REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
03-11-2017	Final Report	19-Aug-2016 - 18-Aug-2017

4. TITLE AND SUBTITLE
Final Report: Enhancing Tele-robotics with Immersive Virtual Reality

5a. CONTRACT NUMBER
W911NF-16-1-0473

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
106012

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
68953-CS-REP.4

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Alireza Tavakkoli
UU	UU	UU	UU		19b. TELEPHONE NUMBER 361-570-4204

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 13-Nov-2017

Agency Code:

Proposal Number: 68953CSREP **Agreement Number: W911NF-16-1-0473**

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Report Date: 18-Nov-2017 Date Received: 03-Nov-2017
Final Report for Period Beginning 19-Aug-2016 and Ending 18-Aug-2017
Title: Enhancing Tele-robotics with Immersive Virtual Reality
Begin Performance Period: 19-Aug-2016 **End Performance Period:** 18-Aug-2017
Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 1

Major Goals: The proposed project aims to develop a fundamental framework for establishing an immersive virtual reality environment for robust and scalable human robotics interaction in a cooperative intelligent architecture at the University of Houston-Victoria (UHV), a designated Hispanic-Serving Institution of higher education. The requested equipment and instrumentation will be integrated into our existing motion capture facilities and will serve as a complement system to enhance our current research and educational capabilities in virtual reality and robotics tele-presence and tele-operation. Furthermore, the resulting integration will provide new and exciting avenues of research in multi-agent virtual tele-robotics as well as stimulating educational tools to engage more under-represented students in STEM.

Several Items of equipment have been purchased as a result of this award. The equipment has been integrated into our current Immersive Virtual Reality and Tele-robotics infrastructure to enhance the entire framework.The system is a combination of several items essential for the enhancement and continuation of the proposed research activities at UHV. The Virtual Reality (VR) component of the proposed system is comprised of a graphics and VR server running Unreal Engine 4 (UE4) as the main VR engine and two sets of VR Clients; comprised of Alienware Area-51 desktops, CyberForce system with 22-sensor Cyber-
Glove data gloves. The Computational backbone is an Nvidia Tesla K80 server to handle the GPU accelerated computation support. The robotics tele-operation agents added to our agent portfolio are a Baxter Research robot for humanoid tele-operation and Solo Unmanned Aerial Vehicles (UAVs) for outdoor aerial tele-presence and automated terrain feature classification and procedural generation of outdoors VR environments.

Accomplishments: Please see the attached PDF file for the accomplishments.

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Training Opportunities: Our population of graduate and undergraduate students within the Digital Gaming and Simulation, Computer Science, and psychology programs have actively collaborated with the PI to integrate the equipment into our current facilities and to engage in several research projects to enhance the computational architecture currently available at UHV. These projects aim to study, assess, and reconfigure suitable visualization and HCI tools for the proposed integrated virtual reality environment for human-robotics interactions. Moreover, through a long-term partnership with industry, the PI hosts an annual robotics program for high school students at UHV. The acquired system will provide a unique opportunity for the robotics program to engage bright high school students in the proposed research and educational activities and to encourage them to pursue a STEM related post-secondary education.

Results Dissemination: Several articles have been presented at international conferences including the IEEE Virtual Reality Conference, IEEE 3D User Interfaces Symposium, IEEE RoMan Conference, and the International Symposium on Visual Computing.

In addition, the PI and his research group, in conjunction with the STEM division at the University of Houston-Victoria, held a one-day Mathematics and Robotics Awareness event in April 2017. There were 250 high school students in attendance. This event is the keystone of bringing high school students to the university to learn about Mathematics and Robotics at UH-Victoria and to encourage them to pursue degrees in STEM, in particular in Computer Science, Mathematics, and Robotics.

Honors and Awards: Outstanding Research and Scholarly Activity Award (Alireza Tavakkoli), UH-Victoria
- NASA ASTAR Fellowship (Brandon Wilson), NASA

Protocol Activity Status:

Technology Transfer: Nothing to Report

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
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Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 13-Nov-2017

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE 3DUI
Date Received: 22-Mar-2017 Conference Date: 18-Mar-2017 Date Published: 22-Mar-2017
Conference Location: Los Angeles, CA
Paper Title: A Robust and Intuitive 3D Interface for Teleoperation of Autonomous Robotic Agents through Immersive Virtual Reality Environments
Authors: Jace Regenbrecht, Alireza Tavakkoli, Donald Loffredo
Acknowledged Federal Support: **Y**

WEBSITES:

URL: https://github.com/CAVE-Lab/CrossSock
Date Received: 25-Oct-2017
Title: CrossSock Socket Server for VR-TeleRobotics
Description: A type-safe cross-platform header-only lightweight C++ networking API.

Final Report

Period of Performance:August 19, 2016 – August 18, 2017
By: Alireza Tavakkoli (PI)
Award No: W911NF-16-1-0473

Foreword

The acquired equipment from this award is used to enhance, an Immerive Virutal Reality Environment that enables us to efficiently interact with the real world around us or in our imagination. To this end, our research team investigates the use of artificial intelligence and visual computing. Numerous fields across the human-computer interaction and gaming research areas, form modeling to visualization, rely on the foundations within this cross-section of computing sciences. The projects for which the equipment is utilized serve in developing a potentially unique bridge at the intersection of two domains. On the one hand a significant amount of research has been invested in digital gaming and simulation to cognitively stimulate humans by computers, forming a $10.5B industry [1]. On the other hand, cognitive computing scientists and roboticists are engaged in developing computational models to enable computers and robots understand physical and cyber environments efficiently.

With the addition of the requested items into our current facilities at the Computation and Advanced Visualization Engineering (CAVE) Lab, a number of research avenues in our ongoing research will be potentially enhanced. The proposed equipment is primarily utilized in three main areas of research; 1) Sensory Data Fusion and Processing; 2) Heterogenous Computational Architecture in support of such processes; and 3) Human Studies.

The establishment and continuation of this research will make significant impacts on a variety of applications in which human operators need to be in communication with and control of cyber-physical systems, when such systems need to maintain a sufficiently high level of autonomy. This efficient human–robot–environment interaction and its associated operations become more important when viewed from the perspective of computational efficacy and deployment experiences to support warfighters' mission and their objectives.

