from signal delay and allows the operator to see the vehicle and its environment, the team chose direct control as the baseline. Because camera-

Table 1. Test Results

Test	Signal Delay (s)	Average Time (s)	Average Cones Navigated
Direct	0	26.0	5.00
Camera	0.9-1.1	101.1	4.67
Camera	4.5-5.5	357.7	4.33
Camera	9-11	583.5	4.33
VR	0.9-1.1	32.5	4.67
VR	4.5-5.5	34.7	5.00
VR	9-11	31.0	4.67

aided teleoperation represents the most common method for current vehicle teleoperation, it made sense to test the VR method against it. Test runs were performed for three levels (one, five and ten seconds) of signal delay. Three runs of each type of test were performed and the average results are shown in Table 1.

These preliminary results indicate that the VR-aided teleoperation system improved operator performance when compared to a lagged video-based teleoperation system. With VR-aided teleoperation, the average time to completion appeared to be unaffected by signal delay, even with delays of up to 10 seconds. In contrast, the camera aided teleoperation system completion times increased markedly with only a modest increase in signal delay. Furthermore, the situational awareness of the operator was enhanced as evidenced by the decrease in the number of cones knocked down when using VR-aided teleoperation. This preliminary research into simulated virtual environments suggested that a 3D world did indeed enhance the operator sense of presence.

Multiple UAV Control Research

Current research into the area of multiple UAV control can be categorized by the level of autonomy used to control the UAVs flight path. While the military does not consider

completely autonomous strategies to be a viable solution, these strategies are presented in order to demonstrate the capabilities of the UAV flight path control algorithms. Two more realistic strategies are currently being researched that build upon this foundation. High autonomy relies very little on the operator for input or guidance but allows broad directives to be given. Mixed autonomy requires a greater degree of human input into the system.

The ultimate goal of these technologies is to allow a single operator to effectively control many UAVs. As these technologies grow, the human's role will change from pilot to manager. A UAV pilot will be valued more for their information processing and analysis skills rather than their flight skills. This evolution will allow a small team to cooperate to accomplish the mission goals. While one team member pays attention to the UAVs' flight paths, another team member could focus on the UAVs' sensor information. Regardless of team make up and size, automation will be needed to achieve the desired human to machine control ratios.

Autonomous Strategies

Autonomous strategies use flight path planning algorithms from the beginning of a mission to its end. Without human intervention, the path planning algorithms must be able to adapt to a dynamic mission environment. This has led to research of great interest not only to UAV control but also robotics. Li et al and Beard et al have addressed the path planning challenges for two different UAV mission types, Suppression of Enemy Air Defenses (SEAD) and Intelligence, Surveillance, and Reconnaissance (ISR) [12][13]. Although these papers represent a very small subset of a much larger research base in path planning for

autonomous vehicles [20][21][22]. These papers were selected for their direct relevance to UAVs.

Current Research

Suppression of Enemy Air Defenses is a long and dangerous mission for manned aircraft. SEAD mission objectives require deep flights into enemy territory for the purpose of striking at the enemy's air defenses. This high risk and demanding mission is a perfect candidate for unmanned aircraft. Using SEAD as a model, Li et al researched the creation of an autonomous flight path through enemy territory that contained static targets, static known threats, mobile known threats, pop up or unknown static threats, and pop up mobile threats [12].

The first step of Li et al's method was the creation of a path that: hit all of the targets in order, minimized exposure to the known static threats and tried to minimize fuel consumption. This end product of this step was a flight path that did not account for mobile or unknown threats. If an unexpected or mobile threat was encountered during the UAV's flight, the UAV used its next waypoint as an intermediate goal [12]. This intermediate goal was used to optimize the local flight plan with regards to threat exposure and fuel consumption. The resulting local flight path was then smoothed to ensure it could be followed by the UAV. The authors' envisioned that their flight path algorithm could be used for a small formation of UAVs. Each UAV in the formation would have a specific offset from the lead UAV.

If SEAD missions are examples of the dangerous, then ISR missions are examples of the dull. Reconnaissance missions demand a tremendous amount of stamina from a human pilot. This is one of the reasons that unmanned aircraft have been used in this arena. Beard

et al described an ISR path planning algorithm for multiple independent UAVs [13]. These independent UAVs had to work cooperatively to cover as many areas of interest as possible, while preferably avoiding threats and collisions. In this scenario, the UAVs also had to stay within communication range to ensure cooperation.

The authors translated these mission parameters into a set of mathematical equations and then solved for the optimal flight paths. Finding these flight paths took non-polynomial computational time and was therefore impractical. In order to deal with this impracticality, they reduced the set of possible paths, which resulted in the creation of two sub-optimal but polynomial-time algorithms [13].

Current Application

Autonomous strategies are currently in use in the U.S. Military. The Tomahawk cruise-missile is a successful example of a system that is both unmanned and completely autonomous. The cruise missile is given a target to hit and then trusted to guide itself to that target without human intervention. There are two reasons that this solution is acceptable, the Tomahawk has a very specific mission to carry out, and the Tomahawk is also expendable ordinance. These two qualities are generally not associated with the control of UAVs. UAV's that are capable of performing the complicated missions of SEAD and ISR are not considered expendable.

Advantages and Disadvantages

Autonomous strategies offer the advantages of a computer's computational speed and power. They take advantage of the fact that modern computers have large memories. The limitation on the number of UAVs is typically dependent upon the path planning's algorithms computational complexity. The path planning algorithm's complexity is usually

driven by the size of the area over which the UAV is flying and not the number of UAVs. Like the Tomahawk cruise missile, autonomous UAV strategies are also “fire and forget”. They require no attention from the human operator except at the mission planning stage.

The major disadvantage is that the human operator cannot correct mistakes in the automation. Errors in the autonomous solutions will crop up due to factors outside the knowledge of the artificial intelligence. Designing an algorithm that takes into account weather for example may not be computationally feasible. Additionally, manned aircraft may have an unexpected need to operate in a region of airspace that the UAV is occupying. Without the ability for human intervention of the UAV’s path, the Air Controllers and human pilots are solely responsible to de-conflict the airspace. Keeping a human in the loop helps prevent catastrophic mistakes by taking advantage of the human’s ability to handle this outside information.

High Autonomy Strategies

High autonomy strategies use path-planning algorithms similar to the ones described above. However, unlike the completely autonomous strategies, high autonomy strategies require human input to accomplish the overall goals of the mission. While the human operator is not responsible for the specific paths taken by the UAVs, the planned paths are generated with the operator’s goals in mind. This type of autonomy level suits the control of a large number of small UAVs often referred to as a swarm [23][24]. Because the control of a swarm of UAVs is beyond the scope of this discussion, swarming algorithms will not be presented here.

Current Research

Miller et al proposed a “playbook” control strategy [5]. The playbook concept was analogous to playbooks found in sports. All UAVs controlled by the operator were aware of a common set of plays. There were two important concepts to note about each play. A play reflected a goal or task that the operator wanted accomplished, and the implementation of a play was not precisely defined. This second concept allowed for flexibility in the play’s execution.

Miller et al defined a set of plays for unmanned aerial vehicles: Overwatch, Track Target, Area Recon, etc [5]. These plays reflected frequent goals of an operator managing multiple UAVs. The operator was responsible for calling the appropriate play. An intelligent assignment agent responded to this play call and determined how to allocate UAVs to carry out the operator’s request. The intelligent agent could report back information on how long it would take for the play to start (time on target), how long the play could be sustained (time off target); and other play related details.

There were two interfaces designed for this system. One interface was designed for a laptop and the other was designed for a PDA. The laptop interface used FalconView [19]. FalconView provided a 2D map view of the operational environment with important information layered over this map. With this interface the operator could monitor the current state of the UAVs and assign plays to a group or a specific UAV, although, assigning plays to an individual was rarely necessary. The PDA interface did not incorporate FalconView but provided widgets that allowed the user to interact with the system in similar ways. The user interface for the PDA did not require users to ever assign plays to specific UAVs due to

the limited amount of situational awareness that the PDA operator would have. But the interface did allow operators to call plays for the entire group of UAVs.

Parasuraman et al experimented with a variation of Miller et al's research [10]. Roboflag, an autonomous systems research platform in which two teams play capture the flag, was used to pit a human controlled team against an autonomous team. The first team to successfully capture the other team's flag was the winner. The human operators were given two different styles of robot control: manual or playbook. In playbook control, the human operator's robots could be assigned plays, such as offense, defense and border patrol. Offensive robots would try to capture the enemy flag. Defensive robots would try to protect the flag and border patrol robots would try to protect the border.

Parasuraman et al found that the human operators' performance was better using the playbook control method. Using the playbook method, the human operators were more likely to beat the artificial intelligence of the other team. The interface for this experiment was similar to the 2D map interface provided by Falconview. The operator could see the position of all the robots and act upon individuals within the display.

Current Application

Two possible use cases of high autonomy strategies are swarm control and close air reconnaissance. With a swarm it is impossible for a single operator to pay attention to a single UAV's behavior. The operator must be able to direct the swarm using higher-level directives indicative of this level of autonomy.

Close air reconnaissance is another use case envisioned for high autonomy strategies. Close air reconnaissance is performed by military personnel in the field that need information quickly but do not have a lot of equipment. Any UAV control system that they might carry

would have to be small, light, and durable. The limited display capability of such a device would limit their situational awareness. High autonomy strategies would allow an operator in the field to call a play in spite of this considerable handicap.

Advantages and Disadvantages

High autonomy strategies, like autonomous strategies, take advantage of a computer's computational power. Additionally, they also provide the opportunity for user input. The human operators can issue overall objectives and commands to the vehicles under their control. The issuing of objectives as opposed to exact paths can reduce the amount of awareness needed to control an individual UAV. This reduction could result in more UAVs under the control of a single operator. Another advantage to the issuing of objectives is that the UAV could optimize its path with regard to fuel while still accomplishing the intent of the user.

This level of abstraction also has some considerable disadvantages. This system may be more prone to what is referred to as mode confusion. Mode confusion occurs when the operator does not understand or has an incorrect prediction of the automation's behavior. In this case the user may not be able to predict how a UAV will carry out the objective or have a misunderstanding on what objective a UAV is carrying out. This confusion could potentially lead to some serious problems.

Another serious issue associated with this level of automation is lack of detailed control. The UAV control problem is unique from other automation challenges. As pointed out by Linegang et al "At times the detailed behavior of an individual UAV can be very important" [14]. A controller may want the ability to change the exact path of a UAV, or alternatively, to access individual UAV's reconnaissance information. If all commands are

high level the user could lose the ability to affect these details. This lack of detailed control becomes more important when UAVs operate in air space that is cohabited by manned aircraft or when they become armed.

Mixed Autonomy Strategies

Mixed autonomy control strategies are often referred to in the UAV community as mixed initiative control strategies. Both the human and the automated system take initiative to accomplish tasks at different times. This requires that the human operator be more aware of the UAV's current state.

The difference between this strategy and high autonomy is analogous to the distinction between a co-pilot and a passenger. A passenger does not expect to take control of the vehicle, but can still offer suggestions as to the vehicle's destination. Only a low level of situational awareness is needed to perform this task. Co-pilots on the other hand have to maintain a greater degree of situational awareness, because they may be called upon to control the vehicle. In essence, the operators' attention demands are much higher than in the previously presented strategies, but the operator's ability to intervene and effect change is better. This places a burden on the interface of the control system.

Current Research

Ruff et al's research explored one example of a mixed autonomy control system [2][3][9]. In this research the UAVs started a mission with predetermined paths based on their objectives. However, whenever an unexpected event occurred during execution, the UAVs requested the human operator's attention. This attention was needed to confirm or reject a new alternative path that the UAV path-planning algorithm had developed.

Two basic methods of human intervention were tested: manage by consent (MBC) and manage by exception (MBE). In MBC the UAV would not change paths without consent, the human operator had to confirm the new flight path before the UAV can act upon it. In MBE the UAV could change paths without the operator's consent and would in fact automatically change paths if the operator did not reject the new flight path within a certain amount of time.

Ruff et al's system relied upon a 2D map interface, called the Tactical Situation Display, to convey each UAV's position and current path. A pop up window informed the user of a UAV's possible flight path change, which could then be examined in order to make an accept-or-reject decision. Several user tests were performed on this system that evaluated the control of one, two and four UAVs [9]. Not surprisingly, operator performance decreased with an increased number of UAVs. Automation error was also introduced to prevent the proposed flight path changes from always being correct. MBC was found to be the best in two measurements: obtaining a favorable operator opinion and user performance.

There were at least two reasons for these results. First, MBE violated the user's trust by acting incorrectly without consent. When automated systems make mistakes it greatly reduces the amount of trust a human has in the system [6]. This distrust caused MBE to receive a poor user rating. On the other hand MBC allowed the user to verify a new behavior before the automation made a mistake. Even though the time it took to verify could cause problems, the users would not feel "betrayed" by the system [9].

In addition, MBC allowed users to prioritize the alerts with greater efficiency. MBC UAVs stay on the current projected path unless told otherwise. This behavior allowed users to have an accurate picture of the UAV's future behavior. This solid situational awareness

allowed users to prioritize alerts based on UAV need. MBE users, however, could not achieve this level of situational awareness, as the future behavior of a UAV was uncertain. This uncertainty made the users choose UAV alerts based on time to ensure that they would get to analyze a path before it was taken.

Another example of mixed autonomy control can be found in DARPA's Mixed Initiative Control of Automata-teams (MICA) research. MICA's goal was to have a single human operator manage multiple UAVs, which were performing different tasks. This goal was split up into two parts: UAV assignment and mission execution.

Task assignment is covered in the research of Xu et al and Linegang et al [15][14]. One of the main challenges of automatically assigning UAVs to mission goals is ensuring that the human operators have a solid understanding of mission resources, goals, and resulting assignments. In order to better understand operator needs a user study was performed. Common questions raised in the study included: what is the weapons status of that UAV? why is that UAV not assigned? and will that UAV take out that target? [14]

Once the UAVs were assigned to mission tasks the mission execution phase began. During mission execution both the human user and the autonomous system were allowed to change a UAV's assignment or flight path. MICA's primary interface was a 2D map based display. Linegang et al performed a user study to analyze what information the user would require for successful mission completion. They found that the map interface alone was inadequate. User's felt that timeline information was also needed.

Penner et al looked into an object-oriented system that would automatically create the interfaces and information displays needed by the user [16]. Each UAV or item of interest in the environment owned a list of information traits and changeable parameters. When a UAV

was queried the UAV object presented all the appropriate information. If a SEAD mission were queried it would contain information about the mission as well as the ability to drill down to the individual UAVs participating in that mission.

