

DEVELOPMENT OF A VIRTUAL HAPTIC LABORATORY

Mehmet Ismet Can Dede, and Sabri Tosunoglu
Florida International University
Department of Mechanical Engineering
10555 West Flagler Street
Miami, Florida 33174

ABSTRACT

In this work, a virtual reality model is developed for a robotics research laboratory along with all the existing robotic devices in the lab. This virtual environment is then used to control these robotic devices through existing controllers such as force-reflecting joysticks and steering wheels. The Virtual Reality (VR) model is built as a haptic environment to send out force information as the remotely controlled device approaches a virtual obstacle. Ultimately, the operator can control the actual robot after having the necessary experience and training with the VR system. The initial tests for the virtual haptic laboratory are completed and results reported by using several of the robotic devices.

INTRODUCTION

Virtual haptic environments are very useful tools for training purposes. The simulators that have virtual environments are generally used to train aircraft pilots, military and medical personnel. Such training teaches the user how to operate a new system or vehicle quickly and inexpensively without needing the actual system. These simulators are usually composed of a screen for the trainee to view the virtual world, and human-computer interface to interact with the environment. This interface is mostly the replica of the interface on the actual vehicle. Some of the simulators also include other types of feedback such as force and aural information.

Simulators are widely used in training aircraft pilots [1], military [2] and medical personnel [3], and in entertainment industry. These simulators are mostly composed of the replica of the actual system with a Virtual Reality (VR) screen to create the most realistic experience for the operators. The effectiveness of the VR training has captured the interest of many researchers in medical field [4], military [5] and aircraft pilot training [6]. Although researchers still discuss the effectiveness of VR simulators, other industries such as entertainment and automobile [7] started to use these simulators for entertainment and training purposes.

The architecture of the simulators is very similar to teleoperation system configuration. There is a controller that the human operates with and a device that is driven

by the demands from this controller. In teleoperation, the controller is referred as the master system while the controlled device is named the slave system.

Simulator Background

The use of simulators is not limited to the application areas presented in the previous section. A group of researchers have incorporated a biomedical engineering application in simulator design to develop a flight simulator using the electromyographic (EMG) signals [8]. The simulator is shown in Figure 1. In this figure, the simulator is depicted on the left picture, the computer interface window to control the simulator is in the middle, and the picture on the right shows the connection of the EMG signals to the computer.

Miner and Stansfield utilized voice recognition in their version of a VR simulation system for robot control [9]. The demands to drive the robot are spoken by the operator. These demands are processed into commands and fed to the robot. As the robot carries out a task, it also sends out audio effects to interact with the operator.



Figure 1. Flight simulation using EMG signals [8]

Researchers from Malaysia [10] developed a PC-based driving simulator using Matlab[®]. The driving simulator cockpit is shown in Figure 2 with a trainee controlling the system via a steering wheel.

This system is composed of the cockpit to send commands to the data acquisition card in the PC and the VR screen to display visual feedback to the driver. The system architecture with these components is shown in Figure 3.

Researchers from Korea have developed a driving simulator which they integrated into a Stewart platform under the cockpit to imitate real world navigation [11]. They also used audio feedback as part of the VR screen.



Figure 2. Driving simulator cockpit [10]

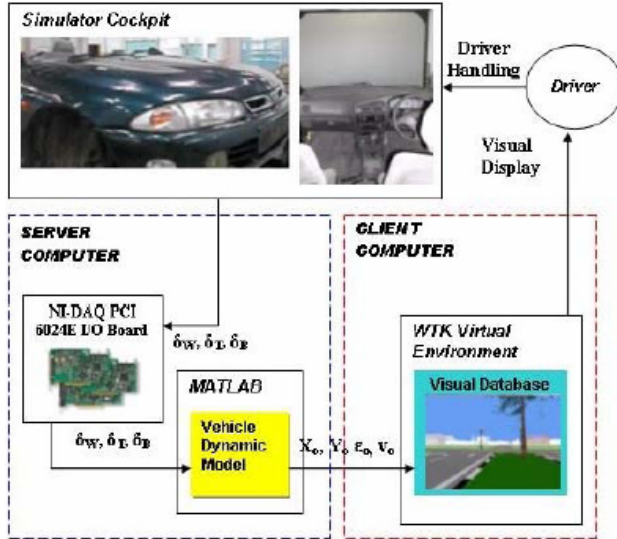


Figure 3. System architecture of the driving simulator [10]

Although some of the systems found in the literature are simpler than others, the ultimate task is to provide training for the operator before using the actual system as realistically as possible. The main difference between the two driving simulators presented in this section is the Stewart platform that is integrated in one of the simulators. This option obviously provides a more realistic experience to the trainee than the other one. Therefore, addition of more feedback information than visual, such as audio, force, etc., enhances this experience.