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Statement of Problem Studied

The equipment is currently being utilized in conducting research in addressing an over-arching question: How can we develop a framework capable of merging an artificially intelligent environment with an immersive virtual one, in a manner that both environments become aware of their user's motives and intentions, while drawing the human operator to intuitively engage with the environment and its agents? In order to answer this question, we are developing a cyber-physical environment capable of perceiving both users' and robotic agents' actions from the real world and within the virtual environment, while processing this information to act accordingly upon the virtual environment and on the real world. The research activities and process flow between the research components in our framework for the integration of intelligent physical environments with an immersive virtual one are depicted in Figure 1. There are two main research motifs; an efficient computational framework for Virtual Reality and Tele-robotics, and the associated human studies in validating the performance and efficacy of the framework.

The first motif is comprised of three research tasks, of which the first two (VRT-1 and VRT-2) are interconnected. The objective of these two tasks is to help build reliable models in order to facilitate information depth and immersion (human's perception) as well as information breadth and interactivity (system's perception). First, there is the problem of modeling interactions between user, environment, and robot from data supplied by a multitude of sensory devices. To approach the issues of breadth of information and interactivity (VRT-1) we rely on robotics and machine learning. On the other hand, we have the problem of the human's perception of the agent's situation and its environmental conditions. This problem is approached from the perspective of the digital gaming field (VRT-2).

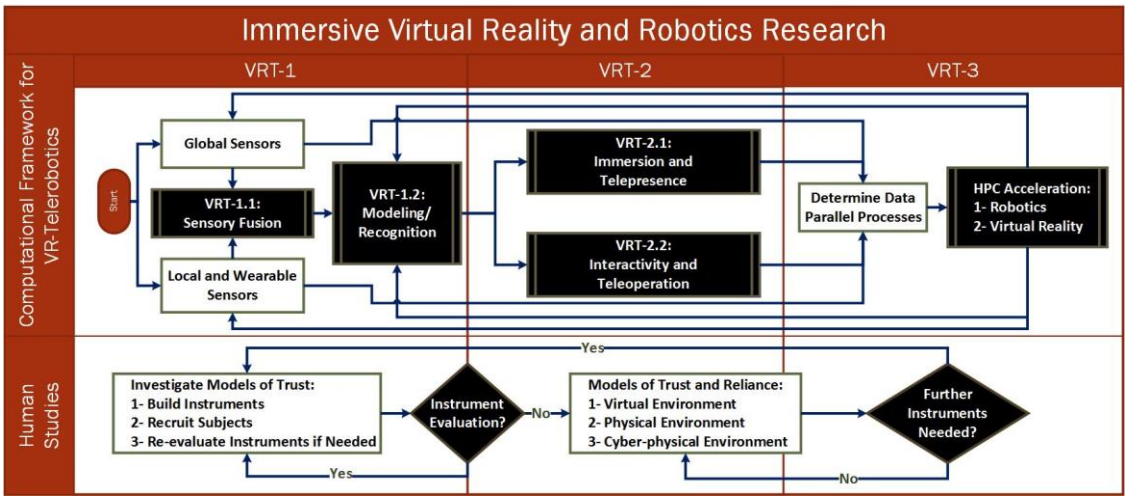


Figure 1. Main Research Activities

The third research task (VRT-3 in Figure 1) in support of this computational platform is to enhance the processing power of the framework and to free on-board computational needs on both robotic agents and the virtual reality components. To achieve this objective we are studying and developing data parallel algorithms for the data parallel processes used across the system. This computation targets NVidia's CUDA heterogeneous computing platform and is currently being performed on servers based on NVidia's Kepler architecture. We showed performance increases of up to 2 orders of magnitude with the acceleration of foreground object detection in our global visual sensory systems [2].

To improve human user's visual and auditory stimulation we utilize head-mounted displays, immersive sound systems, and the Virtuix's Omni, the first virtual reality interface that allows for the player to move freely and naturally in virtual environments. Our platform of choice for the implementation of the virtual reality environment is the Epic Game's Unreal Engine 4 [4]. To achieve the goals of the VRT-2 track, we address two problems: (VRT2.1) to create an immersive experience and (VRT2.2) to enhance interactivity with the virtual world. Our first results of integrating the VR environment for Tele-robtics were discussed at the 2016 International Symposium on Visual Computing [2].

Summary of Most Important Results

The proposed study is situated at the intersection of two conversations. On the one hand, scholars in digital gaming and simulation are researching the burgeoning world of video games, an industry that has penetrated two-thirds of United States households and now constitutes a $10.5 billion industry. On the other, roboticists tirelessly engage in developing computational models to bring physical objects to life, safely and efficiently, in and around humans.

Entertainment gaming researchers and engineers have given much attention to developing technological advances aimed at drawing humans more and more into the game world, through head mounted displays, 3D body tracking sensors, and haptic user interfaces. In a parallel and equally exciting area of research, robotics and artificial intelligence scholars have been investigating theoretical and algorithmic frameworks to make robots work safely and effictively in the real world, in military, industrial, medical, and domestic applications.

The equipment acquired by this award is utilized in a number of projects with the goal of developing two environments: a physical, intelligent environment comprised of unmanned autonomous agents and multiple layers of static and dynamic sensors, and its virtual replica in which human subjects (i.e. trainees and operators) will be immersed to tele-exist with their physical autonomous companions for training and teleoperations purposes.

Current Projects

The sections below describe the current projects in which the equipment is being utilized. First, the overall project will be presented. The over-arching project presents a unified framework for the integration of heterogenous robotic agents within an immersive virtual reality environment is developed.

In the next project we present a mechanism for intuitively engaging the operator of a remotely situated robot to interact with it and to tele-operate the agent. This will enable human operators to intuitively communicate with the robots through gestures acquired from local Leap Motion hand motion capture.

VETO: A Client-Server Architecture for the Integration of Autonomous Robotic Platforms and Remote Users in a Virtual Reality Environment

In this project our previous platform called ArVETO [2] is enhanced to integrate a number of robotic platforms in interactive immersive virtual environments. The architecture, termed VETO (*Virtual Environment for Tele-Operation*), is a client-server architecture that efficiently communicates directly with a state-of-the-art game engine to utilize a virtual environment in support of tele-robotics and tele-presence. This architecture provides easy integration of robot clients and their unique robot interfaces into a GPU-accelerated HPC server, as well as an end-user dynamic and immersive virtual reality enabled 3D environment provided through UE4. The architecture allows for the offloading of computationally-intensive tasks to the HPC server, which facilitates communications between the end-user's UE4 game client and the real-world robot platform. In this way, users are virtually in the same environment as the robot, and can intuitively interact with both the robot and it's environment. User input is then translated to real-world actuators on the robot platform.