Current Application

Currently MICA is exploring a mixed autonomy approach to SEAD and ISR mission types. A small team of operators would control a group of UAVs operating in the field. The ground control station would be close enough to provide effective control of the vehicles. These UAVs would be capable of delivering ordinance on target and also performing reconnaissance missions into deep enemy territory. No published field tests have been conducted at this point.

Advantages and Disadvantages

The primary advantage of mixed autonomy strategies is detailed control. One immediate result of this advantage is flexibility. For example, if a UAV's flight path interferes with another ongoing mission the flight path can be modified without changing the overall goal of the UAV. Additionally, the operator is expected to verify certain UAV behavior, which could reduce the risk of a UAV identifying and destroying a civilian target on accident.

Conversely, mixed autonomy also requires greater operator attention per UAV. The operator has to maintain considerable situational awareness for the entire mission. Compounding this problem, mixed autonomy may also suffer from mode confusion. As the human and automated systems interact responsibilities must be clearly defined. Considerable research must be done to understand how to maintain situational awareness while mitigating mode confusion.

Command and Control Research

Falconview, which allows an operator to visualize airspace in 2D, represents the current state of the art in command and control software and is used extensively throughout the department of defense [19]. Taking advantage of point and click and GUI interfaces, this software permits the user to overlay various UAV state information on a map. The application works reasonably well, but the limitations of the 2-D interface still remain. To better aid its operators in visualizing the airspace, the Falconview developers created the plug-in, SkyView3D. This plug-in takes the 2D world shown and renders a primitive 3-D version in a separate window. The SkyView3D representation of the vehicle's path is not tied to the ground in any way and is consequently hard to place within the 3D world, Figure 3. The path shown below is floating above the ground. The perspective of the camera could get in the way of figuring out the paths position. SkyView3D is also not immersive and so does little to improve the sense of presence with the operator. The fact that most of the interface options only work with the 2D interface further trivializes the 3D interface and view.

Dragon, a 3D command and control interface, was developed at Virginia Tech in 1999 [25][27]. Compellingly visual for its time, Dragon showed strength in conveying the relative positions of the entities on the battlefield. The chosen interface device, a joystick provided the user with a sense of natural and intuitive navigation, but since it only had three buttons, the designers were limited in the number of options they could provide for accessing information about the events taking place on the battlefield. In order to allow their users to select entities on the battlefield, the designers gave the joystick the functionality of a laser pointer. The user could draw a line from the end of the joystick to an object in the scene.

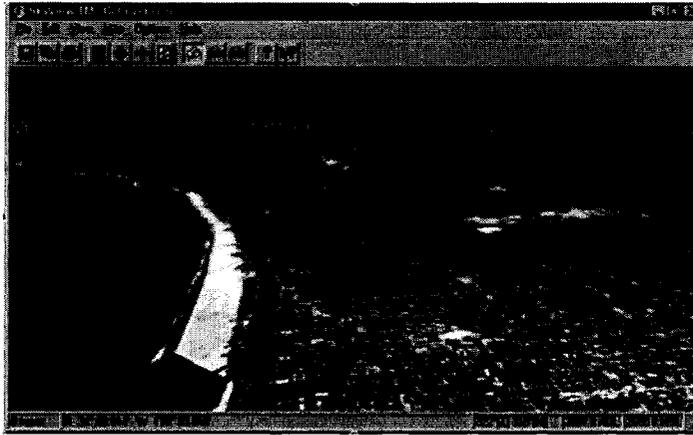


Figure 3. Skyview 3D Screenshot

Unfortunately, this kind of selection is similar to trying to poke a particular leaf on a tree with a long stick. The combination of scene clutter and the imprecision of the line make this an awkward tool. It is generally accepted that the picking problem is a hard problem in 3D [39].

The designers of Dragon ran a series of experiments to test the functionality of their system. [26]. The participants were asked to perform simple navigation tasks with different frames of reference such as egocentric vs. exocentric. The operators also completed these tasks on different display devices, a monitor, a four-wall cave, a VR workbench and a single cave wall. The most immersive of these devices was the four-wall cave. The most interesting finding was that participants performed worse using egocentric navigation in the cave. This contradicts the generally held conception that egocentric navigation is better in an immersive environment. Further investigation into this phenomenon is warranted [26].

In 2000, a research team at Iowa State University's Virtual Reality Applications Center (VRAC) began work with the Air Force Research Lab's Human Effectiveness Directorate and the Iowa National Guard's 133rd Air Control Squadron to develop an

immersive VR system for distributed mission training called the Virtual Battlespace. The Virtual Battlespace integrated information about tracks, targets, sensors and threats into an interactive virtual reality environment that consolidated the available information about the Battlespace into a single coherent picture that could be viewed from multiple perspectives and scales [32][33]. Visualizing engagements in this way could be useful in a wide variety of contexts including historical mission review, mission planning, pre-briefing, post-briefing and live observation of distributed mission training scenarios.

Knowledge gained from the development of the Virtual Battlespace contributed to the idea of creating a cohesive virtual world, representing the status of real time and *a priori* information about an engagement [32][33]. Figure 4 shows the Virtual Battlespace environment displayed on a four-walled stereo projection system, the C4, at VRAC.

Just like the Dragon application before it, the application's strength laid in its ability to convey geographical and spatial data. The Virtual Battlespace showed promise as a center of information fusion because its immersive nature made it a convenient way to present large amounts of information in a single display environment.



Figure 4. Battlespace in the C4

This Virtual Battlespace application was far from perfect. It had limited portability and ran on SGI Irix, which meant it could not operate on a cluster of machines. In addition, the designers experimented with a java tablet selection interface that ultimately proved unwieldy.

Trying to find solutions to these problems provided many lessons for future development. The main reason that the application suffered from performance issues was lack of a fundamental design concept. Over the course of the Virtual Battlespace's development, the code base could not adjust to the growing need for change. The application lacked an easy way to adapt to these new research objectives and became difficult to manage. Answering these challenges ultimately required a restructuring of the battlespace application from the ground up in order to make it both flexible and extensible.

Research Objective

The ultimate goal of the research presented in this dissertation was to expand and improve the tool set available for effective multiple UAV control. To accomplish this, three dependent goals had to be met: the creation of a 3D battlefield visualization platform, the design and implementation of effective 3D interfaces that would allow UAV operators to perform their tasks and a determination of the validity of this new 3D interface.

3D Battlefield Visualization

A flexible software platform is crucial to any future research, therefore, the software foundation of this research had to be stable, flexible, extensible and powerful. Stability was a requirement because important human factors research could depend on the performance of the application; flexibility because the operator's needs and the available facilities might call

for varied display environments; extensibility because researchers or operators might wish to add, revise or remove elements in order to test the effectiveness of individual portions of the interface or to meet the needs of a particular operation and powerful because performance rates need to remain consistent even when an operator is controlling a large number of UAVs.

Accomplishing these goals presented many challenges to a software engineer. A software foundation that supported new interfaces and different display environments must be well designed. Because commodity hardware has made clustering the popular way of displaying in different environments, the foundation must support the ability to run seamlessly across multiple machines. Lastly, the overhead computational cost of the architecture cannot take away from the performance of the application.

3D Interfaces for UAV Control

Effective 3D interfaces should allow an operator to easily interact with multiple UAVs in a 3D environment. These innovations are important to the fundamental goal of the project. The operator must be able to effectively visualize the UAV's operational environment: efficiently interact with a UAV's sensors; quickly react to unexpected situations and correctly identify UAV reconnaissance information. One of the biggest challenges in this goal is overcoming the loss of the mouse. Traditional 2D applications benefit from the presence of the mouse, a familiar interface that is very precise. The 3D immersive analog is the game-pad. Using the game-pad interface the operator can rapidly pick and manipulate objects in the environment and effectively visualize the result. Another challenge to be met is the transition from 2D visual representations to 3D representations.

Determine Effectiveness of 3D Interface

Once an application has been built and designed for a specific purpose it is important to look at the effectiveness of that application in accomplishing its desired task. Novel interfaces are not better simply because they are new. Immersive command and control of multiple UAVs is a fairly new concept that has not been thoroughly explored. And so any researchers developing systems related to multiple UAV command and control should seek user feedback to validate their design.

SOFTWARE FOUNDATIONS

The software foundation was essential to this research and will be fundamental to any future immersive Battlespace research. The application was built with C++, and took advantage of object oriented coding methods to create a stable and flexible platform. In addition to C++ several APIs were used to shorten the development cycle and to take advantage of previous work in the area of graphics and virtual reality. The software architecture was designed to take advantage of these foundations. The result is referred to here as the Battlespace Research Platform.

VRJuggler [34][36] is a powerful open source virtual reality toolkit that has been developed at Iowa State University's Virtual Reality Applications Center. Carolina Cruz-Neira and a team of students developed VRJuggler to create an open source platform to facilitate the development of virtual reality applications. VRJuggler supports flexible VR development by providing an API that an application can be built on top off. An application built in this way can be supplied different configuration files to enable it to run on different display environments. This flexibility allowed the application to be run on a wide range of immersive display devices. VRJuggler also contains some basic tools for clustering an application to run on multiple machines [47].

OpenSG [37] is an OpenGL based scene graph that was used to organize and optimize the graphics of the Battlespace application. It provides many useful tools that simplify the development of a complex OpenGL scene. The Battlespace Research Platform took advantage of the scenegraph management and manipulation tools to create a visually appealing and dynamic environment.

Command Driven Architecture

It was critical to address the challenges posed by creating a flexible, extensible and reliable software architecture to avoid problems that previous versions of Battlespace encountered. The command driven architecture developed for this research meets some of these challenges. The book *Design Patterns* inspired a design, which split the application into major subsystems [41]. Communication between these subsystems was achieved through the creation and processing of commands. The commands were passed between subsystems via a command loop. Because the commands also determined the behavior of the system, they provided an easy way to cluster the application.

Commands

The commands enhanced the flexibility of the overall system by promoting subsystem independence and flexible interfaces. The commands isolated each of the subsystems from one another. The sender of a command did not need to know what other subsystems processed that command. Even when the sender's command was relevant to multiple other subsystems, the additional receivers had no impact on the sender. For example, a subsystem that was responsible for managing the OpenGL camera could broadcast the camera's current position every frame. This subsystem would not need to know if 3 or 4 other subsystems used this command's information. The benefit also extended to the receiver. The receiver of a particular command did not need to know who issued the command. Multiple subsystems could issue the same command, based on criteria that were only known to each subsystem. This was useful when the application had different modes of operation that could be triggered in multiple different ways.

The commands that a subsystem sent and processed determined its interface. This resulted in a highly flexible interface for each of the subsystems. This flexibility also hid the implementation taking place behind the interface. This meant that a new version of a subsystem could be created and swapped with a previous implementation without any change to the other subsystems. This was possible because the subsystems did not share pointers with each other. For example, an egocentric camera manager could be swapped for an exocentric camera manager without changing any other subsystem.

Each command contained a directive, a qualifier and a vector of floats and strings. The directive represented a change in state or an action that had been generated by a particular component of the system. For example, a command directive might indicate that an entity had moved or the user had moved. The command's qualifier specified special conditions that could apply to the interpretation of that directive, e.g. smooth versus abrupt movement. The vectors allowed the subsystems to pass data that might be needed across subsystems. The fact that the vectors were floats and strings effectively prevented the passing of pointers between subsystems. In addition to these parameters the command might also specify a delay. This delay would refer to the number of frames it would wait until issued. This would allow a subsystem to issue a series of commands that would be executed in a specific sequence.

Command Loop

The Command Loop was the unifying element of the command driven architecture that enabled communication between the various subsystems. Each frame of the application was divided into three stages. The update of all subsystems and the creation of any

commands was the first stage. The distribution and processing of these commands by each subsystem was the second stage. The drawing of the frame was the third and final stage. The UAV control application had about 10 different subsystems, as shown in Figure 5, each with an important role in the behavior of the application.

One of the crucial aspects to this type of design is developing an understanding of the scope of each component. If a component's scope is too narrow then the number of subsystems and commands could become unmanageably large. If the scope of the components is too large then the number of components will decrease and the benefits of the architecture's design will be minimal. There are no hard and fast rules on how much functionality should be encapsulated in a component, but there are a few guidelines to consider. A programmer should be able to summarize a subsystem's behavior and responsibilities into one or two sentences. For example in this system: the camera manager was responsible for the camera in the 3D world; the controller manager handled the game-pad interface. Additionally, a subsystem should not be so simple that it only deals with one or two commands. Generally an interface this specific means that its interaction could be consolidated. In the system presented, the SceneManager was an exception to this rule. The Scene Manager was responsible for drawing the terrain and surrounding environment such as the sky dome. It has a very simple interface and responded to only a few commands. But it could not be logically be subsumed by any other subsystem due to the underlying complexity of its task.

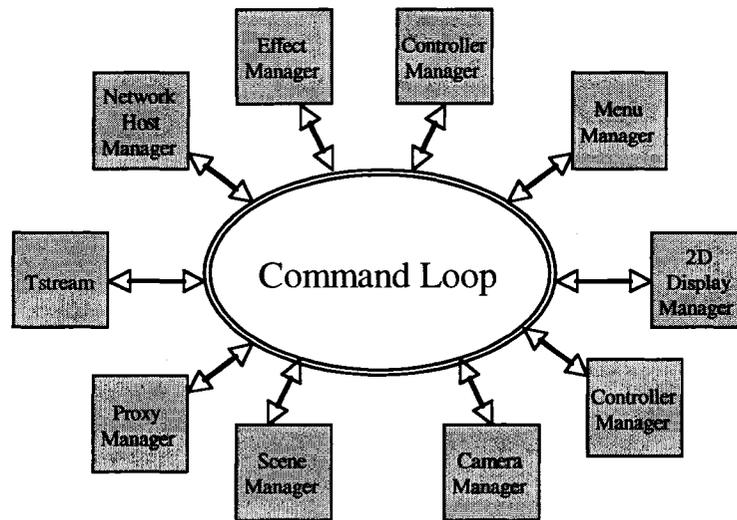


Figure 5. Command Loop

Clustering

A common task in modern computer graphics is to take advantage of multiple display surfaces or multiple computers to either increase the field of view or the resolution of the display. In order to accomplish this an increasingly common technique is to distribute the application over a cluster of networked image generating computers employing multiple versions of the application running simultaneously on each computer in the cluster. As was mentioned earlier, VRJuggler supports the clustering of applications across multiple computers for use in immersive virtual environments. This support takes care of the frame synchronization so that each frame is drawn at the same time. However, it does not ensure that the same information will be portrayed on each screen. With any complicated application there will be time dependent data. The positions of graphical objects will change over time. Since each processor in the cluster maintains its own clock, time calculations can be different across machines.