One of the major research areas of the Robotics and Automation (R&A) Laboratory at Florida International University (FIU) is teleoperation. A number of teleoperation systems are developed and tested as part of this research effort. In most of the tests, the slave robot was designed as the virtual representation of an actual robotic device. The next step in this line of research is to control the robotic devices in the laboratory with the developed human-computer interfaces. Before achieving this goal, operators are required to be trained to use these equipment. Our aim in this paper is to present the development of a virtual laboratory that will be used to train the operators before using the relatively expensive robotic devices. All of these devices are also equipped

with range sensors to sense the obstacles in their task space in order to create a haptic environment.

In the next section, robotic systems in the R&A Laboratory are introduced as either the controller or slave devices. Later, integration of these devices in a virtual environment is explained. Finally, initial results of the VR model of a Civil Engineering Laboratory and R&A Laboratory at FIU is presented with screenshots from the VR screen.

DESCRIPTION OF ROBOTIC SYSTEMS IN THE LABORATORY

There are two sets of robotic systems in the R&A Laboratory. The first set includes robotic controller devices that are used with the PC as part of the human-computer interface. These devices include a gimbal-based force reflecting joystick, a force-reflecting steering wheel, and a Phantom Omni Device from SensAble Technologies.

Robots that are driven by the commands received from the human-computer interfaces form the second set of robotic systems in the laboratory. This type of configuration is very similar with teleoperation applications. Therefore, the human-computer interfaces can be titled as master systems or controllers, and the driven devices as slave systems. In this work, the slave systems are listed as Motoman UPJ industrial arm, a holonomic mobile platform, and two mobile platforms WiRobot DRK8000 and X80 by Dr. Robot, Inc.

Controller Systems

Master systems form a part of the human-computer interface. The operator sends the demands through the master system and the computer receives these demands through an interface. In this work, this interface is developed in Matlab[®] and C++. As the actual or virtual slave interacts with the environment, created forces are then sent back to the actuators of the master in order to create a haptic environment. Therefore, all the master systems used in this work are selected not only to issue demand as the human operates on them but also to resist operator's motions as ordered by the slave side's interaction forces.

The first slave system presented here is a two degree-of-freedom gimbal-based force-reflecting joystick that was designed and manufactured in the R&A Laboratory [12]. Each degree-of-freedom is bedded in between two servomotors. Hence, fault tolerance is achieved through this architecture. If one of the servomotors fails during the manipulation, the other servomotor completes the task. The specifications of the servomotors used are given in Table 1. The interface of this joystick is developed in C++ and later formatted into s-function blocks to be used in Matlab[®] Simulink within the Virtual Laboratory Simulator. The configuration of the joystick is shown in Figure 4.

Earlier, this master joystick has been utilized for teleoperating the holonomic mobile platform [13]. It is also planned to operate two mobile platforms from Dr. Robot, Inc. as well as the Motoman UPJ industrial arm.

Table 1. Specifications of the ELCOM 4441S010 servomotor

Parameter	Sym	Unit	ELCOM
Continuous Torque Max	T_C	oz-in (N·m)	12.00 (.084)
Peak Torque-Stall	T_{PK}	oz-in (N·m)	71 (0.5)
Friction Torque	T_F	oz-in (N·m)	0.15 (1.1×10^{-3})
No Load Speed	S_{NL}	rpm (rad/s)	5780 (605)
Rotor Inertia	J_M	oz-in-s ² (kg-m ²)	6.4×10^{-4} (4.5×10^{-6})
Electrical Time Const.	τ_E	ms	0.18
Mechanical Time Const.	τ_M	ms	5.5
Viscous Damp. - Infinite Source Imp.	D	oz-in/krpm (N·m/(rad/s))	0.038 (2.6×10^{-6})
Damping Const—Zero Source Imp.	K_D	oz-in/krpm (N·m/(rad/s))	12.3 (8.3×10^{-4})
Max Winding Temp	θ_{MAX}	°F (°C)	266 (130)
Thermal Impedance	R_{TH}	°F/watt °C/watt	44 (6.7)
Thermal Time Const.	τ_{TH}	min.	22.8
Motor Weight	W_M	oz (Mass) (g)	17 (482)
Motor Constant	K_M	oz-in/√W (N·m/√W)	4.07 (.0287)
Motor Length	L_1	in max. (mm max.)	4.375 (111.1)

