A Family of New Ergonomic Harness Mechanisms for Full-Body Natural Constrained Motions in Virtual Environments

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ABSTRACT

A family of new virtual reality harness mechanisms has been developed by this investigator to constrain an immersed user within the field of view of a virtual locomotion sensing system while permitting natural motions such as twisting, turning, jogging in place, dropping to the knees or moving to a prone position. The author has also developed a generalized synthesis approach to the design of such harness systems. Unwanted rotational inertial loads felt by the user are minimized while compliant constraints have been tailored to provide natural feedback forces. These ergonomic forces enhance the experience of virtual motion by partially substituting for the missing real-world dynamic loads encountered in locomotion. They also provide subtle, natural cues to the immersed user that aid the user in remaining centered. Unlike some other virtual locomotion systems, these devices are passive, relatively low-cost, easy and natural to use, making them minimally intrusive on the process of learning the simulated task.

Keywords: 3D interaction, haptics, non-visual interfaces, tracking, harness mechanisms, immersion, input devices locomotion, human factors, full-body, prone.

Index Terms: H.5.2 [User Interfaces]; Haptic I/O; H.1.2 [User/Machine Systems]; Human factors; I.3.6 [Methodology and Techniques]; Interaction Techniques; Tracking, Motion.

1 INTRODUCTION

This paper presents a summary of several new full-body harness devices developed to constrain a user as unobtrusively as possible in an immersive environment. These devices are unique in that they permit a great deal of freedom of motion limited primarily by the tracking system employed. They provide a cost-effective compromise between simulation realism and practicality, since they are passive and don't involve any servomotors, actuators, or moving floors. All motions are human powered by the immersed user. At the same time, since the user controls the system by means of body motion gestures similar to those that would be employed in performing the real-world task, there is a potential for higher training fidelity than might be obtained using a low-cost substitute such as a joystick.

Motions such as dropping to a prone position or sudden twists and turns are permitted by these harness mechanisms, making them more useful as real-world training devices than technologies whose dynamics limit the user's ability to make sudden motions. They are ergonomically designed so as to be natural to use and require a minimal amount of mental mapping by the user to correlate what is happening in the simulator to what is intended in the real world. This means that the user is freed to concentrate on learning the task at hand without needing to concentrate on distracting irrelevant issues such as how to balance on a slippery moving surface or how to operate the harness mechanism.

This paper also presents the basis for a new generalized synthesis technique for designing virtual reality harness mechanisms for use with optical or magnetic sensor technologies. This technique allows the design of an entire family of new harness mechanisms having properties similar to the particular examples shown.

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IEEE Symposium on 3D User Interfaces 2007
March 10 - 11, Charlotte, North Carolina, USA
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2 THE PVC FIRST GENERATION

This investigator was contacted about five years ago by Dr. Jim Templeman, head of the Immersive Simulation Section (ISS) at the U.S. Naval Research Laboratory (NRL). Templeman's group was developing Gaiter [1], a powerful system for virtual locomotion that uses a gestural body language to permit moving through a virtual space by walking or running in place in the real world. This system was being developed to train Marines in close-quarter battle (CQB), though it has wide applicability in a variety of other training situations. At the time, the Gaiter group used a wooden frame supporting the standing user by means of a system of ropes. As a simulation would progress, the user often would leave the field of view of the magnetic tracking system. Also, after the immersed

Figure 1 Non-magnetic harness.

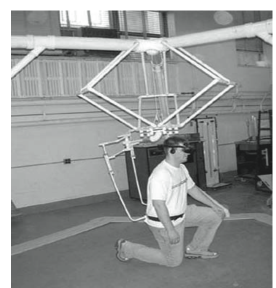


Figure 2 Kneeling in PVC harness.

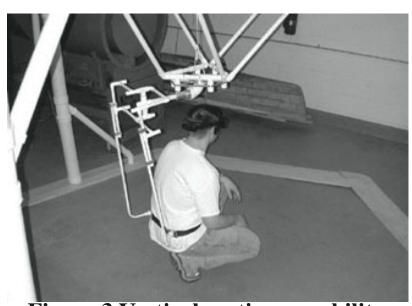


Figure 3 Vertical motion capability.

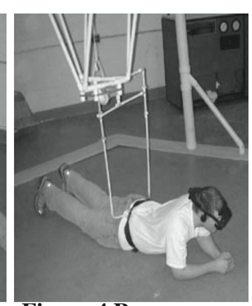


Figure 4 Prone capability.

user had performed a certain amount of turning in place, outside intervention might be necessary to allow the head mount cables to be untwisted.

Templeman asked if it was possible to develop a non-magnetic harness system that would eliminate some of these limitations and also provide gentle force cues to keep the user within the field of view of the sensors. To meet these requirements, I developed the first generation "go prone" PVC harness mechanism shown in Figures 1 — 4.

