UNDERGRADUATE REPORT

Virtual Reality Wand Design and Fabrication

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1. Introduction

As virtual reality (VR) is becoming a more viable option for real world skills training, developers are attempting to uncover the methods and technologies that will lead to the most efficient transfer of knowledge and proficiency of the target tasks. Within these optimization issues lies the question that asks what type of VR interaction device will provide users with maximum control within the virtual environment (VE) while being a convenient and comfortable tool to use. An ideal interaction device should balance the factors of functionality, user satisfaction, and cost while yielding a well-designed product in the process. Although the needs for all VR systems are not the same, popular interaction devices in use today include wired gloves as well as VR wands, the current mode of interaction for study during this summer's REU ISR project.

2. Problem Description

In the most general of terms, the goal of this summer's project was to solve a design problem associated with the VR wand used to interact with the virtual environment provided. Ideally, the new wand would address the design flaws of the current VR wand while maintaining a predetermined level of functionality needed for useful interaction within the virtual environment. Such functionality requirements included a wireless presenter that needed at least two mouse buttons, left and right to activate translations and rotations within the virtual environment, respectively, as well as a directional pad or trackball for cursor control. A full set of design requirements and constraints for the new wand design will be discussed later in this paper. In terms of design grade, the new wand was expected to be of finished quality, a design that could be presented as a working model to the partner VR lab at the Naval Surface Warfare

Center in Indian Head, Maryland.

2.1. Current Wand Design

Training within the virtual environment (VE) currently requires an interactive VR wand that is composed of three functional components: a Targus© notebook wireless presenter (model number PAUM30U), an InterSense© wireless inertiacube3, and an infrared (IR) tracking light from WorldViz©. These three devices are currently integrated into the VR wand through the use of a plastic frame that was designed and prototyped in-house as the platform to which the components are attached. A snapshot of the assembled VR wand is included in *figure 1* below.

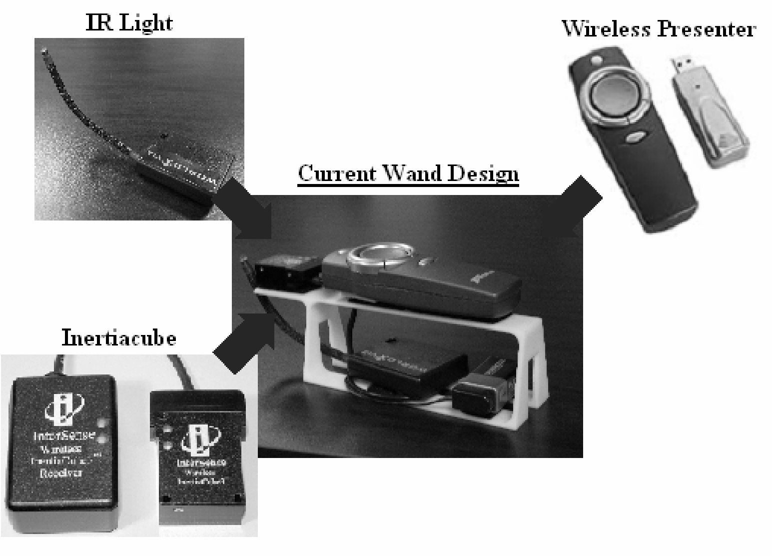

Figure 1. VR wand and components.

The Targus© presenter offers left and right click mouse functions that have been programmed to translate and rotate objects, respectively, within the VE. At the center of the device is a 16-direction mouse pad as well as two additional buttons to activate a laser light and change the function of the device. Additionally, the wireless presenter is equipped with radio frequency technology that allows the device to interact with its receiver without the need for a direct line of sight up to a maximum distance of 33 feet. Lastly, the wireless presenter is powered with 3 V that are provided by two 1.5 V AA batteries within the case.

As the component responsible for tracking orientation, the InterSense© inertiacube is equipped with nine internal sensing devices that provide the yaw, pitch, and roll of the VR wand within the virtual environment. It communicates wirelessly with a USB receiver from up to 100 feet away and is powered by a 9 V battery that attaches to the device via a one-foot power cord.

The IR tracking light by WorldViz© is tracked by employing four optical sensors that determine the position of the VR wand in the X,Y, and Z directions. The device is composed of an infrared diode powered with 6 V from four 1.5 V AA batteries contained in a rigid case attached to the light.

2.2. Issues with Current Wand Design

Although the design and technology of the current VR wand are satisfactory for the task of interacting with the VE, a number of issues were raised that need to be addressed in any redesign assignment. The problematic areas of the current VR wand include: the piecewise rather than integrated design approach concerning the multiple components, the inconvenience of multiple power supplies, the robustness of component connections, the lack of ergonomics, and most importantly, the non-intuitive way in which the user rotates objects in the VE with the current wireless presenter.

As evident in the picture of the current VR wand from *figure 1*, the design distributes the components of the wand linearly along two tiers of the frame. This approach does well to accommodate the necessary components of the VR wand, but fails to form them as a single unit due to the fact that each of the devices is allotted its own particular space that does not impinge upon nor meld with any of the others. Although the benefit of this type of modular design is the easy installation and removal of any of the components present, it fails to use space efficiently and convey the idea of a cohesive working unit; therefore, a redesign with these principles in mind is necessary.

As with any set of off-the-shelf components combined into a single unit, the need for separate, multiple power sources can quickly become an inconvenience for the user. The current VR wand features three power sources that total seven batteries (6 - 1.5 V AA, 1 - 9 V) in all. Resultantly, if it is possible to provide a generic power source for all components, it will be in the interest of the user's convenience to include it within a redesign of the VR wand.

Though it may not be clear in the picture of the wand from *figure 1*, all of the components in the device are attached to the plastic frame with Velcro. This method of connection makes assembly and disassembly of the wand very quick and easy, but does so at the expense of the reliability and professionalism of the overall design. Additionally, the VR wand's response accuracy from user interaction is compromised due to the impermanence of the connection type that allows for unintended motion of the wireless presenter, with respect to the frame, when the directional pad is used.

The current design of the VR wand is sharp and linear in geometry; it features very little in the way of curved surfaces or fitted grips for the comfort of the user's hand. Additionally, the fact that the design mounts the wireless presenter parallel to the horizontal plane means that the user must hold their wrist in an unnatural, and perhaps, uncomfortable way in order to maintain a horizontal line of sight between the VR wand model and the parts to be assembled in the VE. A carefully chosen wireless presenter or well-designed wand would offer an ergonomic shape that will allow users to work longer within the VE thanks to a decrease in hand and wrist discomfort.

Of all the imperfections in the current design of the VR wand, the most important design feature that should be changed in the redesign project is the method of rotational interaction with the assembly parts in the VE. As was mentioned earlier, the current design incorporates the Targus© wireless presenter that features a 16-direction mouse pad. Within the VE, this mouse pad is used to rotate objects around the y and z-axis using the left/right and up/down buttons, respectively. An additional mode of rotation featured in the current design allows the user to rotate objects by translating the wand along the X, Y, and Z directions to rotate around the corresponding axis. The issue with both of these modes of rotation lies in the fact that the wand uses a dissociative mode of interaction to cause the rotation. In other words, first time users have a difficult time mastering the rotation mode because the act of translating in the real world to cause a rotation in the virtual world is a confusing action. Ideally, the redesigned wand would incorporate a rotational interaction device that would allow for a more intuitive method of rotation within the VE.

3. Research Approach

In order to accomplish the task of designing and producing a quality VR wand, a design process was performed to ensure that the functionality requirements of the design project were met and that the entire process from start to finish was handled efficiently. The steps within the process included the selection of a new wireless presenter, the design of a circuit to distribute power to all of the components, the design of the add-ons that would accommodate all of the components required, and the completion of an instruction manual to aid others in following the production and assembly steps required to yield the final product.