This framework employs the Unreal Engine 4 (UE 4) to provide the front-end virtual environment and user controls, while utilizing a comprehensive networking architecture to handle communications between the robots, user clients, and our computational server. In order to accelerate data-intensive computations in support of such an interactive and immersive environment, we utilize the CUDA toolkit and OpenCV libraries to handle any calculations needed on the computational server, as well as common image processing tasks. The strength of the proposed architecture is that it allows for the integration of heterogeneous robotic systems in an intelligent immersive environment for intuitive interactions between the robot and its operators.

By utilizing an immersive virtual reality medium, an operator can more naturally interact with the robot; as buttons and joysticks can be replaced with hand gestures and interactions with the virtual environment. This provides a higher degree of immersion and interactivity for the operator when compared to more traditional control schemes.

The Proposed Architecture

In this section, details about an integrated architecture is presented, that allows the user to control remote robotic agents in an interactive virtual environment, while providing mechanisms for the robots to efficiently send back their sensory data to the server and subsequently the user, as shown in Figure 2. The user controls the robots in a virtual environment. This provides a more immersive experience for interacting and operating remote robots, as the operator senses the presence of the robot and its environmental conditions remotely, while interacting intuitively with the robot.

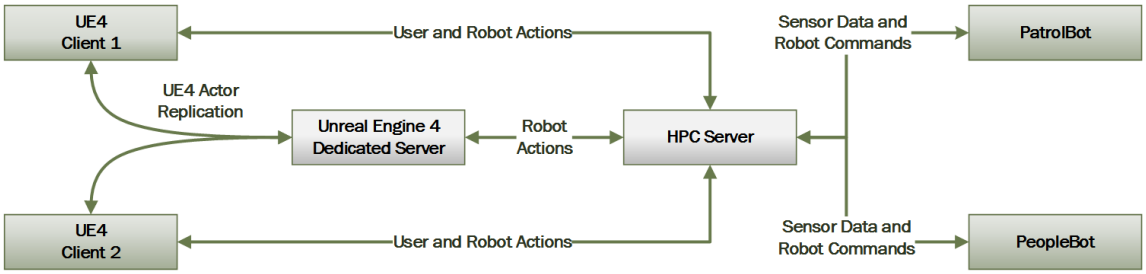


Figure 2. An overview of the VETO network architecture.

Robotic agents provide a wide range of sensors such as sonar, laser range-finders, physical bumpers, and stereoscopic cameras that gather 3D information about their environment. Integrating these sensory data

into a 3D immersive and interactive virtual environment will provide much higher levels tele-presence and immersion for control and operation of remotely situated robots. In the purposed architecture a centralized computational server is utilized in order to mediate the communication between the Virtual Reality (VR) client and the robot client, while performing data-intensive computations required for the proposed architecture and its several components.

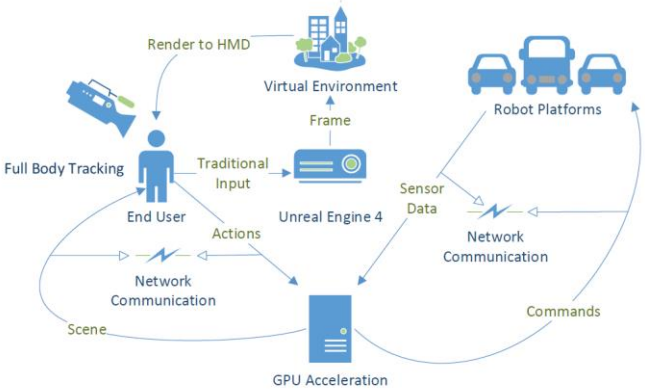


Figure 3. An overview of the proposed framework architecture.

The proposed integrated architecture termd VETO(*Virtual Environment for Tele-Operation*), enhances the previously developed ArVETO (*Aria Virtual Environment for Tele-Operation*) that supports the computations essencial for tele-robotics and tele-presence, implemented within an interactive and immersive virtual reality environment. The proposed system has three major components, comprising of virtual reality clients, a centralized High Performance Computing (HPC) computational server, and a number of robotic clients – each specialized to perform certain tasks. This framework allows for multiple clients to interact with multiple robots in a virtual environment, with the ultimate goal of remotely operating the agents while allowing for high-fidelity tele-presence by the human operators. An overview of this architecture is shown in Figure 3.

There are many benefits and challenges towards the goal of a game client for the purpose of robotic tele-operation. Real-world data must be provided to the game client within bandwidth limitations and with minimal latency, and all environmental data must be processed such that the virtual environment visualization is minimalistic, clean, and optimized. Moreover, all real-world sensor data, user input, and resulting robot commands must be generalized such that they can be applied to various different robot platforms, each employing unique actuators and sensors.

The Virtual Environment for Tele-Operation (VETO) architecture was designed to meet each of these challenges. The VETO architecture is a tele-operation system that works closely with the CrossSock library and Unreal Engine 4 (UE4) game engine to provide a feature-rich framework for developers. This framework can be employed to implement robotic agents into an immersive and VR-enabled end-user game interface. Game levels are generated dynamically on a GPU-accelerated server based on the real-world sensor data from the robotic agents. This data is then broadcasted to all end-user game clients to provide users with a virtual environment that closely represents the real-world robot environment. This environment is used to interact with the robotic platform and its environment in a natural and intuitive fashion.

The benefit of the new VETO network architecture is threefold. First, it provides a traditional client-server architecture that minimizes the network bandwidth required by reducing the total network connections and transactions required by the architecture. In addition, this server can process data-intensive computations needed in support of the entire system. These computations must be performed on the raw sensory data to potentially reduce the amount of the data needed to be sent to each UE4 client and to improve the accuracy of the UE4 virtual environment. Finally, the VETO architecture uses UE4 actor replication, to efficiently stream the robots' properties to further reduce the network bandwidth. Finally, we utilize the concept of network relevancy. That is, each UE4 client in the VETO architecture

communicates to the server from which robot, if any, it requests data. This allows the UE4 clients to cull robots, either because they are out of focus of the operator or because they are too far away from the virtual operator to be of significant impact. This relevancy mechanism reduces network bandwidth even further. This reduce in bandwidth is crucial, as all calculations and transactions in the VETO architecture are performed in real-time.

The Architecture

As previously stated, VETO is comprised of three major components. Each of these components and their implementations are outlined in Figure 4, and each of them are detailed below. This figure shows how communication between UE4 and each of the clients can be achieved.

