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14. ABSTRACT The objective of this initiative was to design, develop, implement, and test the hardware, software, and aeronautical systems necessary to create immersive ground control stations based on virtual reality technology. Our goal was to explore the inversion of the typical paradigm in which information is conveyed to a remote operator. Rather than augmenting real-time visual information (typically from cameras) with information generated from other sensors and systems (e.g., heads-up display), we explored, using a virtual environment of the operating theater as the primary interface context that is augmented in spatial and temporal context with the myriad of information sources available in a modern military engagement. We also explored, developed, and measured the effectiveness of new human interface techniques to enable remote operators to effectively control swarms of semi-autonomous air vehicles					
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FINAL PERFORMANCE REPORT

Virtual Teleoperation for Unmanned Aerial Vehicles

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Introduction

This report summarizes the accomplishments of a multi-year research contract entitled “*Virtual Teleoperation for Unmanned Aerial Vehicles*,” funded via direct congressional appropriation to Iowa State University and administered through the AFOSR/RL.

The initial grant (FA9550-05-1-0384) was funded in FY05 for approximately \$2.8M, for the period 5/15/2005 through 5/14/2007. In FY06 it was supplemented by another congressional appropriation for an additional \$3.3M and the end date was extended for an additional two years to 5/14/2009. In FY07, a third and final congressional appropriation was directed for the project totaling \$4.3M. Rather than supplementing the original grant (FA9550-05-1-0384) a new one was initiated (FA9550-07-1-0475) with the same title and a revised statement of work. Thus the total budget for the “Virtual Teleoperation for Unmanned Aerial Vehicles” project sums to \$10.4M for the period May 2005 through May 2009. In May 2009 a no cost extension of the project was granted for an overall end date of May 2011.

Summary

The focus of this project is the exploration of next-generation command and control interfaces for UAVs based on advanced virtual reality and other emerging interface technologies. Part of our rationale for requesting such a substantial budget was the need for a major investment in our infrastructure to enable the research. Although the research infrastructure at Iowa State University's Virtual Reality Applications Center was substantial when the project was initiated in 2005 it was inadequate to support the vision outlined in our proposal. For example, our two premier immersive interfaces, the fully immersive six-sided CAVE called the “C6” and the stereoscopic display-enabled Lee Liu Auditorium were both developed in 1999 when Howe Hall was built. Thus, our proposal called for substantial investment in enhancing both of these leading edge devices. Although the research effort began immediately and ran concurrently with the infrastructure enhancement projects, the majority of the expenditures during the first two years of the project (2005-2007) focused on enhancing the C6.

The C6 enhancement was a truly revolutionary project - we worked closely with commercial vendors including Mechdyne and Sony to push the boundary of resolution and image generation far beyond what existed before. In fact, the requirements we generated during this process enabled Sony to expand the market for their new SXRD (LCOS projection) technology, designed originally for the digital cinema market, into the visualization and simulation market. At a total of 100M pixels, the C6 is now the world's highest resolution fully immersive VR display system. The C6 enhancement has been an unqualified success, not only enabling the research we originally proposed, but also many new research opportunities for our colleagues at VRAC. It garnered national recognition from the popular press including Wired Magazine, the Discovery Channel, and CNN. It also opened new doors within the DoD, including new research relationships such as our activities with colleagues at Wright Patterson Air Force base. We have hosted visits from colleagues at NASA Ames, and have visited colleagues at AFRL's Human Effectiveness Branch in Mesa Arizona to discuss high resolution displays. In addition, in December 2008 Professor Oliver was invited to brief the USAF Operational Based Vision Assessment (OBVA) Integrated Product Team on our success in developing such a high-resolution display system at the IITSEC Conference in Orlando, Florida. Since its opening in 2007, to our knowledge only one other equivalent system has emerged: the CORNEA, based at King Abdullah University of Science and Technology (KAUST) in Saudi Arabia opened in 2009. Built by Mechdyne as well, the CORNEA is essentially a replica of ISU's C6.