3.1. Wireless Presenter Selection

As the first step in the design process, the selection of a new wireless presenter for integration into the VR wand was a very important procedure that required the aid of decision-making tools to ensure the validity of a decision about what presenter was "best". The selection process was carried out by researching six popular wireless mouse packages (including the model used in the current VR wand) that met the necessary requirements and ranking them based on their performance attributes with respect to one another. In order to be accepted into the pool of acceptable models, a wireless mouse package had to meet three important requirements that included, one, omni directional capabilities (preferably through radio frequency technology), two, an effective range of at least ten feet, and three, the inclusion of at least two programmable mouse buttons in addition to some form of a mouse pad/cursor control button. The wireless presenter models that were researched were as follows:

A. Interlink© Presentation Pilot Pro (VP6450)
B. Globlink© GM-500 RF Wireless Trackball
C. Hiro© 2.4 Ghz Wifi Laser Pointer & Mouse H50064
D. Iogear© Phaser Mouse GME33R
E. Logitech© Cordless Trackman Wheel
F. Targus© Wireless Remote Presenter 900 Mhz

After an acceptable list of presenter models was generated, attributes considered important in the decision making process were listed and weighted using a pair-wise comparison method. *Table 1* within *Appendix A* demonstrates the pair-wise comparison method used for determining the relative weights of the attributes. Nine of these attributes were identified and are listed in order of most important to least important as follows:

1. Omni directional
2. Effective range
3. Ease of use
4. Ergonomics
5. Ease of integration
6. Size
7. Economy of buttons
8. Price
9. Availability

Following the weighting of the attributes, each of the presenter models was given a rank (on a scale of 1 to 10) for each attribute with respect to one another. Using this rank data and the attribute weights from earlier, a weighted decision matrix was compiled in order to determine the overall ranking of the presenter models with respect to one another. *Table 2* within *Appendix A* demonstrates the weighted decision matrix method for determining the relative rankings of the presenter models.

As a result of the weighted decision matrix, it was determined that the Phaser Mouse GME33R wireless presenter by Iogear© was the "best" model from the pool of six. The ergonomic curves of this model, trackball mouse feature, button economy (it features three functional buttons: two left click and one right click), and effective omni directional radio frequency range of up to 50 feet made it an easy decision from among the rest and foreshadowed an interesting design session later in the project. The new presenter also features a laser pointer and is powered out-of-the-box with 3 V from two 1.5 V AA batteries. An image of the presenter can be viewed below in *figure 2*.

Figure 2. Iogear© Phaser Mouse GME33R.

3.2. Power Delivery Design

An important feature of the new design is the reduction in the number of battery packs needed to power the three components of the wand: the wireless presenter, the inertiacube, and the infrared light emitter. A reduction in these power sources will not only be an added convenience to the user, but it will also save space within the designed attachments to complete the wand. In order to reduce the overall number of required power sources from three to two, it was important to design and fabricate a circuit that was capable of providing the appropriate voltages and currents necessary for the normal operation of the infrared light emitter as well as the presenter. Not only will the two aforementioned components be powered by a single 9-volt battery pack, but a single switch will simultaneously control their on/off operations as well. The inertiacube wasn't chosen for wiring into the circuit for two reasons: altering the wiring of the inertiacube would void the warranty, and the power demanded by the unit was simply too large to provide a reasonable battery life with all three components wired into a single power source.

In order to accomplish the task of providing the necessary voltages for the infrared light emitter and the wireless presenter of 6 and 3 volts, respectively, a circuit following the diagram in *figure 3* shown below was constructed. The circuit consists of two adjustable voltage regulators (part no. LM317T Positive, readily available at RadioShack©) and their necessary regulating resistances in parallel with the main 9-volt battery pack, V_{source}. The resistances labeled R_1 are rated at 270 Ω and act as current limiters within the circuit. The resistance labeled R_2 is rated at 1 kΩ and acts as the resistance used to set the output voltage delivered to the infrared light emitter at 6 volts. The resistance labeled R_3 is rated at 360 Ω and acts as the resistance used to set the output voltage delivered to the wireless presenter at 3 volts. A switch was wired into the circuit in order to give the user control of the power delivered to the components from the exterior of the new wand design instead of requiring them to manually detach the battery, as is the case with the current VR wand. An additional physical representation of the circuit board as it was constructed for the new wand is shown in *figure 4* below. Included in the representation are the components, switches, battery hookups used to complete the circuit laid out in *figure 3*.

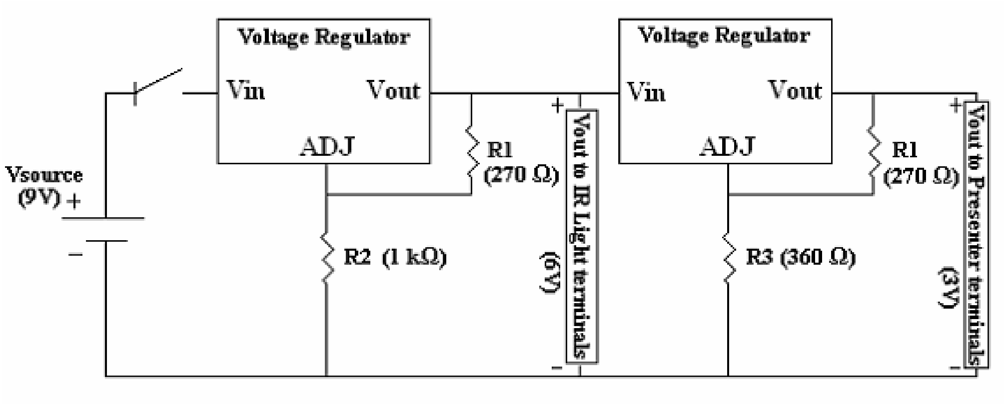

Figure 3. Power delivery circuit for IR light and wireless presenter.

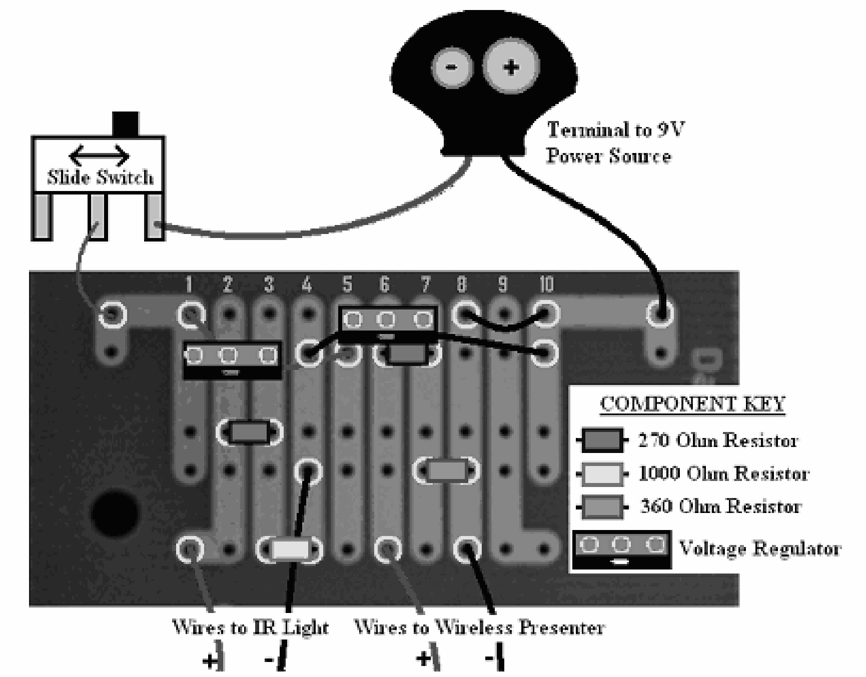

Figure 4. Physical representation of power delivery circuit from figure 3.