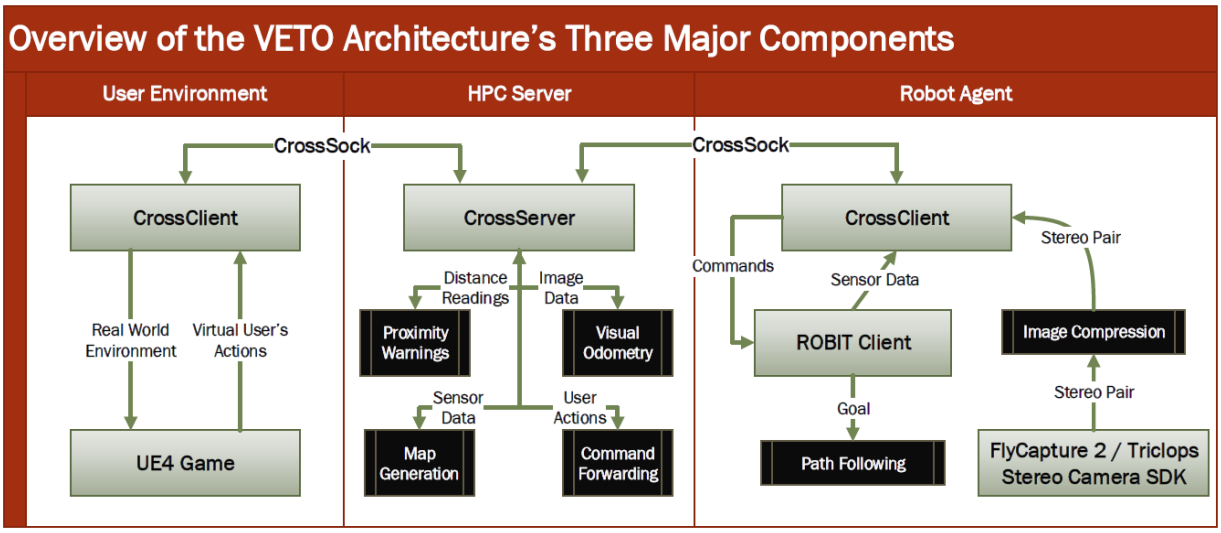


Figure 4. Allocation of work and overall communications between the Cross-Sock Socket Server SDK and Unreal Engine 4 in the proposed architecture.

The architecture is split into three major network components. First, the VETO High-PerformanceComputing (HPC) server provides GPU-enabled services, such as visual odometry tasks and 3D map creation, to the end-user clients and robotic agents. The HPC server is extendable, which allows for developers to implement additional services. The HPC server supports multiple end-user game clients and multiple robotic agents. Next, robotic agents are included in the architecture through the Robot Operating By Itself (ROBIT) client framework. The ROBIT clients must be implemented for each robot that employes a unique robotic interface. The framework exposes functions that allows each ROBIT client to complete critical tasks, such as querying for real-world environment data from the robot or to execute robot commands, such as movement.

Finally, an end-user game client is provided via Unreal Engine 4 (UE4), which can include multiple ROBIT actors. All processed data is provided to developers inside UE4's blueprint visual scripting system, which allows for the easy visualization and integration of new robot agents into the end-user game interface. Basic sensor visualization is also provided, but can be customized for each ROBIT actor. The game interface also provides an intuitive and generalized control interface, which allows end-users to control the robot client in a unified fashion, despite any hardware or software differences between each robot platform.

Results

With the VETO architecture we were able to connect the mobile robots and the VR client to the centralized server to perform remote operations and navigational tasks. This allowed us to control the robot in a virtual environment as it moved through an identical physical environment. The robot was able to successfully navigate through our virtual environment while moving through the physical world.

Figure 5. The robot operation with VETO: Left- PatrolBot in the real world. Right- the PatrolBot as observed and operated in the Virtual World through Oculus Rift HMD (Head Moutned Display).

Figure 5 shows the physical robot in the hallway (the left image) and the virtual robot in the VR hallway (right image), respectively. The navigation of the Patrolbot was done by an operator observing the robot's location via the stereoscopic cameras on both the physical and virtual robot. Autonomous navigation by the robot can be conducted by putting the robot in autonomous mode and without user intervention. The virtual reality environment in which the robot operates is a replica of an indoors hallway with physical objects and obstacles present. This experiment showcases the differences and similarities between the teleoperated robot and the VR robot.

The end-user game interface was developed much like a traditional game, and which has been coined Unreal Robotics. The primary components of the game interface are the Cross Client Manager (CCM), which includes the CrossClient that communicates with the HPC server, as well as the Unreal Robotics Game Instance (URGI), which stores real-world environment data for use by the player actors, ROBIT actors, and any other objects that need access to the real world data.

All of the URGI data is blueprintable, which allows for modification of the project with either C++ source code or blueprint scripting. As such, additional robot agents can be added to Unreal Robotics through simple scripting and the addition of art assets. Furthermore, simple sensor visualization is provided by default for each ROBIT actor, and can be overrided with custom logic. This allows for developers to rapidly add new ROBIT actors to the project, while still allowing for custom logic when necessary. Unreal Robotics is an extensive project, and contains many of the complexities of a traditional game. As such, the specifics of its implementation are omitted in this section. However, qualitative results of the project are provided below, which demonstrates the capabilities of the overarching project.

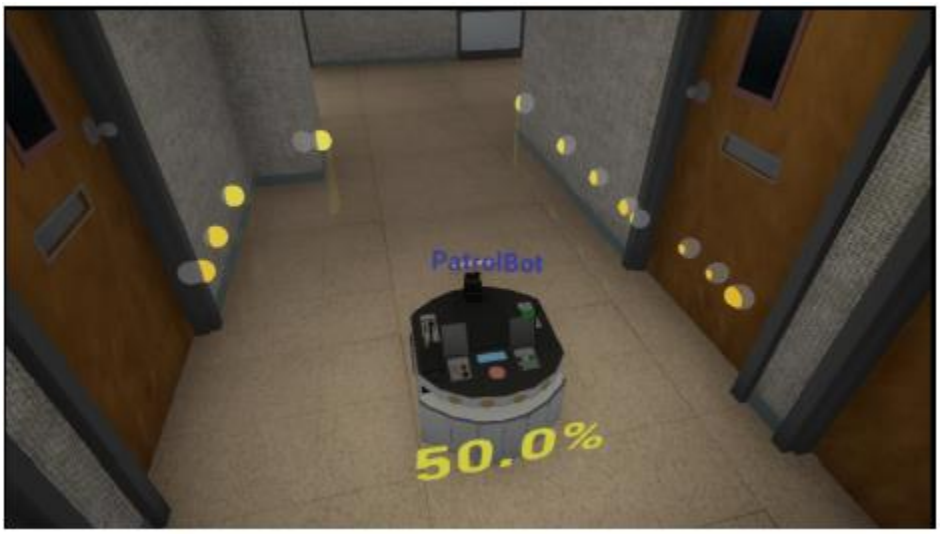


Figure 6. A robot being driven automatically with the VETO architecture through path planning and following.