The command driven architecture and command loop made the process of synchronization simple. The behavior of the application during each frame depended on the state of the commands. If the commands on each machine of the cluster were the same then the state of each node in the cluster would be the same. For example, if all 8 cluster nodes had received all of the same updates on the position of an entity, that entity would be at the same location on all of the machines. The application ensured that the history of commands had been the same by using VRJuggler to synchronize the list of commands to be processed across all machines. If there were time dependent changes that were completely internal to a subsystem, this could be solved by having a command that set the time for each frame of the application.

Networking

Any application that deals with the control of unmanned vehicles must be network capable, because the distances involved will require networked communication. The importance of this capacity demands careful consideration.

The command driven architecture easily supported the development of a separate subsystem to handle the specific communication requirements of any UAV. Additionally, two subsystems were developed to facilitate networked communication between two command driven applications. These subsystems allowed the command and control task to be distributed across multiple environments. This distribution enables research collaboration and will ultimately be necessary for user studies and performance evaluations that have yet to be carried out.

The *NetworkManagerHost* and the *NetworkManagerGuest* subsystems managed the communication between different applications. Each frame, the host determined the appropriate commands that should be sent to the guests via a UDP connection and also checked to see if it had received any commands from its guests. The host was responsible for ensuring that each guest had an accurate representation of the battlefield. The guest could then interact with the data independently and in many cases provide valuable input. The guest might be responsible for a different set of entities, in the case of a simulated battle, or be in charge of monitoring a particular part of a battlefield.

Battlespace Research Platform

The Battlespace Research Platform (BRP) was the ultimate product of the software foundation described above. The BRP provides an operator with the ability to visualize, navigate within and interact with battlefield scenarios. Because it was built upon VRJuggler, the platform supports a wide range of immersive environments. Virtual reality is a flexible technology that allows for multiple sources of information to be integrated in a single, comprehensive view of a battle. A VR display is potentially more intuitive than 2D desktop interfaces that require users to mentally integrate information such as camera feeds and radar, which are displayed in disparate windows. With a control interface based in a virtual world, the operator will generally feel a greater sense of presence.

Generating virtual terrain that fuses satellite imagery, political boundary maps, DTED data and other sources helped to create this sense of presence. Since only general landmark features are necessary to maintain good battlefield situational awareness, the terrain model need not match every contour of the real terrain. The positions of targets and other units,

however, must be as close to their actual real world positions as possible. A virtual world can be used to collate all this pertinent information in a consistent way; one that does not require the operator to mentally maintain the relationships between information feeds.

The BRP can easily be adapted to support a wide variety of data. GPS and radar data for example could be used to position the representations of real world units in the virtual Battlespace environment. Unfortunately, this type of data is typically classified and thus not available for unclassified university research. So in order to simulate the positional data, recorded data was used. The recorded data could either be in a DIS format or, as was the case for the research presented here, in a custom format developed at VRAC.

The interaction device used in the BRP is a wireless Logitech game-pad, which emulates the interaction style of a video game (Figure 6). According to Walsh *et al*, ninety-two percent of youth ages two to seventeen play video or computer games [35]. Because of this trend many of the future operators of UAV systems will be familiar with game-pad interface devices and interaction styles. This familiarity will allow operators to transfer previous gaming experience to the UAV control environment, making the learning curve for this interface less steep.

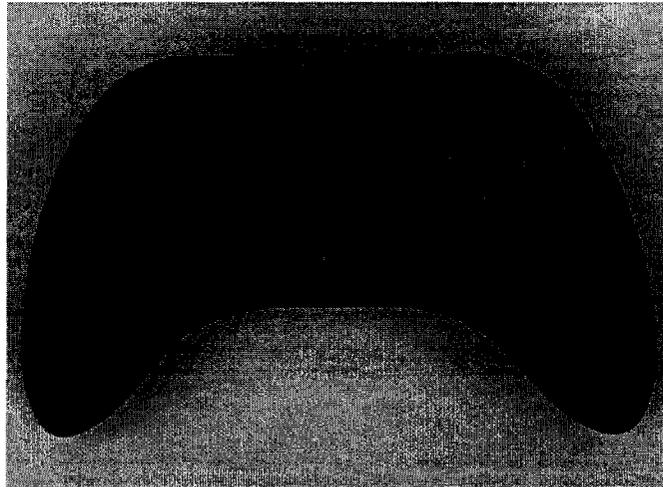


Figure 6. Gamepad Interface Device

The BRP operator can navigate around the battlefield by using the gamepad's thumbsticks. The left thumb-stick moves the operator's view forward, backward, left or right. The right thumb-stick controls pitch and yaw of the user's view. The start button brings up the menu system (shown in Figure 7) that the operator interacts with using the directional pad and other buttons. Consistent with most video games, there is a button that confirms a decision and a button that cancels a decision.

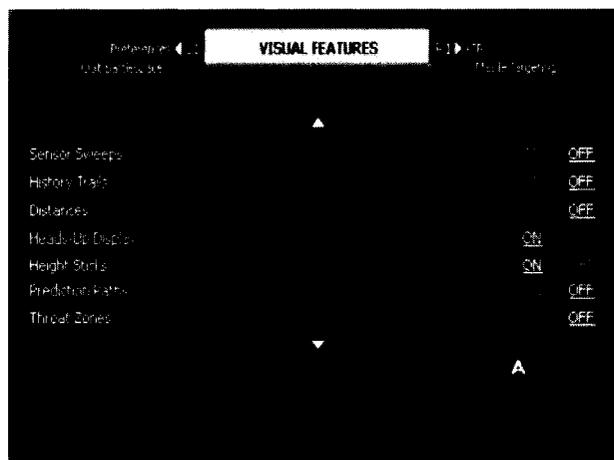


Figure 7. 2D Menu Interface

The BRP has two primary modes of operation. Strategic mode provides the operator a comprehensive view of the entire engagement. This mode is crucial for maintaining overall situational awareness. The second operational mode is referred to as tactical mode. Tactical mode allows an operator to view the battle from the perspective of a single unit within the mission.

Strategic mode, shown in Figure 8, provides a graphical interface that allows operators to easily visualize the position, allegiance and number of entities present on the battlefield. Individual units are aggregated into squads to simplify the visual clutter. As the operator navigates through the battlefield the aggregates dynamically shift their representation to indicate the number of units in that grouping. In the BRP, red units are enemies and blue units are friendlies. Additionally, the strategic models have symbolic meaning, V-shaped models represent fighters and U-shaped models represent bombers and UAVs.

During the course of a mission the operator may need to view the battlefield from multiple different perspectives in order to make the correct command decision. This can be accomplished directly using the game-pad. However, there may be times when an operator needs to recover a particular view more quickly than direct navigation permits. Because of this requirement the operator is also provided with the means to save and recall specific views. The combination of these navigation methods allows the operator to effectively monitor the battlefield.

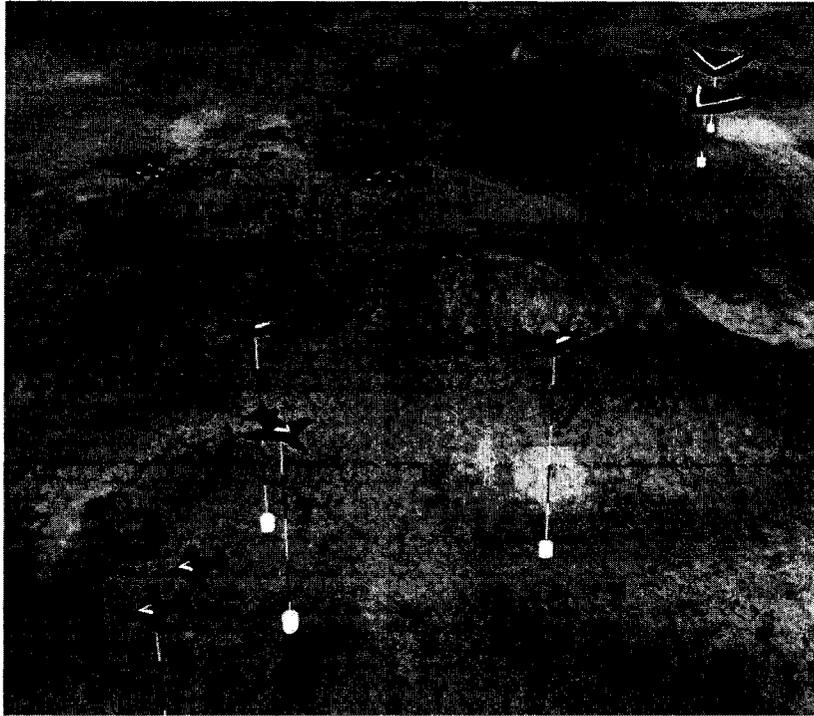


Figure 8. Strategic Mode

A quick selection method is needed to effectively interact with battlefield entities. A new selection method has been developed that will be described in further detail in the next chapter. Once the operator has the desired entity or entities selected, they can interact with that unit or aggregate using the 2D menu system (Figure 7). The menu system provides the means for turning on or off information about an individual or group of entities. The operator can turn on an entity's sensor range, which indicates the extent of its effective radar range; threat zones, which indicate a danger from opposing forces and history trails, which indicate the path that the entity took to arrive at its present location. The operator can also display the distance between selected entities. These features are shown in Figure 9.

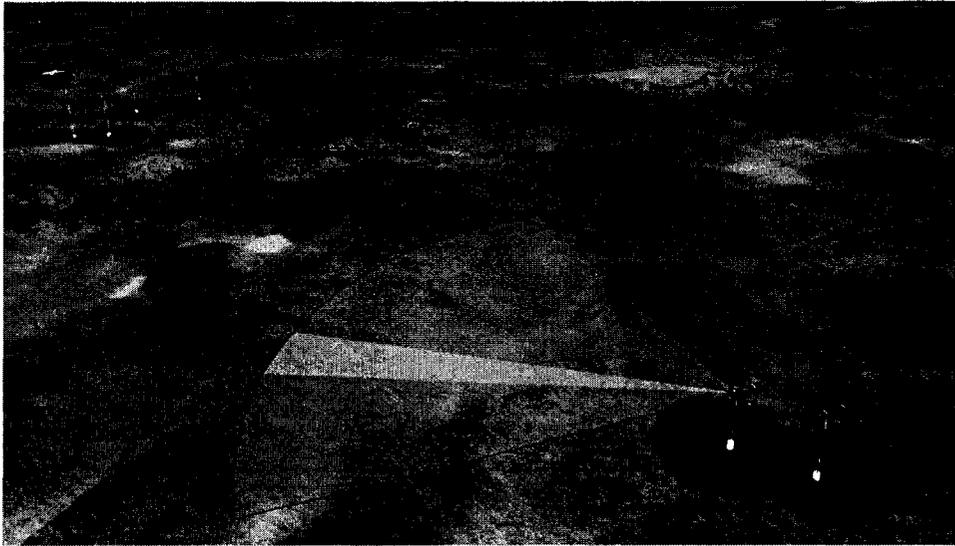


Figure 9. Strategic Mode Features

Strategic mode is not the preferred perspective for every task. Many times an operator would like to get a more detailed view of what is occurring near a particular unit or squadron. For these cases, the operator can switch to tactical mode. In tactical mode, the operator is typically following closely behind a particular unit (Figure 10). In this scale, squadrons are not aggregated and aircraft are not represented symbolically but rather with realistic models.

In tactical mode the operator can easily visualize what the situation is like at the individual unit's level. Other units that are too distant for the individual to pick out clearly are represented as blue or red spheres. The sphere along with the entity's associated height stick allows the operator to see the position of the other aircraft on the battlefield.

A powerful XML configuration system that facilitates environment related changes, allows the BRP to take advantage of the wide variety of display environments available at the Virtual Reality Applications Center. The most immersive of these environments is the 10' x 10' x 10' C6, which features floor, ceiling and four wall projection surfaces all illuminated

from the outside, as shown in Figure 11. Since the C6 may not be the appropriate display environment for all researchers or users, the BRP can scale from a fully immersive environment to a single wall or multiple monitor configuration. A 3 wall system referred to as the babycave is shown in Figure 12.



Figure 10. Tactical Mode



Figure 11. The C6 with Battlespace in it



Figure 12. Battlespace in the Babycave

Statistical Performance Assessment

The functionality of the BRP will not be useful if the application does not have adequate performance. The performance of an immersive application is especially important, because low frame rates can cause an operator to experience motion sickness or fatigue. In order to better understand how many UAVs and entities that the BRP could handle, a statistical analysis was performed. The application executed a series of test runs in which the average frame rate was computed by taking the number of frames rendered and dividing by the test's time. This data formed the basis for a Poisson regression.

The graphical complexity of the BRP made the data collection more complicated. Rendering terrain takes a variable amount of time depending on the position of the Open GL camera and the part of the scene on which it is focused. This variation impacts the number of entities that can be supported while maintaining an acceptable rate of 30 fps. In order to determine the upper bound of supported entities it was necessary to determine the worst-case

performance of the terrain engine. This determination was made via a two-step process. The first step involved finding the slowest render time of the terrain without any entities present. The second step involved executing a series of performance test runs without the terrain. The results of the performance tests were then adjusted by the slowest frame rate required to render the terrain. The test runs were executed on a Dell, Dual 3.2 GHz Xeon, 2GB RAM, and a Quadro FX 4400 graphics card. Table 2 shows the number of entities, the number of repetitions and the average resulting frame rate.

Table 2. Test data

Test	# Entites	Average FPS	Iterations
1	82	32.27878	7
2	63	36.97926	6
3	49	41.76196	6
4	40	44.46703	6
5	29	48.97786	6
6	19	55.51336	6
7	7	64.85737	6
8	0	70.08319	6

The data was analyzed with a Poisson Regression using a statistical analysis package, R [53]. The Poisson regression characterized as:

$$\text{FPS} = e^{(\alpha + \beta x)} + \epsilon \quad \text{Equation 1}$$

FPS = Frames Per Second (rounded to nearest integer)

x = Number of Entities

ϵ = Poisson(0, λ)

With this setup and equipment the slowest performance of the terrain is X frames per second. Equation X represents a model of the frame rate performance of the Battlespace Research Platform depending on the number of entities.

$$\text{FPS} = e^{(4.2126792 - 0.0098507 * x)} \quad \text{Equation 2}$$

This regression captures the variation of the data very well ($R = 0.9838638$) There appears to be some efficiency gained by the presence of more entities, Figure 13, the performance impact of the 20th entity is not as great as the 5th entity.