Although the inertiacube was not integrated into the circuit described above, it too was provided a unique wiring scheme that would allow the user to control the power delivered to the component using an on/off slide switch from a 9 V battery. The circuit constructed for this task was designed to work with the inertiacube wiring already in place, a feature that allows the circuit to be attached to the device when the new wand is assembled, but removes easily when the inertiacube needs to be taken away. This is an important feature to note because throughout the duration of the design project, the inertiacube was needed for use in the current VR wand and therefore had to be removable from the new design. Additionally, the flexibility of this wiring scheme allows for the continued use of the current VR wand without the need for an added inertiacube until the software for the new design has been finalized for use within the VE. A physical representation of the circuit is featured below in *figure 5*.

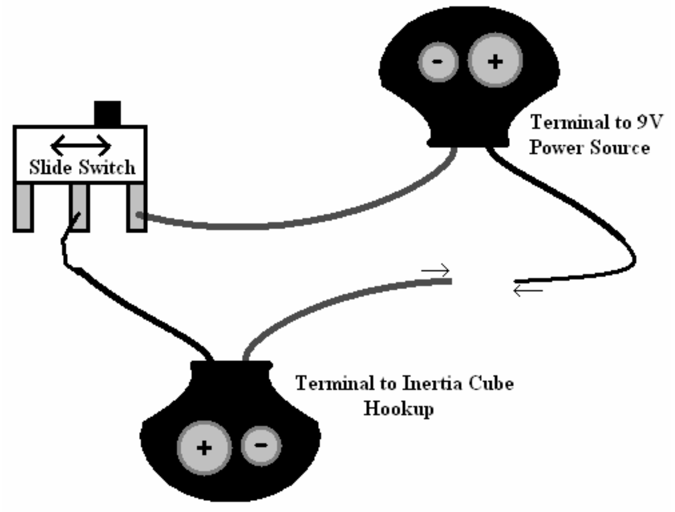

Figure 5. Physical representation of power delivery circuit for inertiacube.

3.3. Attachment Design

With the wireless presenter by Iogear© in hand and the dimensions of the power delivery circuits set, it was time to continue with the next step of the design process: the design of the presenter attachments. In order to accommodate the additional components required for a functional VR wand, the presenter had to be modified through the addition of attachments responsible for such tasks as mounting the inertiacube as well as housing the switches, power delivery circuits, and batteries. All of the design work on the attachments was completed within the CAD program, ProEngineer Wildfire 2.0. After the designs were finalized, they were converted to .STL files and built using a stereo lithography (SLA) rapid prototyping machine. In order to capture the complicated geometries of the presenter's surface, multiple snapshots of the nose and handle of the device were taken and overlaid with a scaled grid for measurements. To ensure the proper scaling of the pictures, a reference length was taken and compared between the photo and the real world. Using the ratio of photo to real world lengths as a factor for the grid measurements, the perspective bias of the camera was eliminated. Sample grid data points and scaling can be viewed in *table 3* within *appendix A*. With a correct mathematical description of the contours and cross-sections around these areas, the behavior of the curves could be accurately depicted within the CAD design program and a successful, integrated design could be achieved. A sample of the scaled photo grids can be seen below in *figure 6*, an image of the bottom of the presenter handle (note: in *figure 6* there existed a horizontal ruler for scaling in the x-direction, but it was removed in the interest of saving space).

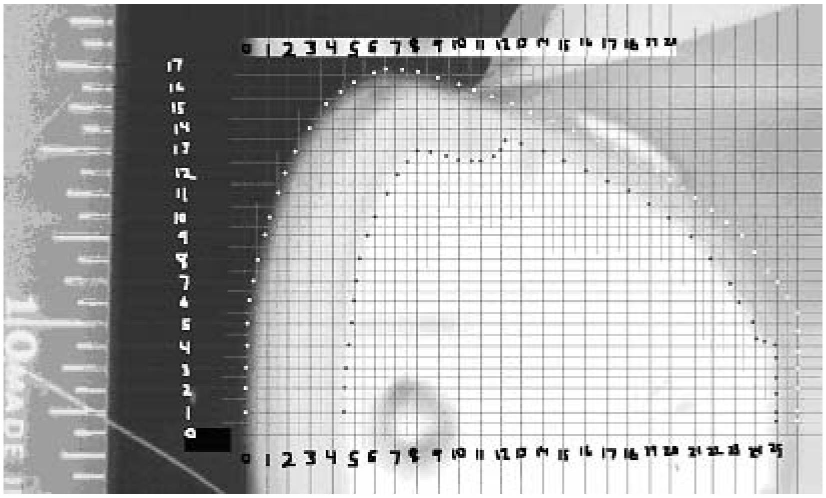

Figure 6. Sample grid for handle bottom.

For the design of the inertia cube mount, a number of constraints determined the size and shape of the piece. First, in order for proper calibration, the inertiacube (IC) mount was required to mount the IC on the horizontal plane parallel to floor of the VR arena. Second, it was required that the mount position the IC at least three inches from any ferrous metals or magnets to prevent them from disrupting the IC's magnetic sensors. Third, the IC mount was required to house all wires to maintain a neat and professional design. Last, the mount was required to position the IR light in a way that would allow two of the four optical tracking cameras to have a direct line of sight to the IR light at all times. As a result of these requirements, it was decided that the most efficient design of the IC mount would be top mounted and able to secure itself using the nose of the wireless presenter. Due to the laser light's lack of functionality in the new VR wand design, modifications to the laser were performed (removal, mainly) to create an available route to run the IR light wires into the presenter as well as create a cavity that the IC mount could lock into. In order to keep the designed parts small, the IC mount is only long enough to accommodate the full length of the IC, approximately 2 inches, in addition to a mounting hole used to bolt the IC mount to the presenter. A small hole, d ≤ 1/8", and corresponding circular passage house the IR light and run wires back to the presenter in order to maintain the professional design aspect. The final CAD design of the IC mount is featured in *figure 7* below.

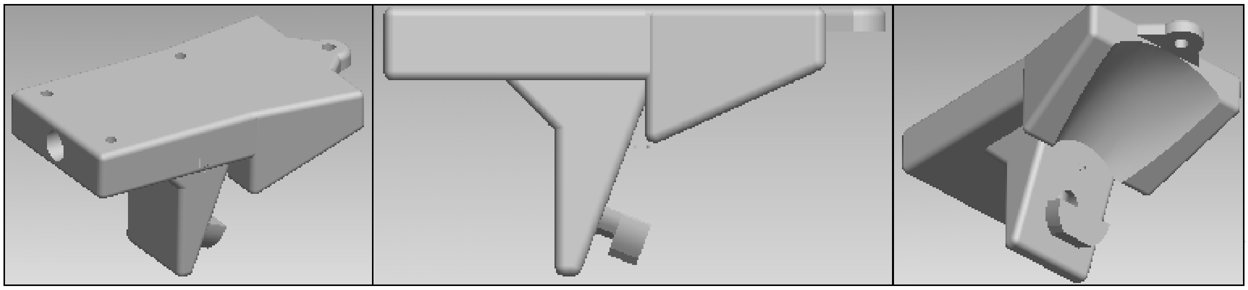

Figure 7. Final IC mount design.

On the other end of the wireless presenter, the battery pack (BP) was designed to house the two 9 V batteries, the switches that control them, as well as the power distribution circuit for the presenter and IR light. Although the only design constraint regarding the creation of the BP was its ability to house the switches, batteries, and circuit board, there were a number of design goals that were present as well. First, it was important for the new design of the VR wand to stand on its own without the need for additional stabilization. As a result, the geometry of the BP base was created as long and wide as possible without wasting space or material. Additionally, the batteries were placed out in front of the handle in order to ensure that the center of gravity of the entire wand assembly was not forward of the leading edge of the BP. Second, it was decided that the locking mechanism of the BP should mimic that of the original piece which enclosed the two 1.5 V AA batteries within the presenter handle. Resultantly, the BP features a clip locking mechanism that is supported and secured by a screw housed within the bottom of the handle. The third design goal regarding the BP was to continue the trend of curved features from the presenter and incorporate them into the body of the BP. Although the transition from the handle interface to the base of the BP is relatively short, the geometries are swept to one another in an attempt to quickly blend the two in the vertical direction. Last, it was important to tailor the design of the BP in order to accommodate an easy and straightforward assembly process. As a result, certain design features such as an offset circuit board from the back wall of the BP allows for the entire assembly of the attachment before connecting it to the handle of the presenter. The final CAD design of the BP is featured in *figure 8* below.