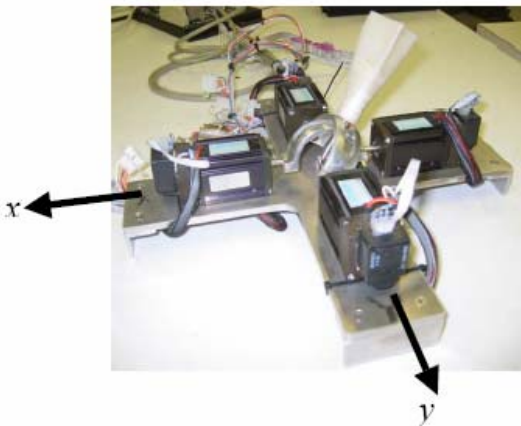


Figure 4. Two-DOF master joystick [12]

Second master system is a force-reflecting steering wheel. This system is a commercial gaming steering wheel from Genius [14], with acceleration and brake pedals and force feedback option. It also has 12 pushbuttons that enhance the interaction of the operator with the VR screen. It is primarily intended to operate the mobile platforms.

The last master system is a six degree-of-freedom Phantom Omni Device from SensAble Technologies as shown in Figure 6. Joint position readings are obtained through the encoders of each joint and the slave is driven with these inputs. However, only the forces can be reflected back to the operator with this device. Therefore, only the interaction forces created in the x, y

and z directions are felt by the operator. The specifications of the device are listed in Table 2 [15].



Figure 5. Genius steering wheel [14]

Table 2. Specifications of the Phantom Omni Device

Force feedback workspace	~6.4 W x 4.8 H x 2.8 D in. > 160 W x 120 H x 70 D mm.
Footprint (Physical area device base occupies on desk)	6 5/8 W x 8 D in. ~168 W x 203 D mm.
Weight (device only)	3 lbs. 15 oz.
Range of motion	Hand movement pivoting at wrist
Nominal position resolution	> 450 dpi. ~ 0.055 mm.
Backdrive friction	
Maximum exertable force at nominal (orthogonal arms) position	0.75 lbf. (3.3 N)
Continuous exertable force (24 hrs.)	> 0.2 lbf. (0.88 N)
Stiffness	X axis > 7.3 lbs. / in. (1.26 N / mm.) Y axis > 13.4 lbs. / in. (2.31 N / mm.) Z axis > 5.9 lbs. / in. (1.02 N / mm.)
Inertia (apparent mass at tip)	~0.101 lbm. (45 g)
Force feedback	x, y, z
Position sensing [Stylus gimbal]	x, y, z (digital encoders) [Pitch, roll, yaw ($\pm 5\%$ linearity potentiometers)]
Interface	IEEE-1394 FireWire® port

Phantom is designated to control the Motoman UPJ industrial arm in the laboratory. It can also be used to control the mobile platforms with the appropriate mapping of the motions.



Figure 6. Phantom Omni Device from SensAble Technologies [15]

Slave Robots

The robots that execute the tasks demanded by the operators are called slave robots. One of these robots is a holonomic mobile platform designed and manufactured in R&A Laboratory [16]. The platform has four omni-directional wheels. These wheels enable the platform to move in any direction at any orientation. Therefore, it can be said that each motion along any axis is uncoupled. The platform also has range sensors to sense the obstacles on its path. This information is then transformed into force feedback to drive the motors of the controller. As a result, the operator feels that the platform is at the vicinity of an obstacle as he/she feels the resistance in the motion of the controller. Figure 7 shows the holonomic platform at its design stage.

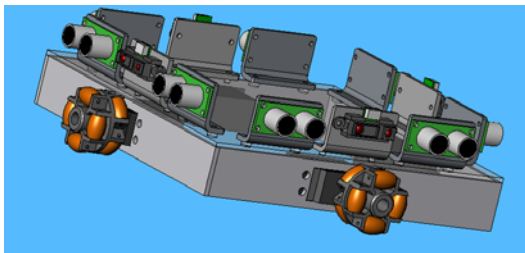


Figure 7. Holonomic mobile platform [16]

The platform has the capability to communicate with the host computer through a Bluetooth connection.



Figure 8. X80 mobile platform from Dr. Robot, Inc. [17]

The next set of mobile robots integrated into the virtual laboratory are the commercially available

systems from Dr. Robot, Inc. The first system in this set is the X80 as shown in Figure 8. It has two 12V DC motors that supply 300 oz.-inches of torque to its 18 cm (7 in.) wheels, which yields a top speed of 1 m/s (3.3 ft/s). There are two high-resolution (1200 count per wheel cycle) quadrature encoders mounted on each wheel provide high-precision measurement and control of wheel movement. It weighs 3.5 kg (7.7 lb.), and can carry an additional payload of 10 kg (22 lb.) as given in its specification sheet [17].