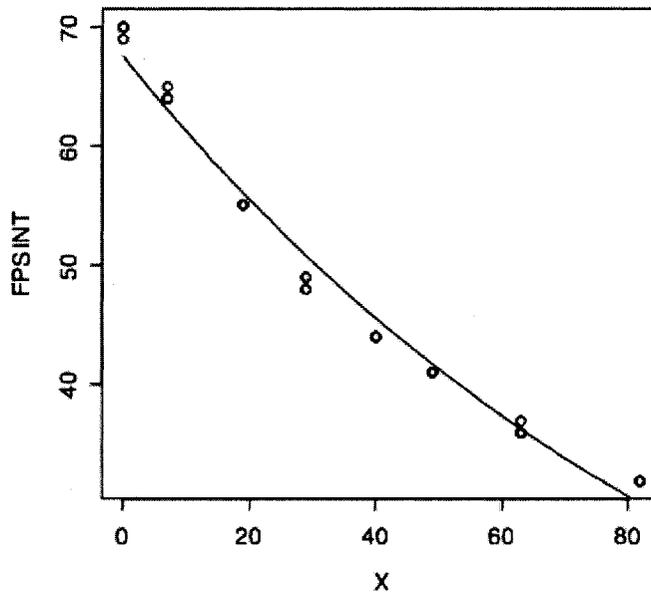


Figure 13. Regression Plot

Ultimately it appears that the BRP can support as many as 80 entities before falling below the 30 fps threshold. Another consideration is that this limit applies to the number of entities visible on one machine's display. As the number of computers in a cluster increases, the number of entities present on a particular display will decrease. In other words if each machine in the cluster takes up an equal amount of display, it might be reasonable to estimate that each machine would have a little less than an equal portion of the total number of entities. This means that the number of entities that can be supported will increase with the number of machines in the cluster. For example a graphics wall that is driven by 8 machines could support as many as 640 entities if everything were equally distributed. Since equal

distribution is unlikely to occur in practice and the cluster synchronization saps some performance, a more realistic figure for the 8 wall machine is probably 30% of 640 or 192 entities.

IMMERSIVE COMMAND AND CONTROL OF UAVS

It has already been established that current UAV control stations use traditional 2D GUI interfaces, which suffer from challenges that have been described previously. One possible solution that has yet to be thoroughly explored is a 3D immersive interface. This type of interface would place mission commanders in an operational environment that could provide superior situational awareness. The BRP is an ideal platform to develop such an interface. In fact the BRP has already been modified to interface with a large swarm of UAVs [24][54].

Since the logistics of swarm management are different than the logistics of managing a small group of UAV's, extending the Battlespace Research Platform to meet the needs of multiple UAV control required a considerable number of interface innovations. The need for operators to be able to interact frequently and rapidly with individual UAVs called for a new way of selecting entities in a 3D space that would scale with the large numbers of entities present in a battlefield's airspace. The operator must be able to interrogate selected entities for relevant information and be able to understand the distances between selected entities. The entity billboard and distance lines help resolve this need. While the gamepad interface allowed for the development of an efficient navigation system for the BRP, the operator also needed a way to maintain their sense of orientation and location at all times. The 2D radar fills this need by providing a consistent visual reference for the operator. Controlling modern UAVs involves the understanding of a UAV's current flight path and waypoints; this fact necessitated the incorporation of 3D path visualization.

In addition to appropriate visual tools with which to understand the battlefield, careful thought must be given to the operator's attention. Steps must be taken to avoid overwhelming the operator. Towards this goal an alert subsystem was developed that is responsible for directing the operator's focus to areas of particular need. The operator often needs to quickly alter a UAV's path in light of a new threat or emergency situation. The operator is provided with a tool to perform this action. Additionally, reconnaissance information gathered by the UAV's sensors may require the operator's training to differentiate friend, foe or otherwise. This information is presented to the user in context to help the operator maintain their situational awareness.

These innovations to the BRP form a new platform, the Immersive Ground Control Station (IGCS). The IGCS strives to allow one operator to manage the flight and sensors of multiple UAVs. However it may be desirable to have a small team of operators working together to control multiple UAVs. The DOD would be able to maintain its desired control ratio if the number of UAVs controlled from this single ground control station were high, no lower than 1 operator to 4 UAVs. Each operator in this team would have a specific role and may need individualized interfaces that are specifically designed for these tasks. These operators would be able to maintain a common understanding through the shared immersion of the IGCS.

Selection

Quick interaction with entities is a critical piece of the IGCS. The first step in this interaction is the ability to select an individual or group of individuals on the virtual battlefield. Once an entity is selected it may be queried or manipulated by the operator. The

UAV control system incorporates two methods to accomplish this task. The first method has been nicknamed “Madden-style” selection. This method drew inspiration from the Madden football video games where different players are assigned different buttons on passing plays. When the operator presses the A button to perform a selection, plus signs appear next to all visible entities, which also become outlined by colored circles and labeled dynamically based on their current screen positions. The labels are letters that correspond to buttons on the gamepad. The circle colors are associated with particular letters. For instance, green will always be found next to X (Figure 8). Once these labels appear the operator can press the appropriate button to select the desired group of entities. The selected units will then start to blink.

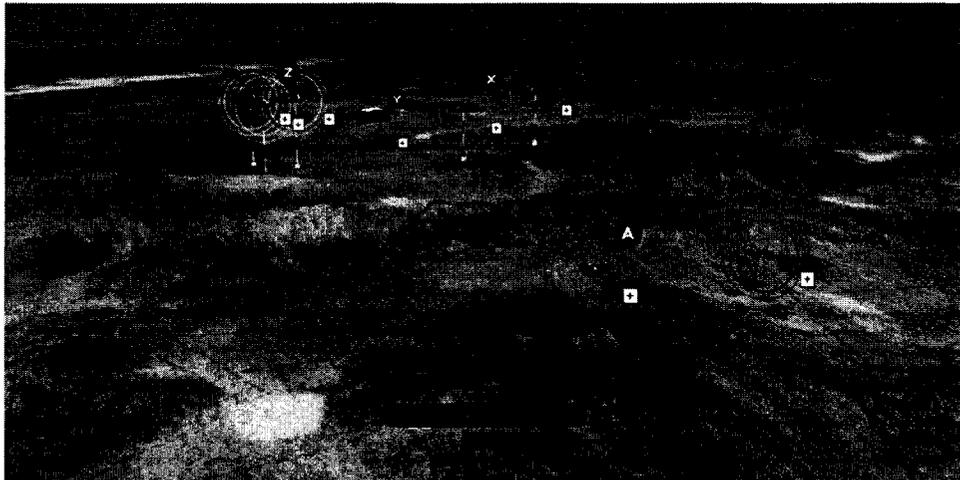


Figure 14. Selection Labeling in Application

Sometimes an operator may want to select multiple groups of units at the same time. For instance, in the scenario displayed in Figure 8, the operator might wish to turn on the threat zones of all the surface-to-air-missile (SAM) ground units (circled in blue above), because a squadron might be trying to fly over that region. At other times, an operator may

wish to work with one set of units at a time, to reduce screen clutter or to better understand what is happening in a specific location on the battlefield. In order to respond to these divergent desires, the BRP incorporates multiple selection and deselection modes.

When the application is set to group selection, the program treats all entities labeled with a particular button and circle color as a collective. Once the user has selected them, any given inputs, such as turning on radars or threat zones, will affect all the units that have been selected. When the application is set to unit selection, it becomes possible to choose between units with the same label. In this mode, hitting the button that corresponds with a group's label, causes the camera to zoom in on that chosen group. The group is then sub-divided and relabeled. The selection task can have many hierarchical layers as the operator drills down to the specific units they are interested in. A selection or deselection at any layer will result cause the camera to return to the previous zoom level. If, at any time, the user wants to back out of layer without making a selection, the B button unzooms. If there is no previous layer then selection mode ends.

There are several visual cues given to help the operator keep track of the current mode. There is a text box that appears at the bottom of the front screen, outside the selectable region, that identifies the current mode; Select Group, Select Unit, Deselect Group, Deselect Unit. The labels also inform the operator. A circle with a plus means selection and a diamond with a minus means deselection as shown in Figure 15. If there are two circles or diamonds around the individual units this means that the operator will be choosing a group. If there is a solitary circle or diamond, the operator will be choosing a unit.

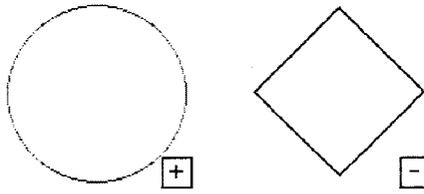


Figure 15. Selection and Deselection Labels

The most interesting aspect of this style of selection is the assignment of groups. If the groups were not chosen in a manner that produces geographically centered groups Madden-style selection would not be nearly as effective. Initially each entity is tested to see if it is in the selectable region. A selectable region is defined by a maximum pitch and yaw deviation from a vector representing the area of interest. In this application that vector is always the one that initiates at the user and points toward the front wall.

Once all the selectable area has been determined the iterative grouping of entities within that region begins. The goal of this iterative process is to reduce the number of groups so that each group can be mapped to one of the four gamepad buttons designated to serve in selection. Two primary weights were used to determine whether or not two groups would be merged, the distance between the groups and the angle between them. Both of these measurements are needed in a 3D world. Two entities could appear to share locations on the screen but actually be far apart. Similarly, the same can be said for angle; entities that are close to each other in the 3D environment may have vastly different angles relative to the camera's orientation. During each iteration of the grouping process the thresholds that determine whether or not to merge two groups get more and more lax. This relaxation eventually forces the number of groups below the ending criteria of 4 groups.

The power of this method can be seen in its logarithmic nature. If entities are arranged in such a way that groups would always be multiples of four (an unlikely situation but useful for discussion) the number of button presses necessary to select one entity from 256 would be 4. While 256 is an unlikely number of entities to encounter in a selectable region, cycling 4 times is a dramatic improvement over cycling 256 times, which could take as many 128 button presses. This method also avoids the challenge of having to point to one specific entity in larger clump.

Entity Billboard

The UAV operator may want to quickly pull up textual information about a particular UAV or entity on the battlefield. Information such as the vehicle's type, speed, heading, and current mission may be critical factors in making the correct decision. To accommodate this type of information, a 2D billboard can be attached to an entity as shown in Figure 16. The 2D billboard is easily activated from the menu system provided via the BRP.



Figure 16. Entity Billboard

The 2D Entity Billboard has several features that make it more powerful and useful to the operator than it would be as floating text. A line extends from the billboard to the entity's present location. This line helps ensure that the operator knows which entity on the battlefield the information relates too and can also help the operator find the entity by tracing the line back to its source. These features are especially relevant when the operator's current focus does not contain the entity that the billboard pertains too. The position that the billboard occupies is determined by the operator's billboard preference. This preference is not presently tied to the type of entity; rather it is tied to the number of billboards enabled. The operator can specify the position for the first, second, third, etc. billboards that are enabled. In this way multiple Billboards can be presented to the user at the same time with each billboard having a specific location in the user's view. For example, if a second billboard were enabled in Figure 16, it would appear to the right of the billboard that is currently shown.

Distance Lines

Another common need for a UAV operator is to get a quick estimate of the distance between two entities on the battlefield. This is especially important with ground entities that may be potential targets for the UAVs. To accomplish this task, the operator simply selects the relevant entities and uses the menu system to display the results of the distance calculations performed behind the scenes by the application. The kilometers between entities appear as shown in Figure 17.

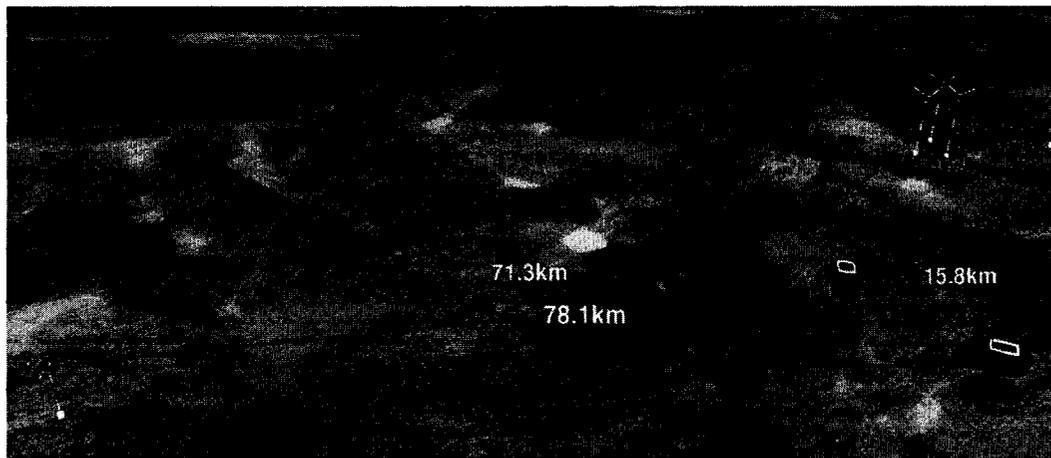


Figure 17. Distance Lines Between Entities

To avoid overlapping text when displaying the distances between multiple entities that are close to one another, a recursive decluttering algorithm was created. Since the intention is to place the text as close to the midpoint of the line between any two entities as possible, the decluttering algorithm finds the midpoints that are in closest proximity and shifts them apart. The entire scene is then tested again to make sure no new conflicts have arisen. If there is a conflict the process is repeated with ever decreasing amounts of shift. If any clutter remains when the shift amount reaches zero then the algorithm halts. This end condition prevents an infinite loop when there is no true solution to the cluttering problem. In practice this algorithm proved successful at preventing the distance markers from overlapping.

Radar

A UAV operator must have a keen sense of position and orientation. A 3D can disorient the operator. To solve this problem a 2D radar was integrated within the 3D environment (Figure 18). The operator's position is indicated by the center of the map. In the

example scene depicted in Figure 7, the operator is currently over the city of Las Vegas, NV and the operator's viewing direction is to the north-west as shown by the semi-transparent wedge. This information is reinforced by the surrounding context of the 3D view shown in Figure X. While the map could be placed anywhere in the display environment, it was determined that the best position for it was the upper right corner of the front wall, because this corner usually displayed open sky.