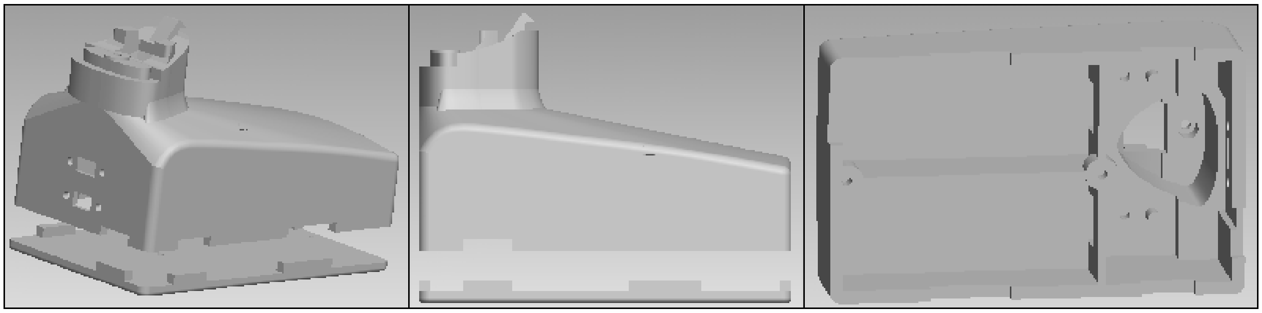

Figure 8. Final BP design.

3.4. Final Design Assembly

With the final designs of the power delivery circuit, inertiacube mount, and battery pack decided upon, it was a matter of performing a number of modifications and circuit wiring to complete the entire assembly. As a rule of thumb for the entire design, all permanent connections would be made using nylon machine screws and matching brass inserts. There were two reasons for this approach, one, the SLA rapid prototype material is not ideal for tapping to create screw holes, therefore, the threaded inserts were needed, and two, in order to mount the inertiacube safely, a nonferrous metal or plastic was necessary, therefore, the inserts were specified as brass while the machine screws selected were manufactured from nylon. With respect to the electrical work during the assembly process, all circuit and connection wiring was completed through solder joints that were secured with heat shrink tubing.

4. Findings

Following the final assembly of the new VR wand, testing has confirmed that the device is mechanically and electrically sound. The integrated components of the new wand design behave as they are expected to, yielding a fully functional, operable VR wand. In addition to the fabrication of a working VR wand design, an instruction manual detailing the assembly process was created in order to foster the transfer of knowledge that was produced during this summer's project.

4.1. Final Design Outcome

Through testing and trial operational runs performed post-assembly, the final design of the new VR wand has been received as a success. The rapid prototype attachments have shown themselves to be near perfect fits at the nose and handle interfaces of the wireless presenter. Additionally, both of the connections are robust and reliable, important aspects when considering the durability of the design. As planned, the VR wand assembly stands upright when the battery pack is attached and the inertiacube properly mounts in the correct position parallel to the floor. All of the circuitry within the new VR wand works properly, delivering the expected voltages to the components while allowing for a new level of control and convenience, due to the integration of the slide switches, that the current design does not offer. As such, the wireless presenter, inertiacube, and IR tracking light are all operational when the new VR wand is fully assembled. Additionally, the effective range for the modified wireless presenter covers the entire VR arena, ensuring that the user within the VE will have control with the wand at all times. A picture of the full, operational assembly can be seen below in *figure 9*.

Figure 9. New VR wand.

4.2. Assembly Instruction Manual

In addition to completing the new VR wand, this summer's project included the authoring of an assembly instruction manual that described in detail how to accomplish the fabrication and modification steps necessary to yield a completed wand after assembly. Pictorial aids were included with the text instructions in order to assist the reader in learning and completing the task more efficiently. Along with the instructions, a quantified list of materials was generated in order to help the reader identify and purchase the necessary components for modification and assembly. A sample of the text and illustration instructions for the inertiacube mount modification is available in *figure 2* of *Appendix A*.

5. Discussion

As with any design project, success is determined by how well the final product meets the goals and functionality requirements that were assigned to it at the beginning of the endeavor. The full assembly of the new VR wand has been an overwhelming success based on these criteria. Although the new wand is now operational, a number of interesting design problems needed to be overcome before the finished project could be presented at the conclusion of this program. Additionally, it is important to discuss the direction of future work within the area to inform others about the long term goals concerning the VR program and how the new wand design will further them.

5.1. Effectiveness of Design

Having completed and constructed a new design for the VR wand, it is important to assess whether or not the final product addresses the issues that are present in the current design. As was mentioned in the problem description section of this write-up, the current wand design is flawed by a number of issues that include: a piecewise design approach, inconvenient power supplies, weak component connections, a lack of ergonomics, and a disconnected method of rotation within the VE. As an improvement upon the current device, the new wand design has provided adequate solutions to each of the issues restated above.

In terms of addressing the piecewise nature of the current wand design, the new wand serves to unify the device through the use of fitted attachments that resemble the existing geometries of the wireless presenter. From the bottom of the battery pack to the top of the inertiacube mount, the geometries of each piece of the assembly flow into one another, giving the impression that the new wand is a single device rather than one composed of three distinct parts.

With respect to the inconvenient number of batteries in the current VR wand, although a single generic power supply was not feasible (due to cost and battery life constraints) in the new design, the reduction from seven to only two necessary batteries brings about added convenience in terms of wand maintenance. Additionally, users will now be capable of controlling the delivery of power easily by using the on/off slide switches mounted to the battery pack.

The weakness of the component connections was remedied in the new VR wand through the use of nylon machine screws coupled with internally threaded brass fittings. In this way, all of the components of the new wand are tightly secured but also removable if necessary.

With regards to the ergonomics lacking in the current design, the new VR wand offers users the comfort of a gun-shaped geometry that accommodates the form of a clasped hand. By starting from an existing presenter that was ergonomically shaped, the new design offers the possibility of longer immersion times within the VE due to added user comfort.

In order to address the difficult method of rotation within the VE, the new design features a trackball mouse pad capable of bridging the divide that exists between real world wand interactions and the resulting VE motions. Although a comparison between the two modes of rotation has not yet been conducted, it is promising that the new wand includes a rotational device that directly correlates to the expected motion within the VE.

5.2. Final Design Troubleshooting

Although the final assembly of the new VR wand has yielded successful results, the initial design on paper was not flawless, and resultantly, a number of design issues that appeared along the way were remedied in order to produce the final product as shown in *figure 9*.

Initial CAD drawings of the connection features for the nose and handle of the presenter required guess and check methods that sacrificed initial connection prototypes in order to refine and perfect the fitted surfaces and locking mechanisms of the attachments for the final design.

Original plans for the inclusion of variable resistances within the power distribution circuit for the wireless presenter and IR light were discarded following the failure of a potentiometer that led to a surge of voltage across the terminals into the wireless presenter circuit. The situation was resolved by installing fixed resistances with values close enough to distribute the approximate values of 6 and 3 volts for the IR light and wireless presenter, respectively.