X80 communicates with the host computer through WiFi (802.11b) wireless communication protocol. It has collision detection sensors that include 3 sonar range sensors and 7 infrared range sensors. The information induced from these sensors are first transformed into force information and then sent back to the actuators of the controllers. It has also a camera that is operated with two servomotors, which can be used for image processing tasks and a microphone that can be utilized in applications that require voice recognition.

The second system is WiRobot DRK8000 as illustrated in Figure 9. The system runs on a wheel-based platform with rotary sensors mounted on each wheel to precisely measure and control wheel motions. The eyes (webcams) can pan and tilt and the neck can pan and tilt as well [18].



Figure 9. WiRobot DRK8000 mobile platform from Dr. Robot, Inc. [18]

Communication with the host computer is accomplished through Bluetooth connection. The operator is able to send commands at a rate of 10-50 Hz. There are 6 ultrasonic range sensors and 1 infrared range sensor placed around the platform to detect obstacles. This sensory information is also sent back to the host computer as force information to be fed into the actuators of the controllers. This platform also has a camera and microphone, which enables it to be used for tasks involving image processing and voice recognition.

Motoman UPJ industrial arm is the final robotic device to be used as a slave system in this work as shown in Figure 10. It is different from the previous systems as it has predefined limited workspace. The workspace and link lengths of the arm are presented in Figure 11.



Figure 10. Motoman UPJ industrial arm [19]

The arm has six degrees-of-freedom and each of the joints is revolute type. It is commonly used in small part handling and assembly, automation, inspection/testing, education, and research applications.

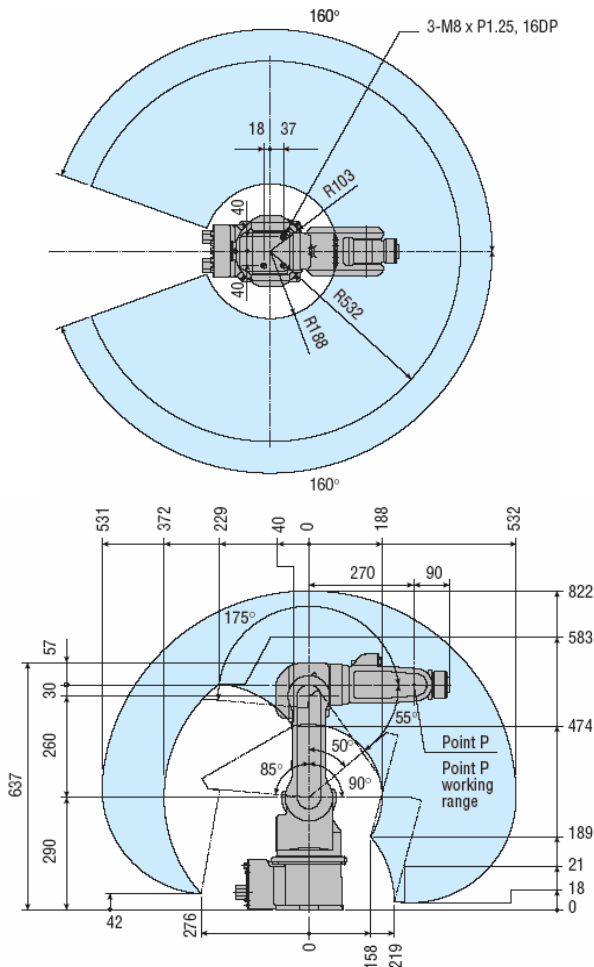


Figure 11. Workspace of the Motoman UPJ industrial arm [19]

The specifications of the arm are summarized in Table 3 [19]. At its current configuration, this industrial arm doesn't have any external sensors such as a range or force sensor. In order to create haptic effects, range

sensing capability is added to the end-effector of the arm's virtual model.