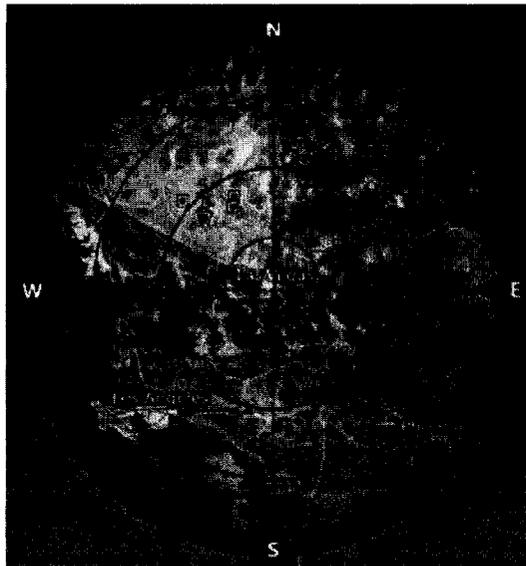


Figure 18. 2D Radar



Figure 19. View corresponding to 2D radar above

The radar is especially important in strategic mode because of that modes exocentric nature. The operator is looking down on the UAV and interpreting position and direction relative to some outside-the-vehicle context. This differs from the egocentric nature of current UAV control stations such as the Predator interface. The operators in the Predator flies based on what they see and the controls are based on their understanding of that world. The interesting thing about this application is that it can operate in both the egocentric and exocentric modes.

The 2D radar represents a paradigm switch. Falconview conveys a 2D world as the primary interface with the SkiView 3D world playing a more minor role. With the BRP, the 3D world is the primary interface for visualizing and understanding the battlefield and the 2D radar is provided to help the operator maintain a sense of context within that 3D environment. This inversion provides greater situational awareness and sense of presence over than can be found in a 2D application.

Path Visualization

A critical component to IGCS is UAV path representation. A UAV's path is its primary control interface, as most modern UAVs are waypoint driven. The UAVs' paths and waypoints must be conveyed to the operator in way that is visually appealing, but, at the same time, not distracting. Doing this effectively will allow the operator to understand not only the UAVs current position and orientation but also its future route. Several iterations of paths were experimented with before the final path representation was developed (Figure 20).

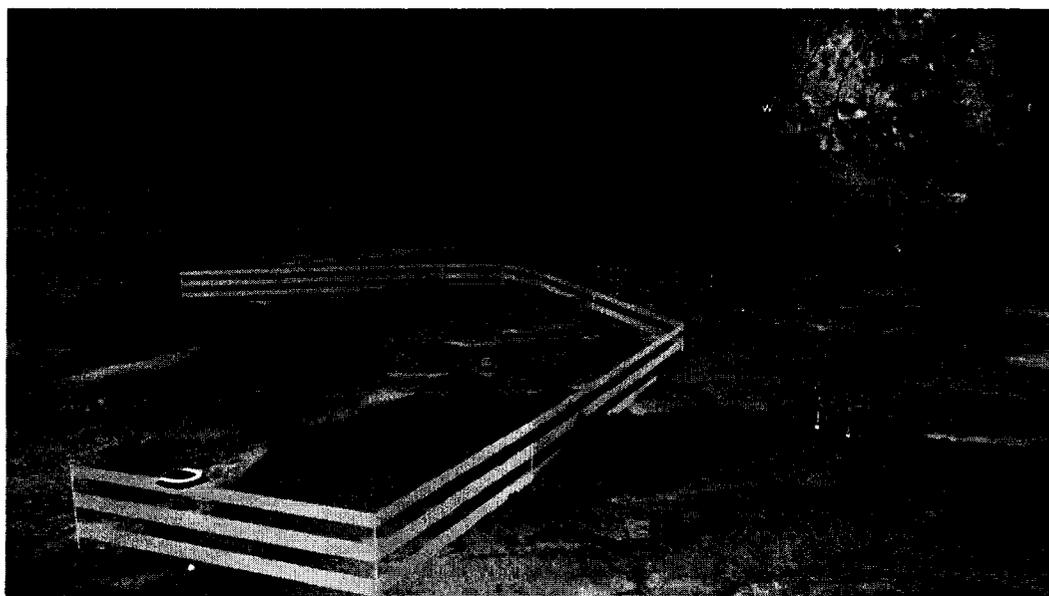


Figure 20. UAV Path Representation

In order to prevent the user from needing to query another interface for path details, the path itself conveys important information to the UAV operator. The ribbons and breaks in the path each correspond to a height of 5,000ft, by counting the breaks and the yellow bands, an operator can quickly estimate path height. For example, the UAV in Figure 20 is currently flying at a little above 25,000ft, and it will clear the mountain it flies over by around 10,000ft. The vertical lines that break up the path indicate the UAV's waypoints. These points are usually of particular interest to the operator and can easily be picked out from the rest of the path. The bright yellow color will be striking to the operator because the only yellow markers in the application are the UAV paths. The vivacity of the color helps indicate the direction of the UAV, because the brightness gradually increases between waypoints. While the subtleties of this symbolism are not intuitive, a trained user can quickly perform height estimates and ascertain a UAV's direction from the color variations.

When locked on to a UAV in tactical mode, the operator will be provided an additional guide to the future path of the UAV. A highway-in-the-sky effect helps the operator visualize the future behavior of the UAV as shown in Figure 21. An operator can clearly see that the UAV below is flying straight and then making a sharp left turn. The head-up-display provides the operator with additional information.

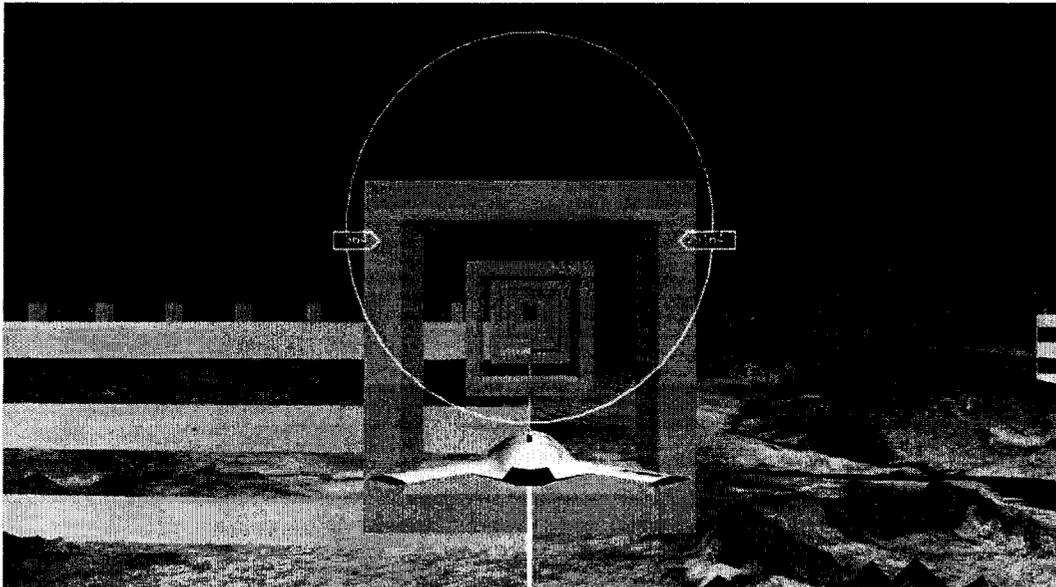


Figure 21. Highway in the Sky

The relative improvement of this path representation is hard to understand without some historical perspective. The height-stick like nature of these paths provides a considerable advantage over the path representations developed by previous researchers.

The Skyview add-on that provides a 3D display for the Falconview application allows an operator to see a unit's path in 3D. However, this path representation does not have any sort of visual reference to the ground, making it very difficult to get an accurate idea of the depth of the path without looking at the corresponding 2D view. This codependence

essentially cripples the usefulness of the 3D view, requiring that the operator use the 2D view to understand where the entity is in space.

The Dragon system does not provide paths but it does provide sticks that at the very least tie the entities to the ground. These sticks however do not convey any altitude information and the operator must guess at the approximate altitude of the entity. The path provided in this system conveys both the position and height effectively, by tying the entity to the ground with height sticks and conveying altitude with the alternating bands. While the bands do not provide precise numerical data, they do allow the operator to get a quick height estimate, which, in many cases, is all that is needed.

Alert subsystem

The purpose of an immersive command and control station is to permit the operator to focus on the overall mission status. With as many as 4 or 8 UAVs under the operator's control, it would be impossible to constantly monitor and micromanage every aircraft. The alert subsystem has a vital role to play in reassuring the operator that when UAVs run into situations that require user input, the operator will be made aware of them. Using a combination of visual and aural cues alerts attract the operator's attention. Figure 20 shows an alert in strategic mode. Note that a box in the upper left warns the operator about new alerts. There are two primary types of alerts: vehicle related alerts and ground alerts.

An alert can be fired for many different reasons including, but not limited to an enemy encounter, a target acquisition or an arrival at a designated area of interest. Some of these scenarios may call for a quick re-routing of the UAV, some may call for confirmation or refutation of a course of action and others may simply call the operator's attention to some

important piece of information. As a result, the alert subsystem was designed to carry out its primary responsibility independent of the type of alert.

The alert subsystem notifies the operator of the presence of an alert and provides a way to see the type of alert. Once aware of a new alert, the operator can use the C button on the game pad view it. This action initiates “Alert” mode. When in this mode, the operator can cycle among active alerts. When cycling among alerts, the application automatically navigates smoothly to the position of the alert. This seamless view transitioning helps the operator maintain situational awareness throughout the process. Additionally, the application will switch to either strategic or tactical mode depending on the type of the alert and then offer the operator a chance to examine it. When the operator chooses to examine an alert, different type-dependant options become available. If the alert is related to the path of an entity the application will enter a dynamic path-planning mode. If the alert deals with surveillance or target confirmation another mode is entered.

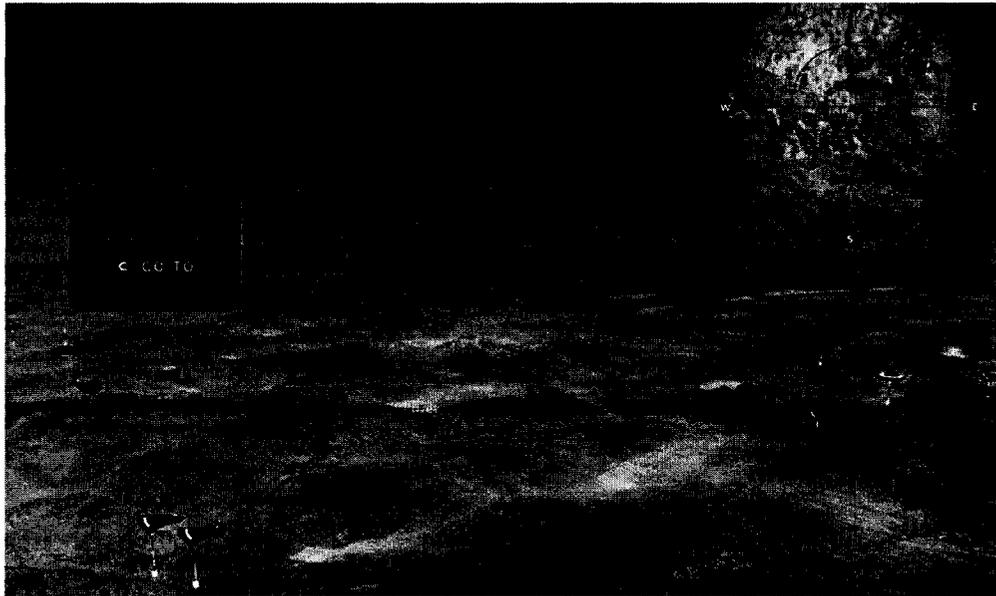


Figure 22. UAV Alerts in Strategic Mode

Real time dynamic path alteration

Real time dynamic path alteration is needed when a UAV is presented with an unexpected threat. Specifically it is possible that the UAV could encounter an unexpected surface-to-air missile (SAM) site. When this happens the operator must be alerted to this dangerous situation and be able to quickly re-task the UAV to reduce its threat exposure. The operator must quickly be able to consider fuel usage, reconnaissance targets and threat exposure.

It is important to consider the impact of the immersive environment on this process. In a conventional 2D interface, the application would have to find some way to convey a 3D path in the 2D interface or restrict the path-planning algorithm to a 2D solution, limiting the alternative paths to changes in direction within the same elevation when in reality an aircraft could also change altitude to avoid threats. A 2D application has many strengths, which should not be abandoned thoughtlessly, but quickly visualizing and interpreting 3D paths is not among them. In the IGCS, the 3D path can be displayed naturally and without unnecessary augmentation. The operator can focus on the decision to be made as opposed to inferring the true shape of the path from multiple disparate interfaces.

When the operator chooses to examine an alert posted by a threatened UAV, the operator will see a variety of automatically generated path options. These path options will appear at a distance corresponding to 30 seconds ahead of the UAV's current position and re-engage with the path when in a safe region. These points on the old path are used as the start and end points of the path-planning algorithm. All relevant threats and the start and end points are passed to the path-planning algorithm for it to calculate new candidate paths. The path planning algorithm used in this research is the particle swarm optimization (PSO)

algorithm described in Appendix A. The PSO path planner is run three times with different parameter weights. One path makes fuel the most important, another path makes threat avoidance the most important and the last path is a middle ground between these options.

Table 3. Gives the Parameter settings for each case.

Table 3. Parameter Settings

Description	Fuel weight	Threat weight
Fuel Conserving	0.95	0.05
Threat Avoiding	0.05	0.95
Blend	0.5	0.5

These paths are then displayed to the UAV operator as shown in Figure 23. A visual cue at the bottom of the front wall is provided to the operator to prompt the next action.

Once the alternate paths are planned and conveyed, the operator must make a choice among the alternatives presented. The choice of path depends on the operator's uniquely human ability to decide which is the best path for the current situation.