The most recent of the design issues regarding the new wand involved the performance of the presenter's radio frequency emitter. Due to the nature of the modifications made to the presenter and IC mount, wires from the IR light and inertiacube were contacting the emitter coils at the head of the wireless presenter circuit within the body of the presenter. This contact between the wires and the emitter provided enough blocking interference to prevent the receiver from picking up signals from the presenter if it were any more than three feet away. A simple change to the internal routing of the IR light wires combined with a modification of the IC power cord entry location quickly solved the problem without compromising the IC mount design.

5.3. Future Work

With the new VR wand assembled and operating, future work regarding the wand will involve the authoring of software to integrate the trackball mouse function of the device into the VR program, Virtual Training Studio, allowing the wand to fully interact with and manipulate parts within the virtual environment. Following the software authoring, usability tests regarding user satisfaction with the new VR wand as compared to the current design will be carried out to ensure that the transfer from the current wand to the new wand will be a beneficial change.

6. Additional Work

Unrelated to the design of the new VR wand this summer, a literature review was performed on nine papers regarding various virtual and augmented reality systems for use in assembly training and their effectiveness with regards to transfer of training. The entire work is available for review within *Appendix B* of this paper.

Appendix A: Additional Tables and Figures

	1	2	3	4	5	6	7	8	9	Sums	**Weight**
1	-	1	1	1	1	1	1	1	1	8	**0.222222**
2	0	-	1	1	1	1	1	1	1	7	**0.194444**
3	0	0	-	1	1	1	1	1	1	6	**0.166667**
4	0	0	0	-	1	1	1	1	1	5	**0.138889**
5	0	0	0	0	-	1	1	1	1	4	**0.111111**
6	0	0	0	0	0	-	1	1	1	3	**0.083333**
7	0	0	0	0	0	0	-	1	1	2	**0.055556**
8	0	0	0	0	0	0	0	-	1	1	**0.027778**
9	0	0	0	0	0	0	0	0	-	0	**0**
									TOT.	36	1

Table 1. Pair-wise comparison attribute weighting.

A		**B**		**C**		**D**		**E**		**F**	
5	0.139	10	0.278	6	0.1668	4	0.1112	5	0.139	7	0.1946
10	0	10	0	10	0	10	0	10	0	10	0
10	1.944	4	0.7776	10	1.944	10	1.944	4	0.7776	8	1.5552
10	2.222	10	2.222	10	2.222	10	2.222	10	2.222	10	2.222
8	1.1112	10	1.389	7	0.9723	10	1.389	8	1.1112	8	1.1112
5	0.5555	8	0.8888	9	0.9999	5	0.5555	2	0.2222	9	0.9999
7	0.3892	10	0.556	7	0.3892	8	0.4448	9	0.5004	9	0.5004
9	0.7497	9	0.7497	9	0.7497	8	0.6664	9	0.7497	9	0.7497
6	1.0002	9	1.5003	7	1.1669	10	1.667	8	1.3336	9	1.5003
	8.1108		**8.3614**		**8.6108**		**8.9999**		**7.0557**		**8.8333**
RANK	**5**		**4**		**3**		**1**		**6**		**2**

░ **Attribute Rank**

▒ **Weighted AR**

▒ **Total Score**

Table 2. Weighted decision matrix.

X	Y	X(in)	Y(in)	**X(in) scaled**	**Y(in) scaled**
0	1	0	0.0625	0	0.040923
0	2	0	0.125	0	0.081845
0.05	3	0.003125	0.1875	0.002046	0.122768
0.1	4	0.00625	0.25	0.004092	0.163691
0.15	5	0.009375	0.3125	0.006138	0.204613
0.2	6.1	0.0125	0.38125	0.008185	0.249628
0.3	7.1	0.01875	0.44375	0.012277	0.290551
0.55	8	0.034375	0.5	0.022507	0.327381
0.85	9.1	0.053125	0.56875	0.034784	0.372396
1.1	10.05	0.06875	0.628125	0.045015	0.411272
1.5	11	0.09375	0.6875	0.061384	0.450149
1.8	12	0.1125	0.75	0.073661	0.491072
2.3	13	0.14375	0.8125	0.094122	0.531994
2.95	14.1	0.184375	0.88125	0.120722	0.577009
3.75	15.25	0.234375	0.953125	0.15346	0.62407
4.33	15.8	0.270625	0.9875	0.177195	0.646577

Table 3. Sample scaling data.

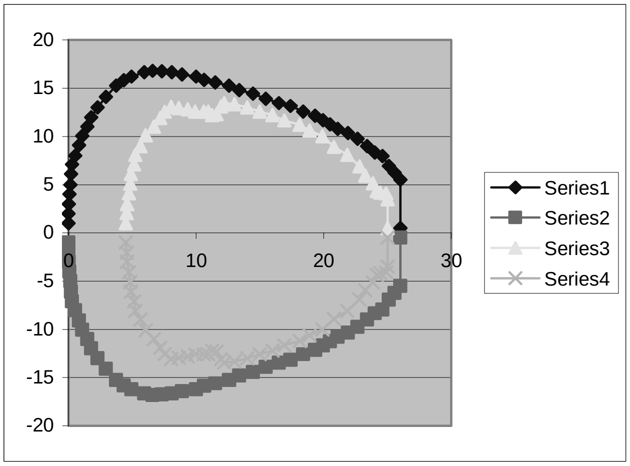

Figure 1. Graphical representation of scaled data.

Inertia Cube Mount Modification Steps

* A diagram (figure 1) featuring hole locations, diameters, and lengths can be found directly beneath the associated steps (1-5) below.

1. Looking top down on the inertia cube mount, identify the three mounting holes for the inertia cube located towards the front of the piece near the LED hole.
2. Drill out these three holes to a new diameter, D_1, of 1/8” and a depth, L_1, of 5/32” (the depth of the original prototyped holes are also 5/32”, so stop drilling once there is a noticeable increase in pressure needed to continue drilling).
3. Take three of the threaded brass inserts and press one into each hole drilled from the previous step. Make sure that the top of the insert is flush with the top plane of the mount.
4. Looking top down on the IC mount, identify the hole used for mounting the entire IC mount to the wand, it is located towards the back of the piece past the curve fitted section.
5. Drill out this hole to a new diameter, D_2, of 7/64” entirely through.

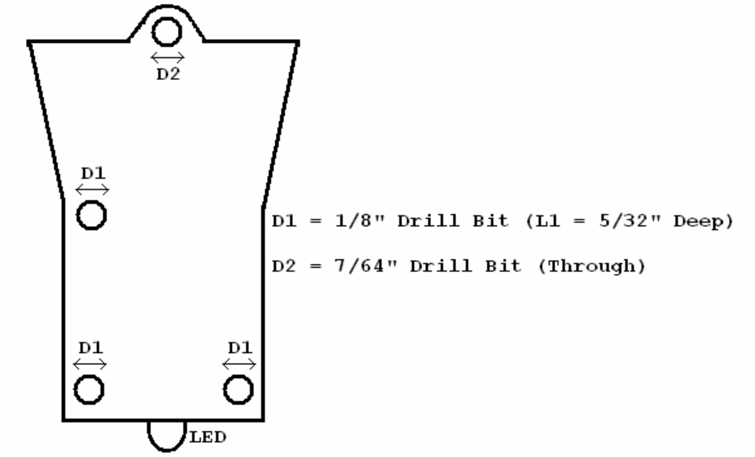

Figure 1. Top view IC mount.

Figure 2. Sample IC mount modification instructions.

Appendix B: Literature Review Material

1) <u>Virtual Training for a Manual Assembly Task</u> - R.J. Adams, D. Klowden, B. Hannaford
Haptics-e Vol. 2, No. 2, October 17, 2001

The purpose of this paper was to identify the benefits, if any, of force feedback coupled with a virtual environment to carry out an assembly-training task. The exercise involved the construction of a LEGO biplane model, completed five times in succession, in order to identify any significant differences in assembly times between differently trained groups as well as iterations within those groups. All three groups were presented a 4-minute video on biplane construction while two of the three were given additional training of 30 minutes within a virtual environment. Of the two groups using the virtual environment, one group experienced the virtual training with force feedback provided by a device called the Excalibur force display while the other group did not.