Table 3. Specifications of Motoman UPJ industrial arm

Controlled Axes		6
Payload		3 kg (6.6 lbs.)
Vertical Reach		804 mm (31.7")
Horizontal Reach		532 mm (20.9")
Repeatability		± 0.03 mm (± 0.001 ")
Maximum Motion Range	S-Axis (Turning/sweep)	$\pm 160^\circ$
	L-Axis (Lower Arm)	$+90^\circ/-85^\circ$
	U-Axis (Upper Arm)	$+175^\circ/-55^\circ$
	R-Axis (Wrist Roll)	$\pm 170^\circ$
	B-Axis (Bend/Pitch/Yaw)	$\pm 120^\circ$
T-Axis (Wrist Twist)	$\pm 360^\circ$	
Maximum Speed	S-Axis	200°/s
	L-Axis	150°/s
	U-Axis	190°/s
	R-Axis	300°/s
	B-Axis	300°/s
T-Axis	420°/s	
Approximate Mass		25 kg (55.1 lbs.)
Brakes		All axes
Power Consumption		0.5 KVA
Allowable Moment	R-Axis	5.39 N • m (0.55 kgf • m)
	B-Axis	5.39 N • m (0.55 kgf • m)
	T-Axis	2.94 N • m (0.3 kgf • m)
Allowable Moment of Inertia	R-Axis	0.1 kg • m ²
	B-Axis	0.1 kg • m ²
	T-Axis	0.03 kg • m ²

HAPTIC VIRTUAL WORLD CREATION

Simulators with VR screen have to have two main components of the actual system. The actual systems for our case are the slave robots introduced in the previous section. The first component is the visual representation of the system that is created in a three-dimensional medium. Three-dimensional Computer-Aided-Design (3D CAD) tools are the most commonly used tools to accomplish this.

The second component is the modeling of the dynamics of the moving parts. Most of the time, the forward dynamics of the systems that are in motion are developed at another programming platform than 3D CAD such as in C++ or Matlab[®] Simulink. The Virtual Rapid Robot Prototyping idea presented previously by Dede and Tosunoglu [20] provides a more convenient option. A translator is used to extract the physical properties from the CAD model into Matlab[®] Simulink environment. These physical properties include the mass, inertia, joint and center of gravity information, and link lengths of the system.

The visual representation created in a 3D CAD environment is also translated into VR format and used with the Matlab[®] Virtual Reality Toolbox. This procedure is also extensively explained in [20]. Although dynamics and visual representation of the system is extracted from the same 3D CAD drawing into Matlab[®], these two have to be linked. As the dynamics simulation runs, the results of the simulation (joint positions, end-effector position) are fed into the Virtual Reality block. Therefore, visual representation of the system is actuated with the results obtained from the dynamic simulation.

There are two ways to create the haptic effect in this setup. The first and the tedious way is to construct the obstacles inside the dynamic simulation using the logic relations. This method is feasible for simple tasks that involve very limited amount of obstacles. The second method is to extract the obstacle information from the VR model. This model contains all the necessary information on the surfaces of the obstacles. Handshake VR Inc. has a commercially available toolbox, proSENSE[™], which extracts the obstacle information off the VR model and also creates force for point type of contact. This way, without developing extensive logic operations manually, the force feedback information can be obtained even for very large scale simulations.

Up to this point, creation of a haptic simulation in Matlab[®] is explained. The goal of this study is to create a VR model of a laboratory with haptic effects, which the operator can interact with it through a human-computer interface. In the previous section, the controllers to be used in this work are introduced. The next step is to integrate these controllers with the haptic simulation environment.

The interface for the commercially available joysticks (Genius Steering Wheel) and the Phantom Omni Device is provided by Handshake VR Inc. as a Matlab[®] Simulink block. This enables to have the interface inside the Matlab[®] simulation. This interface communicates with the external device to receive position information from the encoders and send back force information to the actuators of the device.

An interface had to be developed for the gimbal-based joystick developed in R&A Laboratory. This interface communicates with the motion controller card that derives the servomotors of the joystick. The interface is extensively described in [12]. Although the interface is written in C++, it is then formatted into a Matlab[®] Simulink block to have the same functions described in the previous paragraph.

As the interface is integrated to interact with the dynamic simulation, Real-Time Window Target option of Matlab[®] is utilized to synchronize the procedure with the real-time clock. Therefore, the created system is no longer a simulation but a VR simulator.

INITIAL RESULTS

Teleoperation is one of the research areas of the R&A Laboratory at FIU. Various experiments are conducted by using an actual joystick and one of the

slave robots. The slave robots are used as their virtual representations in these experiments. This type of architecture is very similar with the concept of developing a virtual haptic laboratory. As a matter of fact the only difference is the scale of the experiments. In teleoperation experiments, only one slave was used for a single task. By contrast, in the virtual haptic laboratory, a user will be able to operate any of the slave robots through any of the controllers.