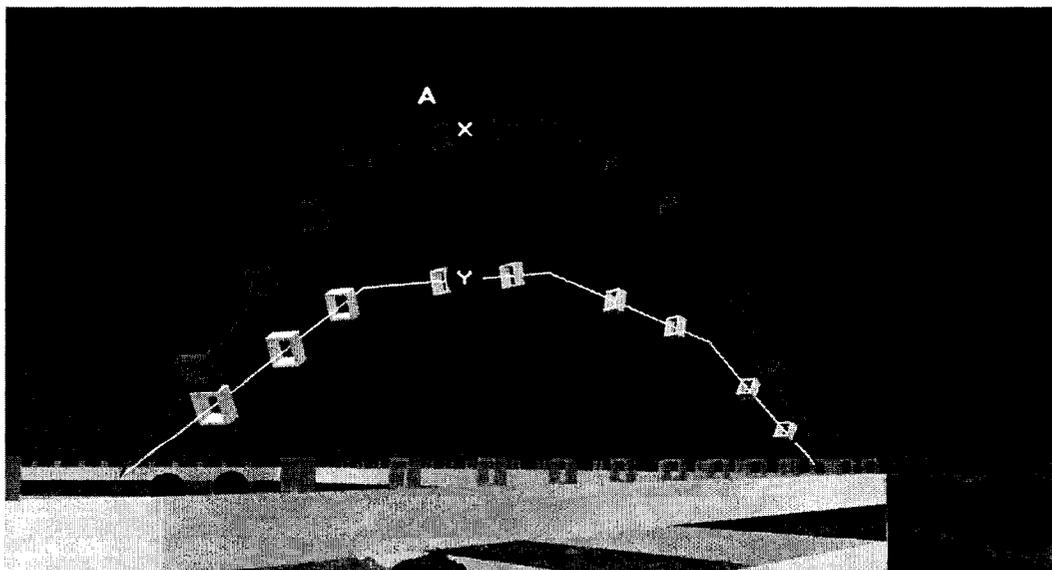


Figure 23. Alteranate UAV paths

There are several tools provided which can aid the operator in weighing the alternative paths and in making an efficient decision. By using the gamepad interface, the operator can cycle between canonical views, observing the path from a traditional 2D perspective, Figure 24, as well as the head on and side views. These views preserve the ability to display the alternate paths in 2D if that is needed for a particular operation or task. In addition the UAV operator maintains the ability to move in a free-form fashion around the battlespace to get a better understanding of the alternative paths from multiple perspectives. This combination of set views and free-form movement allows the operator fully assess the tradeoffs inherent in the various paths.

When the operator finds an acceptable path the game-pad interface is used to choose that path. The paths are represented in different colors and labeled with the corresponding

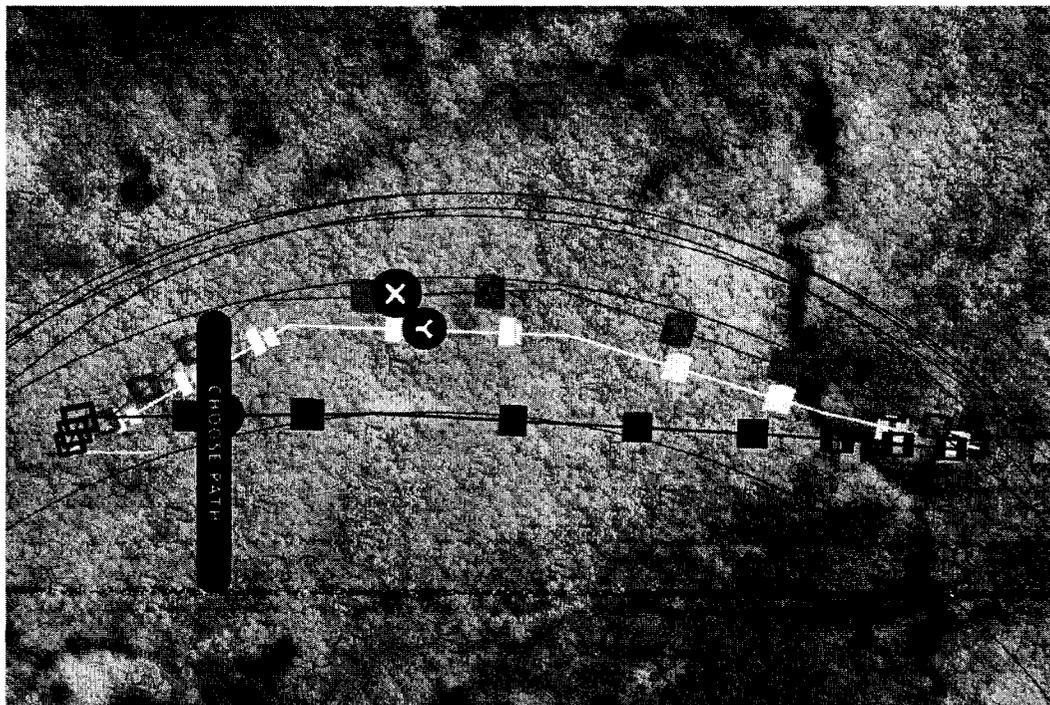


Figure 24. Top down view of alternate paths

game-pad button. To ensure that an incorrect choice is not made it takes two button presses to choose a particular path. The first button press will highlight the chosen path and prompt the operator to confirm or decline this choice, as shown in Figure 25 below. The importance of a UAV's current mission or future mission may demand that the UAV stay on its original path. For this reason the operator is provided with the option to cancel the alternate paths. Additionally, once the UAV is beyond the planned start point the UAV system will assume that it should keep its original path. This is consistent with the Manage By Consent style discussed in the background of this dissertation.

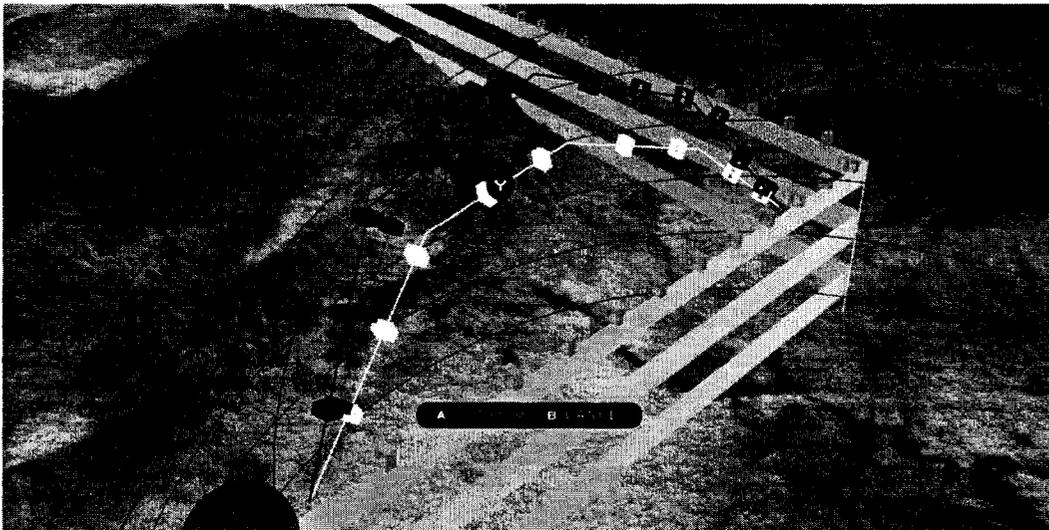


Figure 25. Highlight of chosen path

Target Confirmation

Another common task for a UAV operator is to confirm or refute the results of any information analysis performed by a UAV's computer on any reconnaissance data it has gathered. Just because the UAV has flown to a designated location, taken a picture and determined that it has a target, doesn't mean that it is desirable to let the UAV fire missiles without a human confirming that the structure in question is in fact an enemy weapons

factory rather than a hospital. In the BRP, this reconnaissance data is presented to the operator as a ground alert. A ground alert in strategic mode is a colored marker, while in tactical mode the alert is a colored column of light (Figure 26). Both types rise up from specific points on the terrain, informing the operator of the location of the situation that produced the corresponding alert.

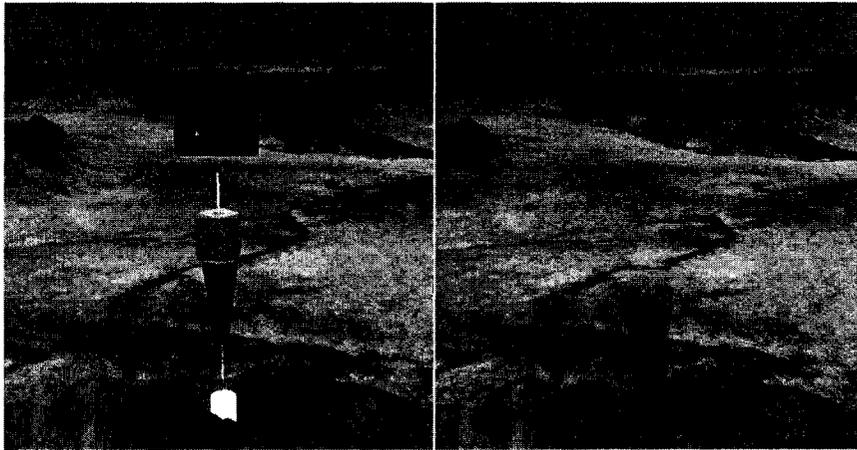


Figure 26. Ground Alert in strategic/tactical mode

Upon examination of a ground alert, the operator will be expected to classify the reconnaissance information based on a list of possibilities, which includes target, threat, friendly and non-combatant. If the operator was alerted in error or the information is irrelevant the operator can dismiss the alert. Instead of looking at the reconnaissance information out of context in a separate window, the picture is put into the context of the 3D world, preserving the information on its real world position and orientation. The reconnaissance pictures are aligned so that images of the target's various angles become visible as the operator navigates around the alert. If the operator is to the east of the ground alert then the picture corresponding to the eastern view of the area of interest is presented as shown in Figure 27.



Figure 27. Alert Information

Once the operator classifies the image data, the alert changes color to reflect its new state. The color of the alert's marker represents its classification: an orange marker indicates an unexamined alert, while the red, blue and green markers indicate alerts which have been classified by the operator as enemies, friendlies and non-combatants respectively.

Virtual Binoculars

As mentioned above, one potential use scenario for the IGCS is a small team of operators using role-specific multi-modal interfaces effective in controlling multiple UAVs. Each of these operators may need access to a different set of individualized interfaces, so the IGCS was designed to facilitate the integration of any type of auxiliary interface. The virtual binoculars, shown in Figure 28, are one example. These particular binoculars are made by

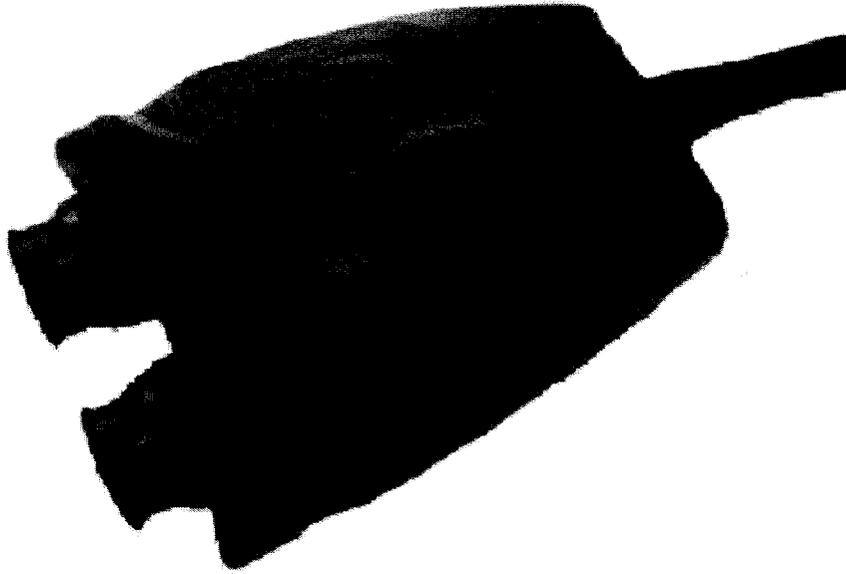


Figure 28. NVIS binoculars

NVIS and are tracked using an Intersense IS900 tracking system. Each eye has a resolution of 1280 x 1024 so the binoculars display crisp images.

The virtual binoculars are used just like real binoculars and in many ways they perform a similar function. Typically binoculars are useful for resolving details about objects that are far away, such as the color of the feathers on a bird. In the IGCS, the operator can point the virtual binoculars at a particular point of interest on the primary display surface, a UAV for instance. They can then zoom in on this object to resolve details such as make and model. This may be useful to an operator who needs to understand more about a distant part of the battlefield, but does not want to abandon their current location to do so. As the operator zooms in, the aggregates break up and change representation so that the individual units can be distinguished (Figure 29).

There are a few techniques that are used to accomplish this behavior. The virtual binoculars behave like a pair of nodes in the cluster, one node is the right eye and the other node is the left. In this way the virtual binoculars are synchronized perfectly with the rest of the application. The zoom feature requires a couple of additional modifications. A *BinocularsCameraManager* replaces the camera manager provided in the BRP. This new camera manager responds to movement commands in a different way. When the user is zoomed in, the binocular nodes will not move in response to *Move_User* commands generated by the game-pad. This is to prevent the operator from getting motion sickness while zooming in. Another adaptation to the code causes the OpenGL application to narrow the frustum when the operator requests a zoom. The display surface stays the same size; however, so the resulting narrow frustum is enlarged on the virtual binoculars' display surface, creating the illusion of a zoom effect.

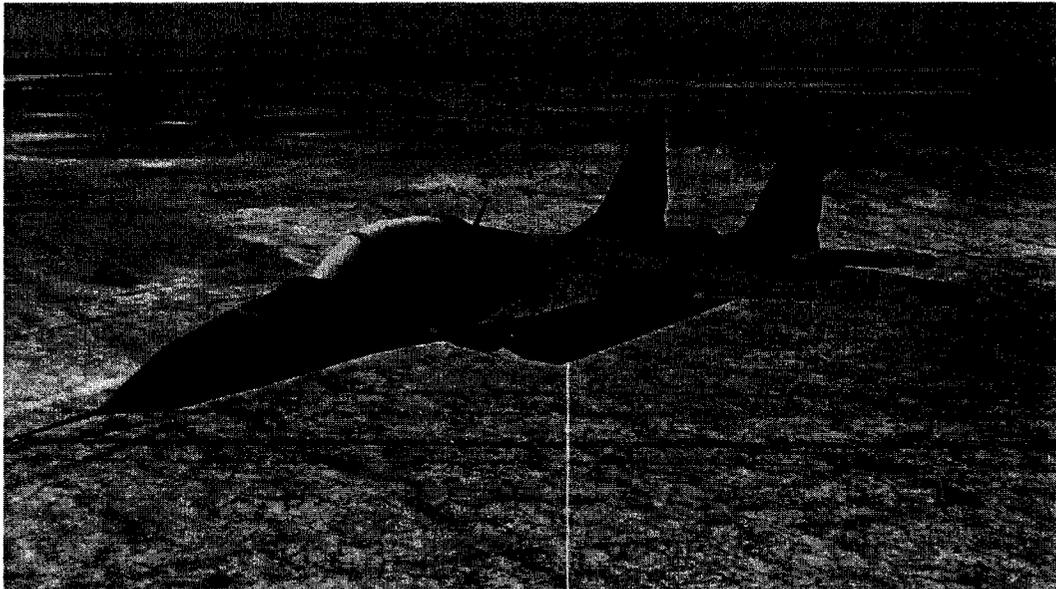


Figure 29. View from binoculars

Tablet Interface

The tablet PC is another example of an auxiliary interface integrated into the IGCS. The tablet interface shows a 2D representation of the battlefield (Figure 30) and uses the networking infrastructure provided by the BRP to stay synchronized with the immersive UAV control application. The operator of the tablet interface can manipulate a UAV's waypoints with traditional click and drag techniques. Without any way of representing the UAVs height visually in the tablet interface, the operator must still look up and down between a 3D and 2D representation of the environment. This makes it a difficult platform for quickly planning 3D paths, but the tablet is useful for accomplishing changes to a UAV's future path in situations that are not time-critical.