Qualitative results have been gathered of the VETO architecture in action, starting with normal usage in an office hallway shown in Figure 6. In this figure, the PatrolBot is being being driven manually down a hall. The environment is known, and is visualized around the robot. The spheres displayed in the virtual environment represent the real-world readings from the robot in real-time from its LRF and sonar sensors. In addition to the environmental data, the current 'throttle' (normalized speed) of the robot is displayed behind it as a percentage. The robots name is shown hovering above its current location.

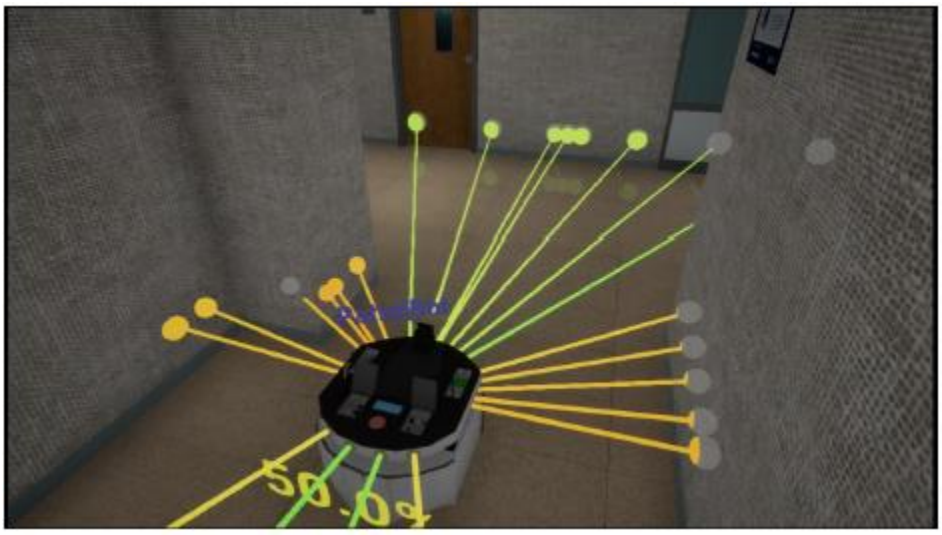


Figure 7. Optional LRF and sonar sensor visualization.

Figure 7 shows the optional distance sensor (LRF and sonar) visualizations as a raycast in the virtual environment from the robot to its final location. This visualization can be enabled on the current robot whenever the proximity warnings are not enough for manual piloting.

Figure 8 demonstrates the Architecture's ability to automatically path the robot from its original location to any reachable location in the mapped environment. In this figure, red waypoints show the path's segments, and the final green waypoints represents the robots goal.

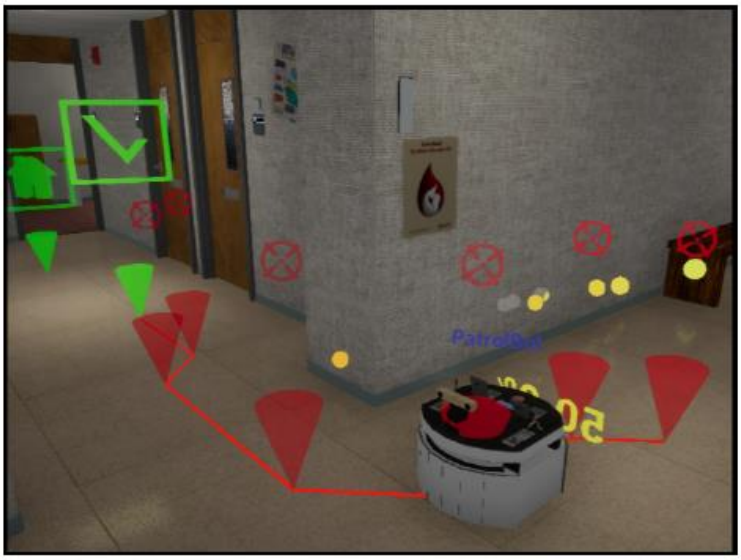


Figure 8. A robot being driven automatically with the VETO architecture through path planning and following.

Obstacle visualization is shown in Figure 9. The circled section is an unknown obstacle not reflected in the map data, which is visible on the stereo camera. The VETO architecture visualizes this obstacle as a free-floating proximity warning.

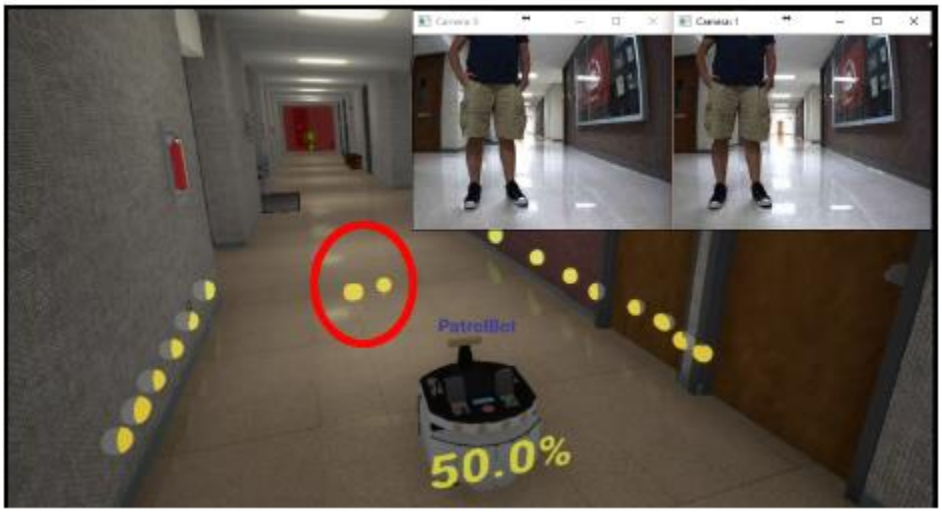


Figure 9. An unknown obstacle visualized as a proximity warning.