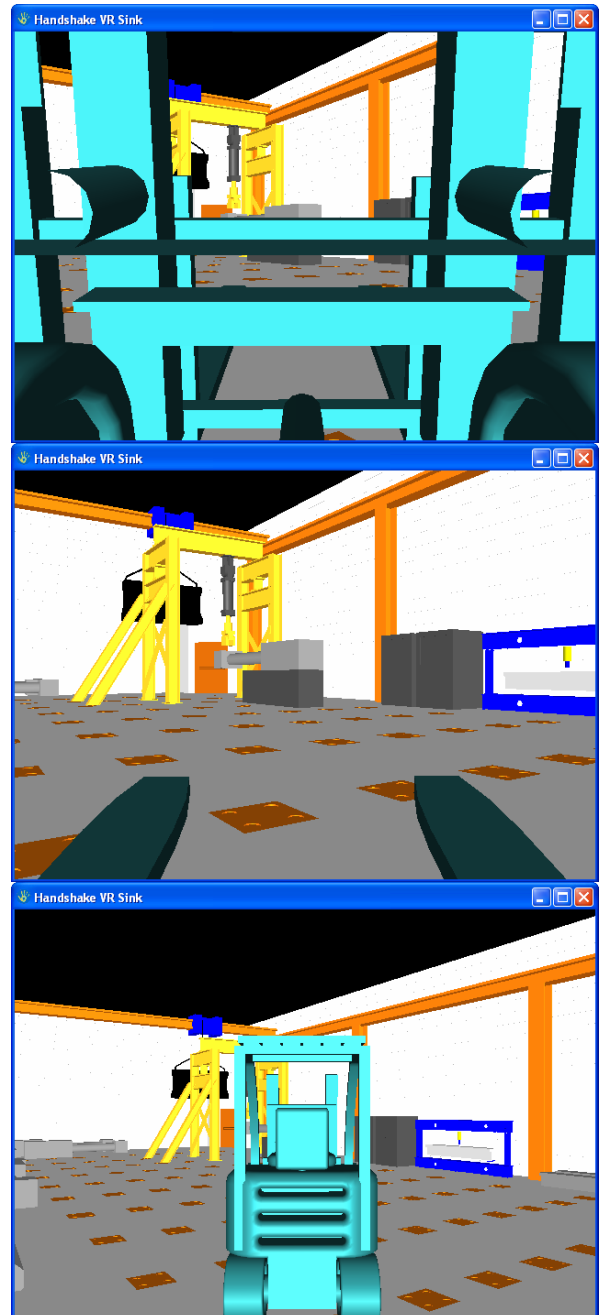


Figure 12. The three camera views from the forklift

The first trial for a virtual haptic laboratory is constructed for a Civil Engineering laboratory at FIU. The task was to drive a forklift inside the laboratory while virtual experiments are conducted.

The forklift is controlled though the Genius steering wheel. The steering wheel controls the rotation of the

forklift while the pedals are used to accelerate and decelerate the vehicle. Two pushbuttons are addressed to shift the gear up or down. Therefore, the vehicle is able to use multiple speed levels as well as a neutral position for the shift and a reverse gear. There are also three virtual cameras placed in the vehicle to view the virtual environment. The first camera is placed in the operator's seat, the second one is placed at the tip of the forks and the last one is placed at the top back part of the vehicle to have a general view of the laboratory as well as the vehicle itself. Three views from these cameras are shown in Figure 12.