The tablet is built using wxWidgets, which is an open-source multi-platform windowing engine. It takes advantage of some of the core classes in the BRP to handle its entity management. The tablet interface is a testimony to the flexibility inherent in the BRP and IGCS. There were very few if any major changes to the IGCS code to incorporate the use of the tablet. The primary modification came at IGCS startup. At startup the IGCS can wait for a connection to be requested by the Tablet. Once the connection is established the IGCS functions normally, except that now entity information commands are being sent to the tablet interface. The tablet interface in response can send commands to modify waypoints and other information. Because of the software's design the tablet acts in many ways like another manager present within the command loop. New interfaces can take advantage of the NetworkManagerHost to behave as new interfaces to the IGCS and other BRP projects without any modification to IGCS or BRP code.

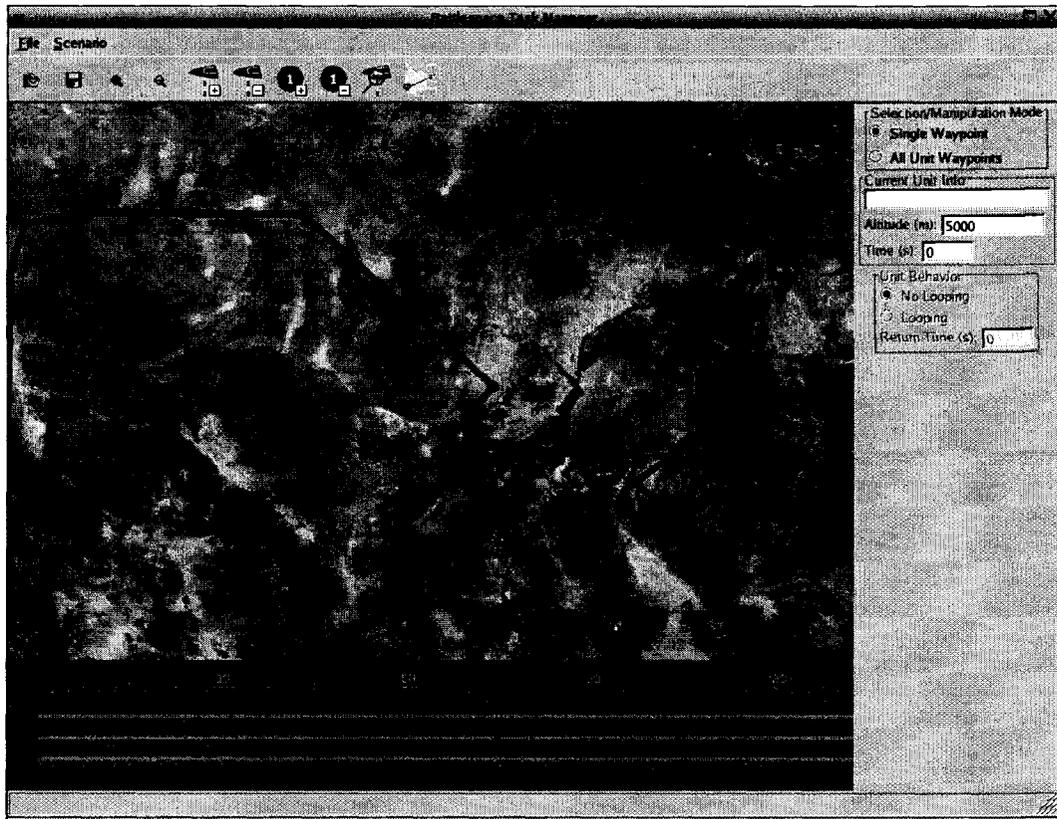


Figure 30. Tablet Interface

RESULTS & DISCUSSION

A common question to ask about a new innovation is whether or not it will be effective. With this radically different approach to UAV control it was important to ask, will a 3D immersive interface provide an advantage over traditional 2D interfaces? Is there a particular niche in which this type of interface would be best suited? The new interface innovations and UAV control application need to be examined for their effectiveness and potential.

To begin to answer these questions, various BRP researchers, including the author engaged in research that would test the validity of the control system. In 2005, Parkhurst et al began conducting a user study to examine the relationship between the number of walls in an immersive environment and situational awareness. Then, informally in 2005 at Interservice, Industry, Training Simulation, Education Conference (IITSEC) and formally in 2006 at the Third Annual Human Factors in Unmanned Aerial Vehicles Workshop (HFUAV), experts provided feedback on their experience with the BRP.

Situational awareness in virtual environments

A fundamental question to ask about an immersive environment is whether or not it improves situational awareness. There has been a lot of research on immersive environments and their effect on a user's sense of presence within an environment. The studies indicate that there is a positive correlation between immersion and a user's awareness of the surroundings. To see if these findings applied to the Battlespace application, a user study was conducted by Parkhurst et al [46].

As mentioned earlier, a version of the Battlespace Research Platform was developed by Walter that can be used to control a large swarm of unmanned aerial vehicles [24]. A scenario based on this research was created for the purpose of the user study. As an operator navigated through the virtual environment, the swarm fired off a series of alerts that had video associated with them. The participant would view the video and classify the units in the video as either friendly or hostile.

A participant was greeted at the back door to the C6 and asked to read and sign the informed consent document. The participant was then given \$10. Next the participant completed a pre-experiment questionnaire. Once this was done, the participant was suited up to run the experiment in the C6. The participant was told that at the end of the experiment there would be a memory test. The participant was not informed as to what the memory test would ask about. The participant was told to try to classify as many alerts correctly as possible. The various features of the BRP were explained to the participant and the experiment was conducted for 30 minutes. After the experiment the participants were given a memory questionnaire that posed questions about the positions and numbers of entities. The participants were also given questionnaires on simulator sickness and workload ratings.

This user study is still in progress but three conditions have been completed that suggest a positive correlation between situational awareness and increased FOV. The three conditions that have been run so far are 4 walls no stereo glasses, 4 wall stereo glasses but running mono graphics, and 4 wall stereo glasses stereo graphics. The presence of the stereo glasses reduces the participants FOV.

Although the research is ongoing, initial results show some positive trends for the benefits of increased FOV. Participants with a higher view rated the situation as less

stable/changed more than participants with the reduced FOV. Initially this may seem like a negative result but the feeling that the scene was changing more could easily be the result of being aware of more change which reflects positively on the participants situational awareness. Another positive indication is that participants with the increased FOV felt that the temporal demand was significantly ($p = 0.01$) less than participants with reduced FOV. The battlefield though it changed more seemed to provide less time pressure on the participant. The last positive trend in the data was that participants got an average of one more question right on the memory test if they were in the higher FOV group. It will be interesting to see what other immersion and FOV effects are discovered when the study is completed. At the very least the results suggest that a higher FOV is better for situational awareness.

Demonstrations

The BRP has been demonstrated at two conferences. IITSEC'05 and the Third Annual HFUAV. These conferences gave Iowa State University researchers the opportunity to present the BRP to other UAV researchers and actual UAV pilots and seek their opinions and impressions of the Battlespace Research Platform and the immersive control of UAVs. At the IITSEC'05 demonstration was held on Nov 29th to Dec 2nd, 2005 where our research team from Iowa State shared a booth with Intersense tracking systems (Figure 31). The IITSEC demonstration featured the tracked binoculars as well as an additional wand interface to the BRP. The binoculars were placed in front of the screen on a tripod for ease of use. This demonstration exposed the Battlespace project to the general military community.

There was a great deal of interest in the 3D nature of the application and the integration of the binoculars.

The second demonstration featured the IGCS research presented in this dissertation. The Third Annual Human Factors in UAVs Workshop, May 2006 was well attended by experts in the area of UAV control. This demonstration included the integration of the tablet interface (Figure 32). The workshop was a great experience that provided lots of positive and informed feedback on the underlying concepts of the system.



Figure 31. IITSEC demo picture



Figure 32. Third Annual Human Factors in UAVs, Mesa, AZ

Expert Feedback

In order to get qualitative and quantitative feedback that would help to assess the validity and inform the future direction of the IGCS, surveys were handed out at HFUAV workshop to those who showed extended interest (five minutes or more) in the demonstration. The survey was also given to other experts in the field of UAVs outside of the VRAC community who have been exposed to the demonstration. The participants from the HFUAV conference were informed that participation in the survey would enter them in a drawing to win an iPod Nano. The subjects' participation was completely voluntary, and they were not required to enter the drawing to participate in the survey. All participants were required to sign the informed consent document, fill out the survey and mail the prepaid

addressed envelope to VRAC. Twelve surveys were completed and returned through the course of the study and the identities of the participants were kept separate from their responses. The survey instrument and associated informed consent document can be found in Appendix B of this document. An important caveat to the responses given to the survey questions is that this is what the experts say. The experts use preferences may be different and separate studies need to be carried out to examine that issue.

The first questions of the survey were intended to gain an understanding of the background of the participants. Nine out of the twelve participants had military backgrounds with at least three years of service. Seven of the participants are still presently in the military. The participants were asked to rate their knowledge of UAVs (10 is expert knowledge and 1 is no knowledge). The mean response was 5.83 (± 1.75 , [4,8]). Most of the participants felt that they had a better than average knowledge of UAVs. Question five gathered information about experience operating UAVs (10 is expert experience and 1 is no experience). These answers varied considerably with a mean of 4.08 (± 2.57 , [1,9]). Participants were also asked to rate the quality of the current interfaces on a similar scale. The current UAV interfaces garnered a mean of 5.75 (± 2.09 , [2,8]). The reason that current UAV interfaces may have rated so highly is the wording of the question in the survey. The question asked about the quality of the current interface. It is true that current interfaces have proven capable of accomplishing a wide variety of missions, so in the minds of the survey takers this may mean a high quality interface. All of the participants observed the demonstration for at least 10 minutes and questions 8 through 15, related to their thoughts and understanditwelve the demonstration and its interfaces.

Question 8 asked about the user's impressions of the game-pad interface device.

Eleven of the twelve participants thought the game-pad interface device was a strong interaction device. With one participant saying that the game-pad was "Easy to use, ergonomic, easily trained for personnel with gaming experience." The gaming metaphor was exactly the metaphor that this research was looking to capture as video games can have some very complex interaction tasks that need to be accomplished quickly and efficiently. The fifth participant thought that it was too complex and suggested that the keyboard interface for Google earth might be a source of inspiration. These responses suggest that the game-pad was well received, but special care should be taken to ensure simplicity of interaction.

Question 9 asked whether or not the participant had the opportunity to use the game-pad. Three of the seven that liked the game-pad had used it and the one participant who did not like had not used it.

Question 10 and 11 related to the participants thoughts on the tablet as an interaction tool. None of the participants indicated that they had used the tablet so the impressions of the tablet were all based on observations. Impressions of the tablet were more varied. One participant thought that the tablet would be slower than the game-pad interface and suffered from a "point-and-click" approach. This comment is interesting because it was originally thought that the point-and-click nature of the tablet would be an advantage. The participants' impressions were perhaps generated from an inadequate understanding of the tablets role within the application. The ability to do 2D manipulation of paths when there are not serious time constraints could be useful to a team of operators. Another participant voiced concern over the ergonomics of the tablet. "A tablet PC is awkward to use when standing up or sitting down unless it is mounted securely or has a secure surface to rest on." This is a

legitimate concern as the weight of a tablet could become difficult to manage over a long period of time.

The next question asked about the graphical representation of the UAVs' paths. All of the participants thought that the paths represented all of the needed information, but most also had an additional comment or concern about the paths. Two experts were concerned that the visual representation may be a bit too "heavy" or "overbearing" and could be distracting in a high-density environment. One of the participants qualified this statement with the fact that this impression may be due to lack of training with the environment. These concerns warrant further investigation. The paths have a high degree of symbolic content and perhaps user studies could be performed to determine how much of the information is necessary to accomplishing mission tasks. Another possible solution would be to develop an algorithm that would test the density of the environment and simplify the representation when content was high. The path representation could change depending on the operator's current task. One participant suggested that the highway-in-the-sky effect in tactical mode could be reduced to a "goal post effect". One concern brought up by the surveys has already been addressed. A participant felt that the alternate paths were hard to distinguish from the original path, so each path now appears in a different color. Another participant thought that the paths provided good situational awareness.

Two final questions finished off the demonstration section. Was anything about the demonstration confusing? And how could the visualization be improved? Two of the participants said that some of the application's symbolism was confusing, but they felt that this could be overcome with training. Another participant felt that the "graphics were generally intuitive enough." In general the participants seemed to feel that the functionality

of the application was relatively straightforward. There were three interesting responses to the second question. One response suggested that a scale be added to help the operator maintain a sense of scale. This is a very insightful comment and a definite concern in a 3D environment. The distance lines are designed to address this issue between entities, but perhaps an overall sense of scale needs to be portrayed for the 3D view. Another comment suggested putting the operator in an information overload situation and test how well they are able to maintain situational awareness. This comment ties in nicely with that the suggestion that there should be a way to perform user selected decluttering. Based on the responses of these surveys more work needs to be done to find out how much visual information can be displayed in the environment before the operator is overwhelmed. However, information overload is an addressable problem. Smart algorithms can be developed to help declutter a scene for particular tasks.