Using an Excalibur force display in conjunction with a virtual environment software package, the experimenters were able to carry out their investigation involving haptics. The Excalibur force display is a "three degree-of-freedom Cartesian manipulator" that acts as the haptic interface between the user and the virtual environment. Steel wires in the x,y, and z directions are tensioned according to onscreen interactions and collisions to simulate the contact forces within the virtual environment. The user grasps the handle mounted at the top of the Excalibur with one hand and manipulates the objects in the virtual environment with the other using a two-button wireless mouse. Subjects within the group training in the virtual environment without force feedback simply used the wireless mouse to interact with the 3-D onscreen display in order to complete the virtual training.

To analyze the findings of the tests, the experimenters used an ANOVA analysis (at the 5% significance level, in other words $p < .05$ signifies a null hypothesis), for each of the iterations as well as the test average, on two hypotheses: one, the mean assembly times for the three different training methods were equal and two, the distribution of assembly skills prior to training was equivalent among the three groups. For the first hypothesis, it was found that for the first and fourth iterations, as well as the overall test average, the p values (.04, .018, .027, respectively) signified that the mean assembly times for the different training methods were in fact different. For the second hypothesis, the p value (.039) for the overall test average signified a difference in assembly skills prior to the training exercises. Using the fact that the first hypothesis was rejected for iterations 1 and 4, the experimenters conducted pair-wise comparisons between the various training methods using the Tukey Honest Significant Difference test. Based on this analysis, it was determined (again at the 5% significance level) that for iteration 1 there existed a significant difference in assembly times between virtual training with haptics and no training at all ($p = .049$) and that for iteration 4 there existed a significant difference in assembly times between virtual training with haptics and no training at all, as well as virtual training without haptics and no training at all ($p = .037, .041$, respectively). According to this data analysis, it was concluded that there existed a significant difference in performance between those individuals who were trained virtually with haptics and those who were not trained at all. Additionally, it was demonstrated by the data that those virtually trained with force feedback also outperformed those virtually trained without it, but due to variance in the data, this conclusion could not be reached through data analysis methods.

The significance of this study lies in the fact that it was able to prove that training in the virtual environment at any level (with, or without force feedback) improves an individuals ability to successfully complete an assembly task in a timely manner. Additionally, the inclusion of force feedback as part of the virtual environment has the potential to increase the speed of the assembly process when compared to that of a virtual environment alone.

2) Virtual Reality and Augmented Reality as a Training Tool for Assembly Tasks -
A.C. Boud, D.J. Haniff, C. Baber, and S.J. Steiner

The purpose of this investigation was to identify whether various types of virtual (VR) and augmented (AR) reality training sessions are effective for the training of manual assembly tasks, such as that of a water pump. Boud, Baber, and Steiner studied the mean completion times of the pump for five distinct training methods: one, conventional engineering drawings for the individual to study, two, a desktop VR that included a monitor and 2D mouse, three, a desktop VR that included stereoscopic glasses in addition to a monitor (to provide 3D images) and 2D mouse, four, an immersive VR that included an HMD, tracking system, and 3D mouse, and five, a context-free AR that included a see-through monocular HMD that provided a static display of the engineering drawings. Once the training sessions were completed, participants were then directed to assemble the water pump in the real world and the mean times for assembly by each training method were calculated for comparison.

In order to conduct the experiment, 25 students with engineering backgrounds were divided into five groups of five and each group was trained for 10 minutes using a different method as discussed above. The group that trained with the conventional engineering drawings was given the full 10 minutes to study the drawings while the groups trained with the VR systems were given 2 minutes to study the conventional engineering drawings and an additional 8 minutes to practice the assembly process within the virtual environment. Those individuals who were trained using the AR system were given 2 minutes to study the conventional drawings and an additional 8 minutes to view the drawings through the monocular viewing screen.

The results of the experiment were as follows: users trained with conventional method averaged a completion time of approximately 4 minutes while users trained with the VR systems averaged a completion time of approximately 45 seconds, and users trained with the AR system averaged a completion time of approximately 15 seconds. Although it is clear that the implementation of the VR and AR systems are superior training methods when compared to the conventional method, it was also statistically proven that there existed a significant difference (at the 1% level, $p < .01$) between the fastest VR (stereoscopic) and AR system results.

These findings again support the hypothesis that VR and AR training systems aid the learning process and lead to shorter assembly times when compared to the conventional methods of training through engineering drawings and written assembly procedures.

3) Virtual Reality: A Tool for Assembly? - Boud, A. C., Baber, C., Steiner, J. Presence: Teleoperators & Virtual Environments, 1054-7460, October 1, 2000, Vol. 9, Issue 5

While the 3rd chapter of this paper rehashes much of what was said in Boud, Baber, and Steiner's paper, Virtual Reality and Augmented Reality as a Training Tool for Assembly Tasks, the 4th chapter introduces the concept of utilizing real instrumented objects (IOs) in order to provide the user with "tactile, force, and kinesthetic feedback" while immersed in the virtual environment. For this study, the IOs used were constructed from wooden discs fitted with magnetic tracking devices that move their representative virtual objects in much the same way that a 3D mouse works. The goal of the investigation was to determine whether the implementation of a "hybrid, haptic-augmented VR system" would improve user performance when compared to real and virtual environment settings.

To achieve this, the experimenters selected four individuals having six months experience with the VR system and had them complete a simple ring and peg puzzle ("Tower of Hanoi") as a basic simulation of an assembly process. The five conditions under which the subjects had to operate were as follows: "immersive VR and 3D mouse, immersive VR and IOs, desktop VR and conventional 2D mouse, real environment with real objects, and real environment, but blindfolded." The setup of the virtual environments follows that described in the first paragraph of Virtual Reality and Augmented Reality as a Training Tool for Assembly Tasks. The mean performance times to complete the puzzle under the each condition were recorded from the data and compared. Additionally, a movement analysis was performed to compare the speeds with which the tasks were performed.

From the data collected, it was demonstrated through an ANOVA, for the total time with the five levels (2D mouse, 3D mouse, IO, real, and blindfolded), that there existed significant differences between the time of completion for the conditions ($p < .0001$). The 2D and 3D mouse conditions required an average of 35 seconds for completion while the IO condition required an average of approximately 22 seconds, the real required an average of 15 seconds, and the blindfolded required approximately 20 seconds. Additionally a Tukey pair wise comparison test identified significant differences between the IO & 2D, IO & 3D, real & 2D, real & 3D, real & IO, and blindfolded for both 2D and 3D. When a movement analysis of the small ring was conducted and compared between the real and IO conditions, it was revealed that movement onto and off of the pegs was 3.5 times faster and interpeg movement was almost 2 times faster for the IO condition when compared to the real condition.

The assembly time superiority demonstrated by the IO condition over the standard immersive VR condition gives reason for the continued research and development of haptic systems to improve the viability and effectiveness of virtual environments for use in assembly training. By allowing users to rely on tactile feedback rather than visual feedback alone, virtual environments that feature haptics have the potential to decrease assembly times through faster learning curves.

4) <u>Artificial Intelligence Applications in the Design of STE Virtual Reality Operation Training System</u> - SHENG-PING HE, ZHENG QIN I, XI-PING HE Proceedings of the Second International Conference on Machine Learning and Cybernetics, Xi'an, 2-5 November 2003

As pointed out by the authors of this study, the conventional methods for the training of assembly and disassembly operations are carried out in the real world on physical prototypes in order for technicians to develop skills. For training involving STEs (special type equipment) which may include radiant, explosive, or hazardous materials, this type of conventional training is largely inappropriate because of the inherent danger to trainees as well as the exceeding cost of prototypes. In response to this realization, these researchers have proposed a virtual reality operation-training simulator featuring artificial intelligence (VROTS-MAD) to assist trainees in acquiring the highly technical assembly and disassembly skills necessary for maintenance of STEs.