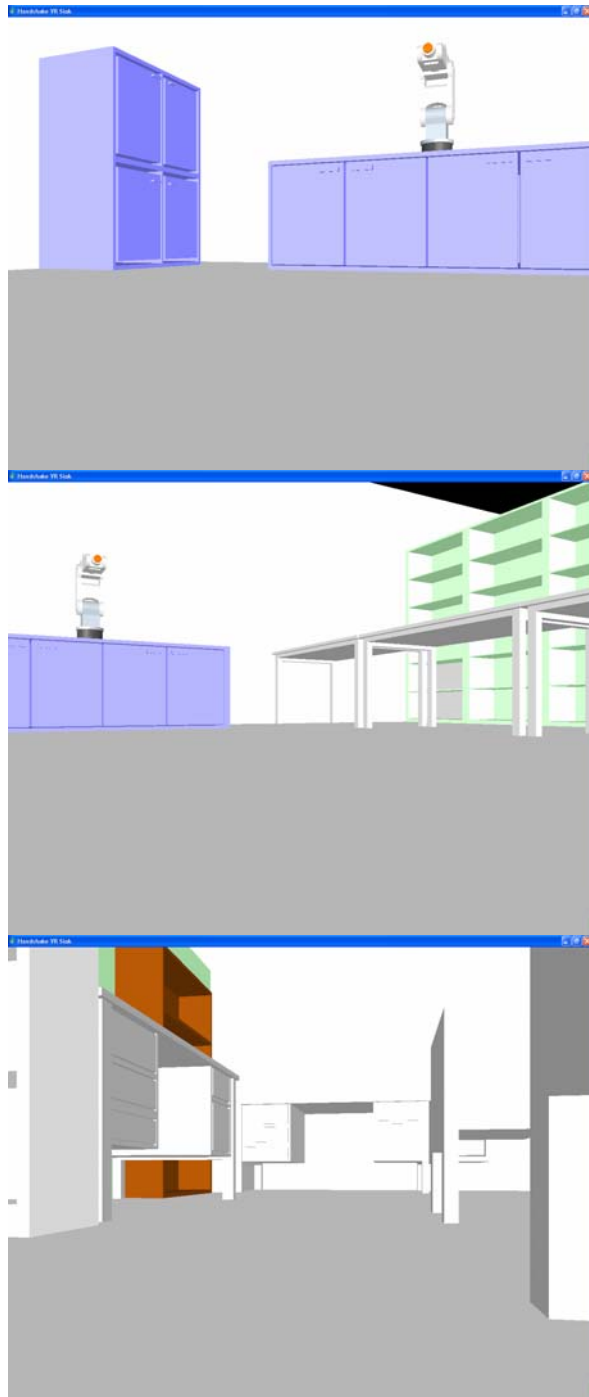


Figure 13. Screenshots from the R&A Laboratory Visual Reality Screen

The virtual experiments that involve applying pressure to the test specimens are controlled through the other pushbuttons of the steering wheel. Another commercially available joystick from Logitech is used to control the crane that carries a work specimen inside the lab. The crane has the architecture of a three degree-of-freedom Cartesian robot therefore all three axes of the joystick are used to operate this crane. Three pushbuttons are also activated to apply and release the breaks for each degree-of-freedom.

After developing a successful but rather simple virtual laboratory simulator, the next step is to configure the R&A Laboratory in the Virtual World. 3D CAD drawing of the laboratory is constructed in SolidWorks. Initially, the WiRobot DRK8000 is modeled to navigate around the laboratory. In order to achieve this, the robot parameters are translated into Matlab[®]. Motoman UPJ arm is also placed in the drawing for future experiments.

Genius steering wheel is selected to control the mobile platform. The camera is fixed to the location of the webcam of the actual robot. Therefore, the operator will experience a more realistic training period with the simulator. The head of the robot that carries the webcam moves as it receives commands from the pushbuttons of the steering wheel. Therefore, the view changes as the head moves in different directions. This is in fact what an operator will experience while using the actual robot. The only visual feedback is through the webcam installed on the head of the robot. This will train the operator not to lose his/her orientation while navigating around the laboratory as the head is in motion. Figure 13 shows a few of screenshots of the VR screen as the robot navigates around the laboratory.

The initial model of the robot was relatively simple, but a more realistic model of the robot is under development. A snapshot view of the robot is shown in Figure 14. The haptic effects are created using the Handshake VR Inc. software and fed into the actuators of the steering wheel as the robot approaches to an obstacle. This effect is accurate for the navigation of the actual robot as well. The range sensors of the robot create haptic effects and send this information to the steering wheel in the same fashion of the simulator.

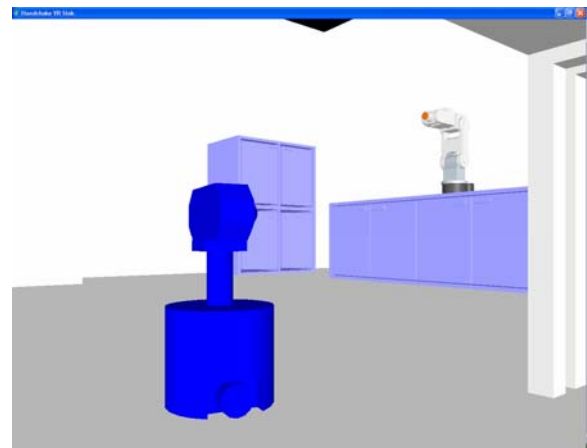


Figure 14. Screenshot of the WiRobot DRK8000 inside the R&A Laboratory Visual Reality Screen

CONCLUSIONS

Today most of the system developers in military, aircraft and medical industries use simulators to train operators before using the actual system. This method saves time and money while supplying the necessary experience to the trainees.

At FIU's Robotics and Automation Laboratory, we have relatively expensive robotic devices that we want to teleoperate using various controllers. Our aim is to train the human teleoperator before using the actual equipment. As a result of this training, the operator will have the experience to teleoperate the robotic system inside the laboratory safely without damaging the equipment.

For this aim, a virtual representation of the laboratory including the robotic devices is constructed first in CAD environment. Later, the necessary information from the CAD environment is translated into Matlab[®] for integration with the controllers. Initially, WiRobot DRK8000 from Dr. Robot, Inc. is teleoperated by using the Genius steering wheel.