While pushing the boundary as we did paid substantial dividends, it took much longer than we had initially planned. In addition to enumerable technical challenges faced by our vendors and their suppliers, we encountered more pedestrian but unforeseen challenges, such as enhanced power and HVAC requirements for the C6, that set the schedule back repeatedly. After a total investment of approximately \$5M, the C6 enhancement was declared “completed” in May 2007, although ongoing debugging and tuning with Mechdyne and Nvidia lingered through summer 2008 leading to a final incremental enhancement of 96 new graphics cards for the C6 image generator in fall 2008.

In 2007 the infrastructure enhancement emphasis shifted from the C6 to the Lee Liu Auditorium. While this project was of substantially smaller scope and complexity, and we had learned much from the C6, it nonetheless presented its own challenges. In order to accommodate the two Sony SXR D projectors, the control room of the auditorium had to be substantially remodeled which required another engagement with university facilities management architects and their procedures. The Lee Liu Auditorium upgrade was completed in April 2008 for a total cost of about \$800K making it the world's highest resolution stereoscopic auditorium display.

Throughout these infrastructure enhancement projects, our research efforts continued to grow and gain momentum. The project supported the research of numerous faculty members (with particular emphasis on junior faculty), several post-doctoral researchers, and many graduate and undergraduate research assistants. Project personnel worked in a coordinated fashion on complimentary aspects of the overall vision.

Research results are documented at our project web site: <http://www.vrac.iastate.edu/uav>. Research supported by the grant has garnered three best paper awards at national conferences, enhancing our visibility and competitiveness for related grants. Graduates of our program are now employed by DoD contractors such as Boeing, Lockheed Martin, and Rockwell Collins, in addition to many others in the software and other high technology industries. Of the total \$10.M budget, approximately \$6M has been expended in the research infrastructure described above, and approximately \$4M in personnel.

Personnel Supported

Through the six-year duration of the project, the following personnel were supported by the grant:

Faculty:

PI:

- James Oliver, Larry and Pam Pithan Professor of Mechanical Engineering

Co-PIs:

- Eliot Winer, Associate Professor of Mechanical Engineering
- Stephen Gilbert, Assistant Professor of Industrial and Manufacturing Systems Engineering
- Derrick Parkhurst, Assistant Professor of Psychology
- Alex Stoytchev, Assistant Professor of Electrical and Computer Engineering

Senior Personnel:

- Soon-Jo Chung, Assistant Professor of Aerospace Engineering
- Chris Harding, Assistant Professor of Geologic and Atmospheric Sciences
- Jonathan Kelly, Assistant Professor of Psychology
- Nir Keren, Assistant Professor of Agricultural and Biosystems Engineering
- Rob West, Associate Professor of Psychology
- Arun Somani, Anson Marston Distinguished Professor of Electrical and Computer Engineering

Post-doctoral Researchers:

- Vijay Kilavarapu
- Eric Foo
- Keehong Seo

Graduate Students:

- 22 PhD Students
- 28 MS Students
- Numerous undergraduate research assistants

Research Accomplishments

In addition to the infrastructure enhancements described above, the following research contributions are summarized below:

Virtual Battlespace – is a flexible VR software platform to support our research in for virtual teleoperation of UAVs. The Virtual Battlespace integrates information about tracks, targets, sensors and threats into an interactive virtual reality environment that fuses available information into a coherent picture that can be viewed from multiple perspectives and scales. Visualizing engagements in this way is useful in a wide variety of contexts including historical mission review, mission planning, pre-briefing, post-briefing and live observation of engagements in progress.

Virtual Battlespace immerses users in a virtual environment that provides them with greater context and awareness of the units under their control as well as the overall mission. By integrating radar tracks and UAV video feeds, the virtual world can provide access to the latest real time battlefield information. The virtual world is constructed from a mix of *a priori* information and real time sensor feeds to act as an organizing context for the operator, resulting in a mixed reality system, in which real-world video and radar tracks augment a dynamic virtual world. Using real-world data to augment the virtual world is an inversion of the more typical paradigm of augmented and mixed reality where virtual information is used to enhance real world data and imagery.

To facilitate modular enhancement, Virtual Battlespace incorporates a command architecture that abstracts message passing among components as well as stream input so that any arbitrary input stream can be accommodated including terrain generators, path planners, and voice recognition input.