The next two questions asked if 3D visualization would be advantageous to a UAV operator and for what applications would it provide the most benefit. Ten out of the twelve participants felt that 3D Visualization would be useful to a 3D operator. One of the participants qualified this statement with the caveat that it would be useful in some situations but not all. While this might be seen initially as a negative response it fits in well with the application's capabilities. The 3D visualization can be seen as the overall organizing context while separate 2D interfaces may be developed that are designed to accomplish a specific task. The tasks or applications for which 3D was believed to be most important included multiple aircraft control, variable terrain situations, flight path visualization, direct teleoperation and maintaining situational awareness. The two participants that responded with a negative response to this question sighted two different reasons. One sighted depth

perception as a problem with 3D world. This is interesting because another participant sighted depth perception as an advantage of 3D. The other reason was that it would only be useful to the sensor operator but not the operator. This may be a product of the questions wording. Which asked if 3D would be useful to the UAV operator. The participants were also asked if 2D provided any advantage over 3D in the operation of UAVs. A concern was expressed that the 3D world could lead to greater spatial disorientation on small and maneuverable UAVs. Considering that the intention of the BRP is to make it so that the operator does not need to micromanage individual UAVs, they would not be limited to a particular aircraft's point of view, so this concern may not be an issue. Another expressed advantage was the ease with which a 2D interface conveys the scale/distance between two ground entities. This may be true, but the distance lines present in the BRP allow the operator to quickly discover the distance between any two entities on the battlefield.

The next set of questions asked participants to rate the importance of various aspects of UAV research. In order to get a normalizing factor for their responses each participant was asked to first rate the priority of UAV research in general. All of the responses had the same scale, 10 is high and 1 is low. There were three categories pertaining to UAVs, human computer interaction research, 3D visualization research and path visualization research. Probably due to the low numbers it was difficult for statistical significance to be established. It was determined that HCI research was significantly more important ($p = .0005$) than path visualization research although this does not come as much of a surprise since path visualization could almost be considered a subset of HCI research. The mean normalized priority of HCI research was 1.2178 (± 0.16) and the mean normalized priority of path visualization was 0.8779. A mean of 1 would indicate that the priority of that field was of

equal importance to UAV research. The priority the participants would give to 3D visualization research fell between both HCI research and path visualization research, but was not significantly different from either area. All of the scores were fairly high with a mean priority of 8 given to UAV research. This is not surprising considering the audience that the survey was given too. The important fact to take away from these questions is that 3D visualization research for UAVs is as important as UAV research in general and HCI research pertaining to UAVs is more important than general UAV research. This result may reflect the notion that HCI innovations in UAV control could be applied to other fields.

The final sample size for the expert survey was not as large as was originally desired, but the results of the survey proved insightful despite the small sample size. The expert feedback was generally positive and validating this direction of research, while at the same time pointing out potential improvements that can be addressed by future BRP researchers.

CONCLUSION & FUTURE WORK

The recent *Time* Magazine article “Long-Distance Warriors” relates the personal cost of the stress faced by Predator UAV operators [58]. The Predator has seen considerable military achievement through the course of the war in Iraq, but its success has come with a price. Non-stop twenty-four hour operations have forced operators to be so tightly scheduled that “crew members have to ask permission to go to the bathroom” [58]. Morale has suffered and “crew members are experiencing more problems in their personal lives, including separation and divorce” [58]. Scientific studies only reinforce this grim reality.

A recent study compared the stress levels of a Las Vegas, NV Predator control squadron to those of an AWACS crew stationed in IRAQ. They found that the predator operators suffered significantly higher levels of physical stress, mental stress, fatigue and burnout [51]. Operators reported an astounding 165% increase in irritability after a shift at the Predator GCS. Combine this with a 111% increase in sleepiness and 33% reduction in Talkativeness and it is no wonder that the personal lives of these Predator operators are being negatively affected. Operators find the operating environment boring and not surprisingly performance degrades over the course of a shift [51]. Unless a better interface design can be found, these problems will only be magnified with multiple UAVs [51].

As bleak of a picture as this story and research paints, there is hope. Research will continue to explore solutions to the human factors issues that the operators of one and multiple UAVs face. This dissertation presented research that could be part of the solution to these problems, breaking new ground by creating a 3D immersive ground control station that was capable of dynamic real-time path re-planning and in-context target confirmation. A 3D

immersive environment is more visually stimulating than a traditional 2D GUI. In a way, the video game industry may hold some answers for solving the problem of operator boredom. Video games are capable of holding a person's attention for hours at a time while demanding constant interaction for continued success. It may seem simplistic, but a more stimulating operating environment that provides a greater sense of presence could convey to UAV operators that their personal success is at stake and reduce their boredom.

While this dissertation does not present a system that is ready for military use, it does outline a series of advances that move the state of the art closer to that goal. The game-pad represents a powerful emerging tool for scientific and engineering tasks in part because the emerging generation of users will find it both familiar and accessible. Already, almost everyone who has observed the BRP or IGCS and especially those who have handled the game-pad directly have responded to device with enthusiasm. Its prevalence within the video game industry is not a sign of inelegance. Witness the simplicity with which the game-pad solves the 3D selection problem.

Picking objects within a virtual environment has often been a frustrating and time-consuming task. The game-pad made possible an innovative and versatile sports-videogame inspired selection style. As long as the target entities are known to the application, the new picking method provides a quick and easy way to choose individual entities or groups of entities. This method could even prove effective for other immersive applications that have a large number of objects that the user would like to be able to select.

The feedback that has been received from experts within the field of UAV control seems to indicate that the IGCS is a relevant and interesting concept that warrants further investigation. Great care must be taken in developing and refining the set of interfaces that

the UAV control team will use in this application. Both manned and unmanned pilots should be consulted so that the factors that affect the human operators of the system are taken into account. In addition, these experts can provide critical and constructive feedback that when combined with user studies will ensure this interface grows into its full potential.

The BRP provides a solid foundation for continued command and control research. It is a highly stable flexible application that can be expanded to meet the needs and research interests of a variety of future projects. Arizona State University's Decision Theatre is already looking at adopting the BRP, and a partnership is forming between Iowa State and Rockwell Collins that could fund more research relevant to this work.

Future Work

Without question there is more research to be done and a large number of interesting research questions that could be asked and answered in future work. There are a host of interesting user studies that could be run on a slightly modified versions of the current IGCS. Further research effort could be spent on the representation of a UAV's path. Missing mission critical information could be integrated within in the IGCS to improve the operator's decision-making tools. More work could also be done to ensure that the operator will not suffer from information overload.

First and foremost is the need for a user study that directly compares and contrasts 2D and 3D interfaces that have similar capabilities. Specifically, the researcher would want to pay attention to the operator's situational awareness, the operator's ability make correct decisions, the amount of time it takes the operator to make decisions and the level of UAV threat exposure. If this test were designed to incorporate dynamic path planning, the research

could be structured to determine whether or not the 3D path representation helps the operator significantly.

Another interesting specter that the Predator story raises is the issue of long-term use. An interface may have better performance in the short term over another interface but does this short-term improvement translate into the long-term use. A user study that was designed to capture an operator's level of boredom over a longer mission could provide critical human factors information on what sort of interface will help alleviate this problem.

In addition, other human factors studies could look at specific aspects of the BRP environment such as the path representation, which concerned some of the expert survey participants. A formal user study that tested the operator's ability to make correct decisions based on different path representations would allow BRP developers to tailor their symbolism to the specific needs of the intended operators. This users study could be used to try to find the balance point between providing the operator with the information necessary for a successful mission and causing information overload.

One point that was raised multiple times during demonstrations of the BRP is that weather is a critical decision making tool in mission planning. It was also suggested that if the BRP could display weather conditions in 3D that would give it a significant advantage over 2D systems. Other pieces of information that are missing from the current implementation include no fly zones and restricted air space. Knowledge of where these areas are located is vital for the safe operation of both manned and unmanned aerial vehicles.

Screen clutter is another concern expressed at the demonstrations and through the expert feedback that relates back to information overload. In modern conflicts the United States, airforce and naval planes operate in crowded airspaces. Add to that confusion the

presence of enemy units both in the air and on the ground and occlusion becomes a significant problem for both 2D and 3D interfaces. A display can quickly become visually overwhelming. A program capable of smart information management would be of considerable interest to the armed forces. The information management tool could take into consideration the UAV operator's current task and overall mission objectives and only show information that would pertain to the safe execution of that task.

Critical to any future work on the Battlespace Research Platform and the Immersive Multi-UAV control platform is the involvement of both manned and unmanned pilots. Even with a limited sample size, the insights gained from the expert survey were useful in pointing out the weaknesses and strengths of this immersive ground control station. As the stories of Predator operators attest, command and control research cannot reasonably progress without the input of the men and women who are its intended users.

APPENDIX A. PATH PLANNING ALGORITHMS

The dynamic path planning method will not work without solid path planning algorithms. These algorithms at the minimum must be able to avoid obstacles such as the terrain and other aircraft. Additional capabilities that are needed are the ability to avoid threats, conserve fuel, and stay close to reconnaissance objectives. There has been extensive research in the area of path planning especially in the artificial intelligence, optimization, and video game communities[42][45][56]. One of the most popular path planning algorithms in the video game/artificial intelligence communities has been the A* path planning algorithm. The A* algorithm strength lies in the ability to heuristically judge or value the best path from point to point. If this cannot be done with reasonable accuracy then the A* method will not be very effective [43]. This may not be very possible considering the dynamic nature of the battlefield and the variable cost of particular parts of the environment based on differing criteria. Because of the variable cost nature of the types of path planning that will be done with UAVs a particle swarm optimization (PSO) method of path planning was developed [44]. The PSO path planner should be able to incorporate a large number of variables and cost functions and work effectively and efficiently.

The particle swarm optimization algorithm works in many ways like a genetic algorithm. There are generations, mutations, and cost functions that are performed in an attempt to find the best-fit solution in a very broad solution space. The PSO path planner begins with information on the start and end points of the path to be planned, the threats which should be avoided, and objective points that the path wants to try to stay near. In anticipation for future improvements a NURB is used to represent a curved path. Currently

the PSO path-planning algorithm uses a NURB but creates a simpler straight lined path for the UAV to follow. The number of control points used for the path is two plus the number of threats and objective points. This means that the more constraints the more direction changes that the path is allowed. The first path that is tested is the naïve path of going straight from the start point to the end point. Assuming this path is not satisfactory an initial set of random paths are generated by manipulating the control points. During each generation each path is evaluated against three cost functions. The first cost function is based on the amount of threat exposure. The higher the amount of threat exposure the higher the threat cost will be. The second cost function is the length or fuel conservation cost function and the longer the path the greater the fuel cost function will be. The last cost function imposes penalties for being far away from objective points, the farther away the path is from the objective points the higher the objective function cost. Each cost function carries a weight that ranges from 0 to 1. If the weight is zero then that particular cost function is unimportant for a particular run. The cost weights should add up to 1 in total. These weighted cost functions are then added together to form the cost of a particular path. Each other path tries to mutate towards the current best path and the generations best path. The mutation involves moving each control point of the NURB curve randomly closer to both the current overall best solution and the generations best. These mutations provide agitation to the system, which allows new leaders to formed and to be subsequently be followed. Eventually over many generations this method produces a best-fit path which is an optimization of the path function based on the particular weights provided to the algorithm. The best-fit path is returned as a series of straight lines by finding the “nodes” of the NURB curve.

APPENDIX B. SURVEY INSTRUMENT

INFORMED CONSENT DOCUMENT

Title of Study: Expert Feedback on 3D Virtual Environments for UAV Control.

Investigators: Derrick Parkhurst, PhD, Assistant Professor Psychology and Human Computer Interaction

This is a survey to obtain feedback on the Battlespace Unmanned Aerial Vehicle Control application developed at Iowa State University. You must be at least 18 years old to participate in this survey. Please take your time in deciding if you would like to participate.

INTRODUCTION

The purpose of this survey is to gain expert feedback on the strengths and weaknesses of the Battlespace Unmanned Aerial Vehicle Control application. You are being invited to participate in this study because of your interest in the demonstration of this technology at the Human Factors of Unmanned Aerial Vehicles Workshop.

DESCRIPTION OF PROCEDURES

If you agree to participate in this study, your participation will last for an estimated 5-15 minutes. During the study you may expect the following study procedures to be followed. A series of questions will be presented to you. Answer the questions as honestly as you can in the space provided. You may skip any question that you do not wish to answer or that makes you feel uncomfortable. When the survey is complete you must return the results via US mail using the prepaid envelope provided.

RISKS

There are no foreseeable risks to participating in this survey.

BENEFITS

Your input could help improve military software and eventually help save civilian and military lives.

COSTS AND COMPENSATION

There will be no costs for participating in this study other than 5-15 minutes of your time. If you decide to participate in this study you will be entered in a drawing with a chance to win an iPod nano. The estimated value of the iPod nano is \$200 and the estimated chance of winning will be approximately two percent.

PARTICIPANT RIGHTS

Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled. You must however return the consent form to be entered in the drawing.

CONFIDENTIALITY

Records identifying participants will be kept confidential to the extent permitted by the applicable laws and regulations and will not be made publicly available. We are required by University policy to keep a copy of the informed consent. However, no records are kept that allow us to associate your name, address, personal information, which is on the informed consent form with your answers. Your participation in this study is completely confidential.

QUESTIONS OR PROBLEMS

For further information about the study contact Derrick Parkhurst, 515-294-4549, derrick@iastate.edu. If you have any questions about the rights of research subjects or research-related injury, please contact Ginny Eason, IRB Administrator, (515) 294-4566, austingr@iastate.edu, or Diane Ament, Director, Research Assurances (515) 294-3115, dament@iastate.edu

SUBJECT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered.

Subject's Name (printed) : _____

Subject's Signature

Date

Name: _____

Email Address: _____

Mailing Address: _____

Would you like to be put on the Virtual Reality Applications Center UAV, mailing list?
(Circle: Yes No)

Would you like to be entered into the drawing for the iPod nano? (Circle: Yes No)

14. Was anything about the demonstration confusing? Please explain.

15. How could the visualization be improved?

16. Would 3D visualization provide an advantage to a UAV operator? (Circle: Yes No)

17. For which UAV applications do you think 3D visualization would provide the most benefit?

18. Could 2D visualization provide an advantage over 3D visualization in the operation of UAVs? Please explain.

19. What priority should UAV research be given?
(1 is low and 10 is high) _____
20. What priority should human computer interface research for UAV control be given?
(1 is low and 10 is high) _____
20. What priority should 3D visualization research for UAV control be given?
(1 is low and 10 is high) _____
21. What priority should path visualization research for UAV control be given?
(1 is low and 10 is high) _____
22. How important is it to keep a human-in-the-loop for UAV control?
(1 is not important and 10 is very important) _____
23. How important is tele-operation to UAV control?
(1 is not important and 10 is very important) _____
24. For what applications is tele-operation most important?

25. How important is autonomy to UAV control?
(1 is not important and 10 is very important) _____
26. For what applications is autonomy most important?

27. Do you have any other comments or suggestions?

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