Finally, Figure 10 demonstrates the superiority of the virtual environment in remotely controlling a robot after the visual sensory information has been lost due to sensory malfunction or environmental conditions. In such scenarios, if the actual environment has not been affectd, the Virtual Environment may

be fully utilized to perform the required safty tasks on the remotely situated robot until the lost sensory data is recovered.

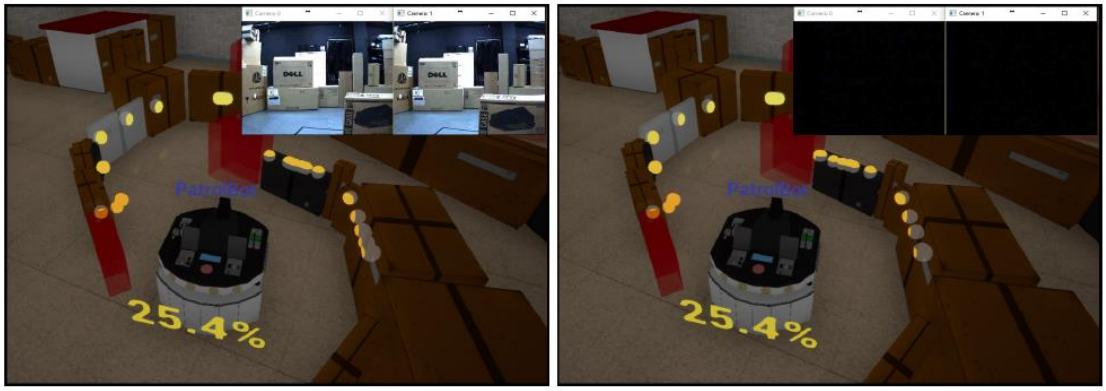


Figure 10. The robot operation with VETO: Left- PatrolBot in the real world with lights on (visual feedback available). Right- the PatrolBot PatrolBot in the real world with lights off (no visual feedback available).

A Robust and Intuitive 3D Interface for Teleoperation of Autonomous Robotic Agents through Immersive Virtual Reality Environments

In this project an intuitive human interface is presented which allows for an operator immersed in a virtual environment to remotely control a teleoperated agent with minimal cognitive overload and minimal risk of accidental input. Additionally, a cursor-based interface is presented allowing for the placement of navigation nodes for the agent, thus facilitating robot's autonomous navigation functions to be executed.

Methodology and Approach

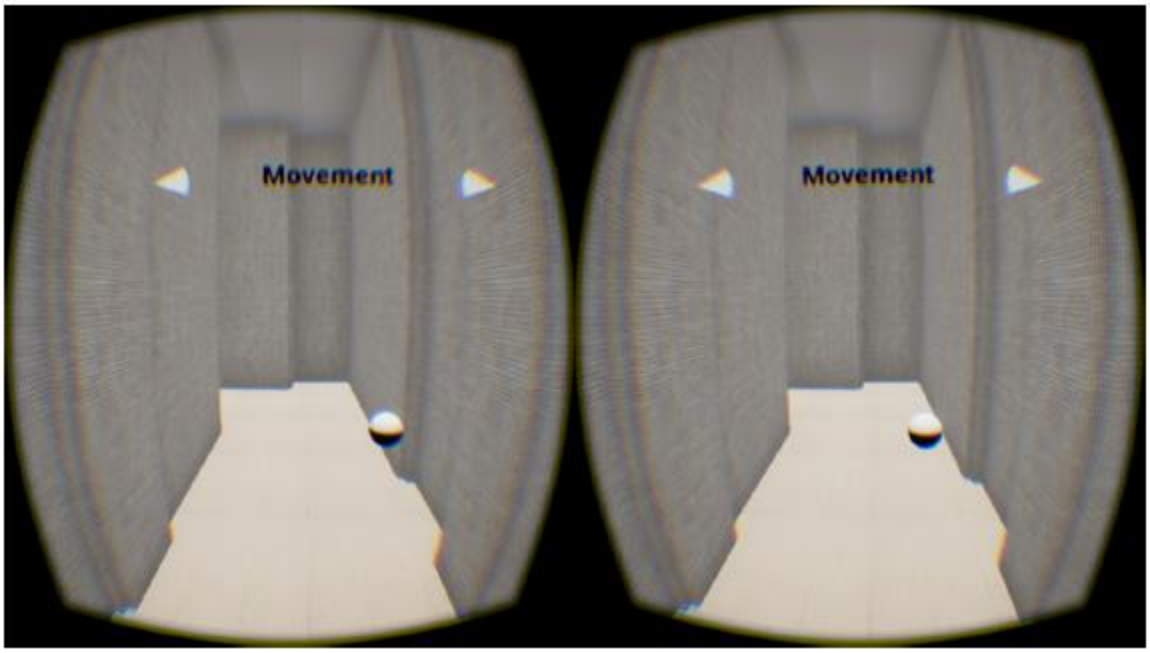
In order to minimize the cognitive load and to reduce errors, we propose the use of a virtual reality interface designed around a noncontinuous toggle-based concept, in which the operator only engages control input when they intend to perform certain tasks. This addresses the fatigue problem that limits full-body control mechanisms. Our interface utilizes a Leap Motion device, mounted on the front of an Oculus Rift HMD thereby giving the operator the ability to interact within the virtual environment, allowing for the use of virtual control interfaces for seamless agent interaction and control. The interface sends commands to the robotic agent based on the operator's movement of virtual trackballs [3]. Additionally, a crosshair-based cursor interaction interface is also modeled, allowing an operator to place and manipulate navigation nodes for autonomous agent movement. This project presents an extension to our previous work in designing intuitive and robust user interfaces for the control of remote robotic agents through an immersive virtual reality environment [3].

Our platform of choice for the implementation of the virtual reality environment is Epic Game's Unreal Engine 4. The game engine, developed by Epic Games Inc., is comprised of an advanced graphics rendering engine, sound engine, and physics and animation engines. This game engine is capable of delivering unparalleled performance in 3D realistic gameplay, simulation and visualization [4]. Unreal Engine 4 (UE4), the latest major version of the engine, was released in April 2014. New to this release are several completely redesigned architectures that we are planning to utilize in this research.