According to the paper, there are three goals established for the VROT system: one, to provide an immersive training environment, two, to act as an operational tutorial and dynamic aid for assembly/disassembly processes, and three, to provide force feedback in the virtual environment to allow the user "a kinesthetic sense of when he/she interacts with the virtual object." In order to accomplish these goals, the authors have described the groundwork and features necessary to develop such a system which include an intelligent kinematics modeling system, a VE manager capable of hosting and categorizing interactions with the user, and an operation monitoring system capable of identifying difficulty with the assembly/disassembly process and provide the appropriate dynamic cues to assist the user.

The proposed kinematics modeling system works by dividing the part motion into two kinds: the motion controlled by the user's hand, and the uncontrolled motion such as dropping or sliding of an object. By using information from the virtual environment to provide an estimation of how the parts should act while part of a controlled or uncontrolled motion, the modeling becomes an economical approach and allows for a reasonably accurate representation of the physics of the parts within the VE while saving computational power. The virtual environment manager described by the authors is responsible for defining the assembly relations and the correct order for the assembly/disassembly process in order to assure the validity of the training program. Both the assembly relations and the order of the processes are defined within the manager using semantic constraints that identify what the assembly is named, how it is performed, and what entities are involved in the process (i.e. <ID, Description, Constraint-Set, Entity-Set). In order to provide the trainee with feedback and assistance during assembly sessions, the VE manager also includes the ability to detect the recurrence of incorrect assembly/disassembly motions by comparing them to a predefined set of ideal movements and act on them by providing the user some type of dynamic cue (video, audio) to help the trainee correctly complete the incorrect task.

The discussion of this proposed STE virtual reality training system identifies features that are important for virtual environments to be effective training aids for assembly/disassembly processes. By developing and describing their own system to deal with STEs, the authors have demonstrated that their vision of an appropriate VE includes a smart system with the ability to adapt to differently skilled users, physical feedback, and efficient modeling of part physics.

5) Augmented Reality for Skill Transfer in Assembly Task - Nattapol Pathomaree, Siam Charoenseang 2005 IEEE International Workshop on Robots and Human Interactive Communication

This paper sought to identify whether the implementation of augmented reality (AR) was capable of transferring the skill of an assembly process more effectively than conventional methods. In order to carry out the investigation, the authors gathered 20 participants to complete two sets from one of four experiments which included 2D assembly task with AR training, 2D assembly task without AR training, 3D assembly task with AR training, and 3D assembly task without AR training. During the 2D and 3D assembly tasks without AR training, the participants were asked to complete the puzzle given to them after witnessing a single complete build. Once the first unassisted build was completed, the participants were again asked to build the 2D or 3D puzzle a second time (both completion times for the builds were recorded). For the 2D and 3D assembly tasks with AR training, the participants were provided the assistance of augmented reality for the first build and then were asked to complete the build a second time without the aid of AR (both completion times for the builds were recorded).

In order to provide their test subjects with AR training assistance, the authors constructed a system that featured an overhead camera for the tracking of the puzzle in the real world, a graphics program to provide the additional assembly information overlaid on the feed from the camera, as well as an HMD to relay this augmented scene to the user completing the puzzle. Through the use of tracking, the AR system was able to detect and track all pieces of the puzzle. Additionally, the inclusion of the CAMSHAFT tracking algorithm gave the system the ability to track and identify all pieces of the puzzle so that it could calculate the goal position of the remaining pieces and communicate the necessary solution to the user through the display of text instructions.

The results from the experiments were as follows: the completion times with the assistance of AR training were 85% shorter than those without for the 2D puzzle on the first build, while completion times with AR were 61% shorter than those without for the 2D puzzle on the second build. For the 3D puzzle, the reduction in times using the AR system was even better with saves of 96.2% and 92.6% for the first and second builds, respectively. Additionally, the total number of steps performed to complete the puzzle was recorded and were as follows: with AR training for the 2D puzzle, 80% less steps were used to assemble during the first build while 65% less steps were used during the second. For the 3D puzzle, AR training saved 93% and 84% of steps during the first and second builds, respectively. As a result of this data, the percentages of skill transferability were calculated to be 81.5% for the first build in 2D, 61.5% for the second build in 2D, 96.2% for the first build in 3D, and 92.6% for the second build in 3D. Lastly, it was calculated that on average, users of the AR training system made 0 excessive assembly steps on the 2D puzzle and .4 on the 3D puzzle.

As the results show, the utilization of an AR system to train an assembly sequence greatly improves user retention and performance. Not only did the AR quicken the user's ability to complete the puzzles provided, but it also demonstrated that it was an effective teaching tool through the minimization of unnecessary steps completed by users trained on the AR as well as the user's ability to perform at the same level during the second build after the AR was disengaged.

6) The Effectiveness of Augmented Reality as a Facilitator of Information Acquisition - R. Brian Valimont, Dennis A. Vincenzi, and Sathya N. Gangadharan

According to the authors, although simulation and virtual reality dominate the training community, the lack of cost effective real world cues to aid in information retention is limiting the field's potential. Although augmented reality (AR) clearly affords trainees various physical associations with the training information they are provided, it has yet to be proven that AR is an effective means to convey training information when compared to conventional methods. Their hypothesis states that through the support of multi-sensory interaction while training, users of AR systems are more likely to retain the information provided to them over conventional methods of training provided by video or paper. Additionally, the authors claim that AR is a superior teaching tool because it directly associates the learning and task environments in the user's mind as well as serves to exercise visuo-spatial abilities that have been linked to effective recall of semantic content based on location knowledge (basically the familiarity of the location is linked to learned information and therefore makes it easier to recall).

In order to conduct an experiment to validate their claim, these authors gathered 64 participants and divided them into four groups of 16 in order to train for assembly each group using four distinct methods: video instruction (observe group), interactive video instruction (interact group), AR instruction (select group), and print-based instruction (print group). The subject of the training sessions was the assembly of a Lycoming T-53 turbine engine vane-type oil pump for reasons that it was readily available and easily acquired. During training, the select group was allowed interaction with the disassembled oil pump and was shown the technical information through the AR system (composed of a video camera, a TV for image output, and ARToolKit ver. 2.431 AR software). As for the other groups, the observe group was provided a 3-minute video of the pump and its disassembled components, the interact group was provided the same video with the inclusion of the AR annotations, and the print group was provided 9 freeze frame photos from the AR session with the necessary technical information. For the training sessions, individuals were given eight minutes to study the oil pump using their assigned group method after which they were immediately tested (three minutes after the training was complete) on their comprehension of the functions, locations, and assemblies of the various oil pump components. An additional long-term retention test was also administered a week after the training session. Both tests were scored on a scale of 0 to 100 based on the individual's comprehension of the device.

Based on the results of the experimentation, an ANOVA analysis of the mean test scores for all four training groups failed to find a statistically significant difference for either test. Although this was the outcome, it is clear from the data provided by the authors that the individuals trained with the AR system were able to initially absorb more information than the other groups and interestingly enough, were able to retain more of their information later in the week than other groups (the difference between the select and observe group in 2nd grew wider by the end of the week).

The results from this study, although lacking statistical significance, are encouraging because they continue with the trend that AR systems are more effective at conveying information than conventional methods. Additionally, the fact that at the end of the week the select group trained with the AR system was retaining more of the information than other groups may be evidence that training with AR encourages the storage of information in long-term memory.