Some unique features of the Virtual Battlespace include:

- Ability to read in terrain data in most open formats such as DTED and GIS.
- Models such as SAM sites, aerial and ground vehicles, and other graphical objects displayed with varying levels of detail (LOD) and aggregation/disaggregation glyphs based on viewer distance and function.
- Ability to render environment for stereographic viewing over arbitrarily large cluster computers and display channels
- Communication server implementation to listen for DIS/HLA updates
- Integration of spatial sound in an immersive environment to facilitate interface experimentation
- Semi-automated UAV path planner incorporating constraints for reconnaissance, threat avoidance, and terrain features
- OneSAF-based integration of multiple simulators for multimodal interaction
- Generally abstracted controller hardware and graphical interfaces facilitating deployment on a variety of VR platform architectures

Sparsh UI – To facilitate multi-modal interaction via multi-touch surface-based interaction, a research team led by Professor Stephen Gilbert developed and released Sparsh UI (<http://code.google.com/p/sparsh-ui/>), an open source API that enables users to create multi-touch applications easily on a variety of hardware platforms. Sparsh UI enabled group-based multi-touch interaction with the Virtual Battlespace via its command architecture.

Physical Vehicle Integration – Cyberphysical interfaces to the Virtual Battlespace were developed by Professor Somani's team to enable interaction, control, and telemetry of physical, real-life UAV/UGV platforms. To generalize the classes of air and ground vehicles that Battlespace could integrate and control an ad-hoc onion routing architecture via a TCP/IP protocol stack was implemented, which delivers Battlespace data packets to the appropriate application thread on the UAVs/UGVs and vice versa. This provided four benefits. [I], it allowed Battlespace to control the UAVs/UGVs over the Internet, hence isolating the operators from the immediate dangers of having to be within visual, or radio-range to the physical mission. [II], due to the distributed nature of the system, there is no single link that can be compromised due to severing the connection between the Battlespace and any UAV/UGV. [III], the design

prevents intermediary parties from knowing the origin, destination, or contents of Battlespace communications protocol, thus providing forward secrecy. [IV], it was particularly well suited to work with the existing Virtual Battlespace command architecture.

Extension into LVC – Expertise gained through the course of the project, particularly in the architecture of state-of-the-art DoD simulation technology, as well as in the variable scale, and information visualization techniques developed, enabled to the same core team (Gilbert, Winer and Oliver) to develop a successful collaboration with the US Army RDECOM resulting in a funded project called “*Advanced Live Virtual and Constructive Training*”. This new project, which commenced on 10/01/09 and is funded through 9/30/13 for a total of \$4.3M, leverages much of the infrastructure and research results developed during the course of the subject UAV project, and has enabled us to reach a much broader audience of DoD stakeholders spanning government research labs and the DoD contractor community.

First Responder Training – Professor Keren’s group used support from this grant to explore the feasibility of integrating biometric sensors and integrating the information collected to enhance decision-making and training. The result is a new research platform called SEER: Simulator for Enhancing Emergency Response Under Stress. Professor Keren and his team work closely with the LVC team and are currently focused on securing state-level and DHS support for developing first responder training. A white paper describing SEER research thrust and some preliminary results are attached as an appendix to this report.

Workshop/demo – As the Virtual Teleoperation for UAVs project approached its conclusion in spring 2011, the PIs planned a workshop to feature its results as well as the preliminary results and vision for their recently commenced LVC project. The workshop at Iowa State University’s [Virtual Reality Applications Center](#), was held on June 21, and brought together partners from The Boeing Company, Rockwell Collins, US Army RDECOM, Wright-Patterson AFB, Dignitas Technologies, and the University of Iowa to explore opportunities for collaboration in next generation command and control and LVC training. Twenty-two attendees gathered to view demonstrations of each other’s work and hear presentations from military stakeholders about current DoD research needs. The VRAC demo featured at this workshop built significantly on the Virtual Battlespace technologies, integrating them with systems for live, virtual, and constructive training. In a scenario depicting an IED diffusing mission students played the role of Command Center staff using the Virtual Battlespace for surveillance with UAVs as well as coordination of a UGV for disarming the IED. The overall situational awareness afforded by the Virtual Battlespace was integral to the success of the mission. A video of this demo can be seen at:

<http://www.youtube.com/watch?v=kWTvIxxkziUk>

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