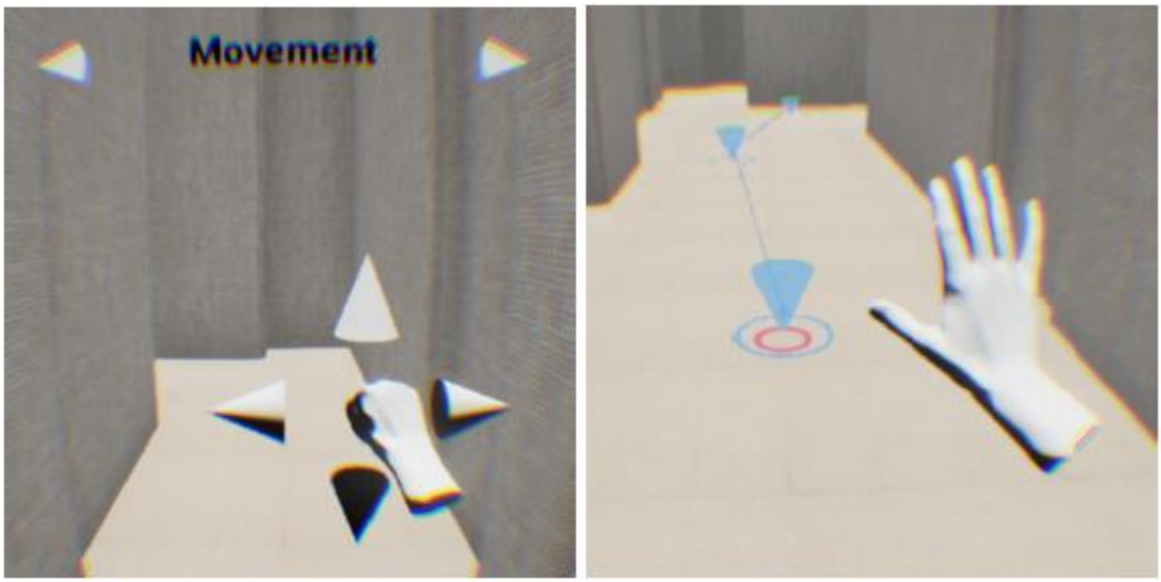
We generated a range of qualitative results using two different skeletons in Figure 11. Figure 11(a) depicts the initial setup of the interface with the virtual movement trackball and the mode of operation UI positioned in front of the operator. In our interface both the robotic agent and the operator's virtual position can be controlled by two separate virtual trackball interfaces. For both interfaces *X* input values correspond to rotation control, while *Y* values serve as forward/backward movement commands (in Figure 11(b)).

In our cursor implementation the operator can place and manipulate agent navigation nodes by using right hand activation gestures (Figure 11 (b)). If the operator attempts to make an invalid placement, the cursor color will change to red, while valid placements have a green color to provide appropriate visual feedback. The validity of a node's placement is currently determined by the slope of the surface on which it is placed, if it is currently intersecting any objects.

Left hand cursor activations allow the operator to delete previously placed nodes in the environment. Preliminary usability experiments suggest the the proposed interface is quite intuitive for users to utilize with minimal training required while producing minimal to no accidental inputs.



(a)



(b)

Figure 11. Sample results achieved by the proposed system. (a)- Stereographic view of interface setup. (b)- Movement mode (left) and cursor mode (right).

Bibliography

[1] Entertainment Software Association Rating Board. (2014). *Video Game Industry Statistics*, http://www.esrb.org/about/video-game-industry-statistics.jsp.

[2] Matthew Bounds, Brandon Wilson, Alireza Tavakkoli, Donald Loffredo. (2016). "Automatic Environment Map Construction for Mixed Reality Robotic Applications", *in the Proceedings of International Symposium on Visual Computing, Las Vegas, NV, December 2016*.

[3] J. Regenbrecht, A. Tavakkoli, and D. Loffredo, "An Intuitive Human Interface for Remote Operation of Robotic Agents in Immersive Virtual Reality Environments," in 2016 IEEE International Sumpoiums on Human Robot Interactive Communication (RoMAN), August 2016.

[4] Alireza Tavakkoli. (2015). *Game Development and Simulation with Unreal Technology*, AK Peters/CRC-Press, August 2015, ISBN: 9781498706247.

Appendixes

Appendix A – Equipment and Budget Description

A. Senior/Key Personnel Salary & Wage

None requested.

B. Other Personnel Salary & Wage

None requested.

C. Equipment

This proposal requested the funding for a enhancing an architecuture currently developed at UHV for tele-operation of robotic agents in an immersive virtual reality environment. Three components are essential to establish this research capability. Each one of the following components is integral to the research agenda and additional educational utilization. **Together, Components 1-3, including modules A and B of Component 1, comprise a single system. On its own, an individual component would lack utility value.**

System Component 1: Virtual Reality Component

The Virtual Reality Component will consist of two cooperative modules, a Virtual Reality Engine (A) and virtual reality client components(B).

Module A – Virtual Reality Graphics Server Module

The purpose of this module is to provide a centralized computing architecture capable of massive amounts of single-precision computation for the graphical purposes required in this project. Data and Human Kinematic movements are captured accurately and robustly through a Vicon-based sensory system as well as via communications from remotely operated robots. This server will be the hub (centralize point) in which all interactions will be performed in the virtual domain. This module consists of the following:

Mercury GPU408 4U Tower Server AH-GPU408-SB21: 2xE5-2629 v3 @2.4GHz six-core, 128GB DDR4, 4xGTX TitanX GDDR5 12GB PCIE3.0, 2x Intel 480GB SSD ,and 2X 4TB 7200RPM SATA [$11,829.20]. Logitech Wireless Desktop MK260 Mouse & Keyboard Combo [$28.41]. UltraSharp 24 Inch VIS, Widescreen, VGA/ DVI/ DP Monitor [$261.36]. Microsoft Windows 7 Professional SP1 64-bit English (One-Pack) [$168.75]. 8TB SATA 6Gb/s 3.5 Inch 7.2K RPM Disk Drive [$452.81]. Shipping [$250.00]

SUBTOTAL: [*$12,990.53]*

Module B – Virtual Reality Client Module

The purpose of this module is to facilitate the immersion of human users and operators into the virtual reality environment, and acquire motion patterns to enable interactions between virtual components of the system and virtual environment. This module consists of the following:

Two Area 51 Base (210-ADHC) Desktop computers of $3,559.75 each ($7,119.50 total) will be used exclusively to ensure that graphics and visualization processes run efficiently via their NVidia Graphics Processing Units. The desktops are needed to supplement the computers in the CAVE lab for general use by devoting these two computers to usage related especially expanding the research aims of the proposal and, as applicable, to educational utilization.