Future work includes placing all the slave robots described in this paper inside the virtual world and performing tests with different controllers to provide a capability to train operators for all available devices.

REFERENCES

- [1] T. J. Connolly, B. B. Blackwell, and L. F. Lester, "A simulator-based approach to training in aeronautical decision making," *Aviation Space Environment Med*, Volume 60, Issue 1, pp. 50-52, 1989.
- [2] E. H. Page, and R. Smith, "Introduction to Military Training Simulation: A Guide for Discrete Event Simulationists," *Proc. 1998 Winter Simulation Conference*, pp. 53-60, 1998.
- [3] M. Dinsmore, N. Langrana, G. Burdea, and J. Ladeji, "Virtual reality training simulation for palpation of subsurfacetumors," *Proc. IEEE Virtual Reality Annual International Symposium*, pp. 54-60, 1-5 March, 1997.
- [4] N. E. Seymour, A. G. Gallagher, S. A. Roman, M. K. O'Brien, V. K. Bansal, D. K. Andersen, and R. M. Satava, "Virtual Reality Training Improves Operating Room Performance: Results of a Randomized, Double-Blinded Study," *Annals of Surgery*, Volume 236, Issue 4, pp. 458-464, October 2002.
- [5] R. T. Hays, J. W. Jacobs, C. Prince, and E. Salas, "Flight Simulator Training Effectiveness: A Meta-Analysis," *Military Psychology*, Volume 4, Issue 2, pp. 63-74, 1992.
- [6] H. H. Bell, and W. L. Waag, "Evaluating the Effectiveness of Flight Simulators for Training Combat Skills: A Review," *International Journal of Aviation Psychology*, Volume 8, Issue 3, pp. 223-242, 1998.
- [7] K. Guo, H. Guan, and C. Zong, "Development and applications of JUT-ADSL driving simulator," *Proc. IEEE International Vehicle Electronics Conference*, pp. 1-5, 1999.
- [8] C. Jorgensen, K. Wheeler, and S. Stepniewski, "Bioelectric Control of a 757 Class High Fidelity Aircraft Simulation," *3rd International Symposium on Intelligent Automation and Control*, Maui HI, 11-16 June, 2000.
- [9] N. E. Miner, and S. A. Stansfield, "An Interactive Virtual Reality Simulation System for Robot Control and Operator Training," *Proc. 1994 Conference on Robotics and Automation*, Volume 2, pp. 1428-1435, 8-13 May 1994.
- [10] H. S. Kang, M. K. A. Jalil, and M. Mailah, "A PC-based Driving Simulator Using Virtual Reality Technology," *2004 ACM SIGGRAPH International Conference on Virtual Reality Continuum and Its Applications in Industry*, pp. 273-277, 2004.
- [11] W. S. Lee, J. H. Kim, and J. H. Cho, "A Driving Simulator as a Virtual Reality Tool," *Proc. 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, pp. 71-76, May, 1998.
- [12] M. I. C. Dede, and S. Tosunoglu, "Development of a Real-Time Force-Reflecting Teleoperation System Based on Matlab[®] Simulations," in *Proceedings of the 19th Florida Conference on Recent Advances in Robotics*, Miami, Florida, May 25-26, 2006.
- [13] M. I. C. Dede, and S. Tosunoglu, "Control of Teleoperation Systems Experiencing Communication Loss," submitted to *Robotics and Autonomous Systems*, June 2007.
- [14] <http://www.geniusnet.com/> accessed September 2007.
- [15] Phantom[®] Omni[™] Haptic Device <http://www.sensable.com/haptic-phantom-omni.htm> accessed June 2007.
- [16] M. I. C. Dede, and S. Tosunoglu, "Design of a Fault-Tolerant Holonomic Mobile Platform," *Proceedings of the 19th Florida Conference on Recent Advances in Robotics*, Florida International University, Miami, Florida, May 25-26, 2006.
- [17] X80 by Dr. Robot, Inc. http://www.drrobot.com/products_item.asp?itemNumber=X80 accessed June 2007.
- [18] WiRobot DRK8000 by Dr. Robot, Inc. http://www.drrobot.com/products_item.asp?itemNumber=DRK8000 accessed June 2007.
- [19] Motoman UPJ Industrial Arm <http://www.motoman.com/products/datasheets/UPJ.pdf> accessed June 2007.
- [20] M. I. C. Dede, and S. Tosunoglu, "Virtual Rapid Robot Prototyping," in *ASME Early Career Technical Journal*, Volume 5, Number 1, pp. 7.1-7.8, October 2006.