7) Training in virtual environments: transfer to real world tasks and equivalence to real task training - F. D. ROSE, E. A. ATTREE, B. M. BROOKS, D. M. PARSLOW, P. R. PENN
ERGONOMICS, 2000, VOL. 43, NO. 4, 494-511

The authors of this paper set out to understand whether training in virtual reality offers the true potential for skill transfer when compared to that in the real world. Additionally, the study was an analysis of whether training in the virtual environment (VE) is cognitively simpler than that in the real world. In order to study these comparisons, the authors gathered together 250 participants to perform three distinct experiments that were based on the completion of a steadiness test (the steadiness test was selected because it allowed for the equivalence of sensory and motor aspects of the real and virtual training worlds). The steadiness test involved the navigation of a deformed length of wire using a wire loop that signals the user when contact is made, much like the kind you would find at an amusement park. The first experiment was designed to study the extent of training transfer from the VE to the real world and was conducted by training three different groups of individuals in the real world, VE, and not at all and recording the number of errors made while navigating the wire length (the result of this experiment was that training in the real world and VE yielded similar performances on the real world skills test, I say this as an aside because the other two experiments are more important, and this type of conclusion has been reached by many other studies). Using the outcome from the first experiment, the authors set out to determine whether there existed any significant differences in the way people learn from the VE and real world training exercises and what portion of their cognitive resources they used during the training through the second and third experiments, respectively. In order to do this, the second experiment was conducted by dividing the VE and real world trainees into two sub-groups: motor interference and cognitive interference. Members of the motor interference sub-group were required to tap on a Morse code key to the cue of a tempo at 2 beats/second while completing the steadiness test while members of the cognitive interference sub-group were required to listen for the names of predetermined fruits interspersed within strings of random words and say ‘yes’ when they occurred during the testing. The third experiment was conducted by subjecting the participants in the two training groups (real and VE) to visual (5 colors displayed on a nearby TV screen) and auditory (3 distinct tones) cues to be recalled at the completion of the steadiness test.

After the results from the second experiment were analyzed, it was determined that the motor interference during testing had a more disruptive effect than the cognitive interference for both the VE and real training sessions. Additionally, it was determined at the statistically significant level that the VE trained participants were less influenced by the introduction of interference than those who were trained in the real world (2x2 analysis of covariance, $p = .05$). As for the third experiment, it was determined through independent t-tests that there existed no discernible difference between the real and VE trained participants for either the visual ($p = .68$) or audio ($p = .11$) cues recalled.

Although the results from experiments two and three appear to oppose each other (the reasoning is that the conclusion from experiment two points to the fact that VE training is less cognitively taxing and therefore should lead to higher performance during recalling cues for experiment three, which was not the case) there exists a theory that may explain the trends of the data. As theorized by the authors, in VE training, the disconnect of visual feedback from other sensory feedbacks that are commonplace in real world training make the task in the virtual environment more difficult and cognitively taxing than its counterpart in the real world. As a result, when VE trainees move into the real world to test their trained skills, they are graced with a surplus of cognitive capacity allowing them to cope with interference as was supplied from experiment two. The significance of this outcome might suggest that all complex or dangerous assembly tasks be trained for within VEs in order to ensure that trainees have the maximum cognitive capacity while working on the real world task.

8) <u>Assembly Guidance in Augmented Reality Environment Using a Virtual Interactive Tool</u> - M.L. Yuan, S.K. Ong and A.Y.C. Nee of Singapore-MIT Alliance

A characteristic of many augmented reality (AR) systems in use today is the need sensor systems or markers in order to keep track of the components being used and ultimately track the progress of the user within the assembly sequence. The authors of this paper have proposed an AR system with a predefined, easily accessed assembly sequence that uses a unique technique to track an interactive pen used to access the assembly data, all without the assistance of markers or sensor systems. The proposed system features a virtual interactive tool, Virtual Interactive Panel (VirIP), which hosts virtual buttons that provide meaningful assembly information in addition to a visual assembly tree structure (VATS) to manage information and access assembly instructions.

The input device of the system for this proposal consists of an interactive pen featuring a segmented image map and an interactive point extracted as the input device. Using an RCE neural network, the VirIP is able to visually track the position of this interactive pen, which allows the user to select virtual buttons (by holding the interactive point on the pen over the desired button) that assist in the assembly process without the need of any sensing devices. These virtual buttons are capable of accessing different directories within the VATS so that users can provide themselves with additional information concerning a specific assembly step. The VATS is composed of organized, predefined instructions (in the case of this proposal, images with text instructions overlaid) that allow the user to start the assembly process from the beginning or access data referring to specific parts and subassemblies. The authors of this proposal used the assembly of a 'fun train' in order to demonstrate the AR system using both HMD and desktop configurations. As was demonstrated by the paper, the user is able to employ the interactive pen to select the assembly database necessary, and through the use of confirmation VirIP, continue through the assembly process and visually displaying the subsequent assembly steps by confirming the completion of the prior step.

As the paper has demonstrated, it is possible to create a functioning AR system that does not need object markers to guide the user through an assembly task. With further development of the VirIP software, the possibilities for AR training without the need for sensor systems include make it a prime candidate for complex assembly procedures where numerous markers make the standard AR approach too difficult to monitor.

9) Transfer of Training from Virtual Reality Environments - Christopher James Hamblin

This dissertation was composed to evaluate the transfer of training and training efficiency of virtual environments (HMD and screen display based) for a complex manual assembly task. The two tasks selected for the completion of the investigation were the post training assembly of a Lego forklift model as well as that of a Lego racecar that utilized the same parts as the forklift model but with a different configuration (to determine the transfer of learning). During the study, 48 participants of comparable assembly skills were divided into two groups of fast and slow builders to ensure an even distribution of build times. These groups were further broken down into four divisions within each of the fast and slow build groups in order to administer the different training methods: immersive virtual reality (an HMD and a pair of touch gloves), PC-based virtual reality (computer screen and 2D mouse), real world, and none at all. With regards to the three active training methods, participants of these groups were trained a total of four times over four days in order to familiarize them with the technologies they would be using to complete the training as well as observe and interact with the assembly sequence they would be tested on at the end of the study. Each training session consisted of the participant completing the assembly of the forklift one time within their assigned environment as quickly and accurately as possible (time used for familiarization of the hardware used was not counted as training). During the experiment, the participants were asked to perform an initial build, pre-training, and an additional build, post-training (for the forklift model). The assembly times for these builds were recorded for analysis between build and training groups.

From the data collected, it was determined through a 2x4 between-subjects ANOVA that there existed a significant difference in improvement times (post-training assembly time subtracted from pre-training assembly time) across the training methods ($p < .001$). A comparison analysis using Tukey's HSD revealed that the real world training group improved the most while the HMD and PC based virtual reality methods were similar to one another and showed significant improvement over the group with no training. In terms of transfer of training ($(C_{pre} – X_{post}) / (C_{pre} – C_{post})$ X 100), where C is untrained control group and X is one of other training methods), it was demonstrated through a 2x3 between-subjects ANOVA that there existed a significant difference across the training methods ($p < .001$). Again the real world training method led the pack with the highest ratio of transfer of training (approx. 225%) while the virtual reality training methods both achieved moderate, insignificantly different levels at approximately 140 percent. The transfer of learning study conducted with the assembly of the racecar after the forklift assembly provided inconclusive data ($p = .65$) due to a high amount of variance, but the author claims that visual inspection of the data shows that some learning did occur for individuals within the slow builder group trained using virtual reality. Although this is not all of the data analysis provided by the author, it is my opinion that I have pulled out the chunks that are pertinent to our causes, determining whether VE training provides an effective learning environment for assembly tasks.

The conclusions that can be drawn from this study from data presented above are as follows: one, VE training is an effective method for training real world tasks, although not as effective as real world training itself, and two, real world training is more efficient than VE training at teaching skills that may be transferred to other tasks, although VE does an effective job in this department as well. Due to this outcome, it seems fair to say that VE training is better suited to training dangerous or otherwise costly tasks in the real world whereas if safety and cost are not a concern, real world training is the way to go.

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