[*$7,119.50*]

Two of CyberForce System Data Gloves including CyberGrasp and 22-sensor CyberGlove Right and Left hands (2 pairs) of $17,995.00 per glove ($64,728.00 total) are important tools for achieving precision in tracking minute movements of users' hands and fingers and transmitting this information. The system requires the use of VirtualHand SDK ($4,585.50) and a 3rd party Tracker with four receivers ($7,995.00). A shipping estimated cost of $1,000 is included.

[*$78,362.50*]

SUBTOTAL (Before Discount): $86,070.00
SUBTOTAL (After Discount): $78,362.50

System Component 2: Computational Backbone

The purpose of this component is to support the computational needs for the machine learning and pattern recognition algorithms for building and evaluation of models of activities, intents and emerging interactions between virtual and physical worlds. The research team will utilize this component of the overall system to calibrate visual and non-visual tracking data acquired from T-160, Bonita, Virtual and Cyber Gloves, and other sensors to establish and validate models of activities, intentions, and tracking. This component consists of the following:

The Mercury GPU210 AH-GPU210-SX23, pretested with x4 Tesla K80 Graphics Processing Units (GPUs), 2x E5-2630 v3@2.4GHz eight-core, priced at $25,336.06 (including $250 shipping estimate), is crucial to handle processing for the high volume of data generated in the capture environment and building models for the autonomous agents. This tool will allow us to synchronize the robots with the virtual reality system as it performs modeling, training, and simulation processes. It consists of a tower, motherboard, keyboard, speakers, and 3-year warranty, among the items listed in the quotation. Important components include two Intel Xeon E5-2630, 8C, 2.4GHz processors and four K-80 NVidia Tesla, 24GB GDDR5 PCI3.0 GPUs.

SUBTOTAL: [$25,739.47]

System Component 3: Autonomous Operational Robots

This component is the physical component of the system which directly interacts with humans. As such each of the proposed robots will play a major role in enabling our team to study various means of co-operation and tele-operation needed for this project. It consists of the following:

One Baxter Research Robot at $25,000.00 along with its Pedestal designed for standing workspace heights, on casters for movement with leveling feet for stability ($3,000.00); two Electric Parallel Gripper (EPG) Kit. Includes: Parallel Gripper, Fingers- 4 Types, Fingertips, Hex Key for installation, Custom Hard Plastic Carry Case, and a User Guide ($1,750.00 each); two Vacuum Gripper Starter Kits ($1,750.00 each) and One year Baxter Research Robot warranty includes parts and labor and advanced phone tech support ($3,000) is central to our human teleoperation studies. It will be used for tasks such as calibrating the motion capture facility, teleoperation tasks, and autonomous tasks within the environment. Without this robot we could not perform complex tasks which require a functional robotic arm with the required degrees of freedom. Shipping costs are $600.

[$38,600.00]

Two Solo Unmanned Aerial Vehicles (UAVs) (at $8,661.36 each) are our air borne robotics agents. These UAVs will be utilized for the airborne teleoperation tasks. Moreover, these robotics agents will be utilized to capture aerial imagery by utilizing Sony S100 12.1MP digital cameras and the powerful image processing tool, SiteScan Software, to create highly accurate, georeferenced and orthorectified mosaics. For these robots, we will be utilizing the Site Scan software.

[$17,485.90]

TOTAL EQUIPMENT COSTS: $180,297.90

D. Travel

None requested.

E. Participant/Trainee Support Costs

None requested.

F. Other Direct Costs

1. Materials and Supplies

One Alienware 17 (210-ACKC) Laptop of $1,812.99 is requested for remote applications, and an external harddrive of $69.99. It is essential to the outreach and dissemination components of any

research to provide demonstrations and present findings, as Dr. Tavakkoli intends to do at high schools and academic conferences. It will be used in tandem with the requested equipment only. [*$1,882.98*]

For our remote applications Alienware 17 (210-ACKC) laptop, we request a travel briefcase of $99.99, already included in the quotation. The Vindicator briefcase is made specially to fit this laptop and provides a high quality of protection. [*$99.99*]

SUBTOTAL: $1,982.97

2. Publication Costs

None requested.

3. Consultant Services

None requested.

SUBTOTAL: $0.00

4. ADP/Computer Services

None requested.

SUBTOTAL: $0.00

5. Special Circumstances

None

SUBTOTAL: $0.00

TOTAL OTHER DIRECT COSTS: $ 0.00

G. Direct Costs (Total)

$180,297.90

H. Indirect Costs

None requested.

I. Total Direct and Indirect Costs (Total Federal Request)

Budget

Final Budget: $180,297.90 **Award Budget: $179,297.51**

Difference was covered by UHV HEAF funds.

Appendinx B – Final Budget

Equipment

W911NF-15-R-0025 Budget		Year 1
A	**Direct labor - Key Personnel**	$ -
	PI: Dr. Tavakkoli	$ -
B	**Direct Labor - Other Personnel**	$ -
	Total Direct Labor Costs (A+B)	$ -
C	**Direct Costs - Equipment**	$ 180,297.90
	Baxter Robot/Humanoid Robot	$ 38,600.00
	CyberGloves	$ 78,362.50
	22-sensor CyberGlove, RH (2x)	*$ 32,391.00*
	22-sensor CyberGlove, LH (2x)	*$ 32,391.00*
	Virtual Hand SDK	*$ 4,585.50*
	Polhemus's Tracker G4 w/ 4 Recievers	*$ 7,995.00*
	Shipping	*$ 1,000.00*
	Unmanned Aerial Vehicle System (SiteScan)	$ 17,485.90
	Hardware (2x)	*$ 17,322.72*
	Batterypack (4x)-Included	*$ -*
	Software (2x)- Included	*$ -*
	Shipping (2x)	*$ 163.18*
	High Performanc Computing	$ 38,730.00
	K-80 Clucster	*$ 25,739.47*
	1080-X VR Server	*$ 12,990.53*
	Alienware Area51- Desktops (2x)	$ 7,119.50
D	**Direct Costs - Travel**	$ -
	Domestic	$ -
	Foreign	$ -
E	**Direct Costs- Participant/Trainee Support Costs**	$ -
F	**Other Direct Costs**	$ -
	Other	$ -
	Other	*$ -*
G	**Total Direct Costs (A+B+C+D+E+F)**	$ 180,297.90
H	**Indirect Costs**	$ -
I	**Total Direct and Indirect Costs (G+H)**	$ 180,297.90