This first generation harness utilized a number of unique spatial mechanisms, many not obvious from looking at the figures. An original over constrained "Sarrus style" overhead linkage constrained the user to remain centered while permitting up and down

Figure 5 Central pivot with slip rings.

Figure 6 Independent roll capability.

translational motions. Constant force springs counterbalanced the static vertical loads and provided a slight amount of "buoyancy" for safety in case the user broke loose from the harness. (Nothing would fall on the user!) Multiple force paths transmitted loads between the user and the frame allowing a light responsive system that would keep the rotation axis vertical. Beneath that subsystem was a slip ring cable management subsystem to allow the user to spin about a vertical axis in an unlimited manner. It would carry enough lines to drive a high bandwidth head mount, audio lines, and auxiliary signals such as gun trigger switches and heel strike switches, etcetera.

Beneath that was a spatial linkage that allowed independent motions of the user's hips in small amplitude motions such as jogging in place or rolling on the ground. This arrangement uncoupled the rotational and vertical translational inertias and meant that the user could spin about a vertical axis without needing to accelerate the relatively massive mechanism required to provide the up and down motion while providing the rigidity to keep him/her centered. The unique lower linkage also provided the necessary degrees of freedom and constraint to allow small independent vertical motions of the user's hips encountered in walking or jogging.

These small symmetric vertical motions (one hip going up while the other went down) were uncoupled from the main vertical translation system so that they didn't necessitate motion of the main vertical straight-line overhead mechanism. All this meant that the user felt a minimum amount of reflected inertia and could move freely. Orthogonalizing the inertial effects from the vertical translation subsystem from those of the rotational subsystem meant that the rotational inertia was minimized. This is important since users are most sensitive to the dynamic loads required to start and stop sudden turns. Static vertical loads can be counterbalanced out and the vertical dynamic loads are relatively unimportant since they are carried through the user's legs to the floor. The overall system was made of PVC pipe and some aluminum so as to be non-magnetic and not disturb the tracking system. It was also designed to serve as a flexural restraint. Beam bending in this flexural PVC design would provide tailored stiffness allowing some deviation from the central rotation axis but with increasing centering force cueing the user when he or she strayed too far off the central axis. This force feedback to the user would subtly and naturally indicate to the immersed user as to how to return to the central position.

Unlike NRL's earlier Gaiter harness system and most other devices such as pods or the VirtuSphere, this mechanism allowed a user to drop to the knees or to a prone firing position. A user could even roll while on the ground. There was ample clearance for a weapon. Due to the use of slip rings, the head mount cables would never tangle.

3 ALUMINUM SECOND GENERATION

Unfortunately, no one explained to typical users such as Marines that they were supposed to respond to subtle force cues and stay centered when they were fully immersed and in the heat of virtual warfare! It quickly became obvious that a more robust design would be needed. An aluminum go-prone harness system was designed to be compatible with the magnetic sensors.

Although this aluminum harness system worked well with trained users, it was felt that it too wasn't sufficiently robust to be deployed in the field for immersive CQB training of Marines. Fortunately, the sensor technology being employed by Gaiter was also changing so it was no longer necessary to make the harness out of non-magnetic materials. Cameras and visual markers meant that a steel harness could be employed in the next iteration.

Figure 7 Aluminum vertical motion mechanism.

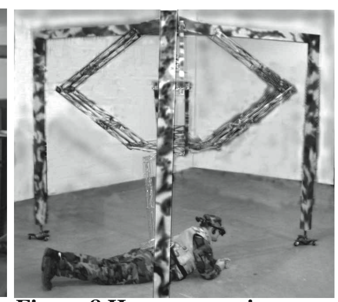


Figure 8 Harness user in prone position.

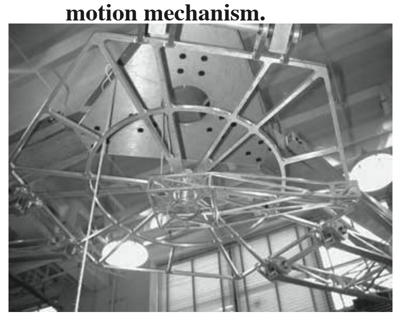


Figure 9 Aluminum center hub mechanism details.

4 INTERIM TEST BEDS

While we were developing a more robust go-prone system, we delivered a series of test-bed prototype mechanisms to the NRL which would allow motions such as walking or jogging in place, rapidly turning, bending the upper body to peek around corners, etcetera. These interim devices also allowed us to experiment with various levels of compliance and "springiness" to determine what was necessary to allow the immersed user to feel free to move as naturally as possible and still keep them centered in the field of view of the VR camera system. These devices were a great improvement over the older harness systems but they didn't allow kneeling or dropping to a prone position. One of these interim harness systems is shown here. It used a pivoted slider system that was biased to the center by a pair of independently adjustable "bungee" cords. This allowed independent control of the stiffness of the system in the fore and aft direction. In this way, a user could lean back into the harness, say to fire overhead, and feel secure. Alternatively, the user

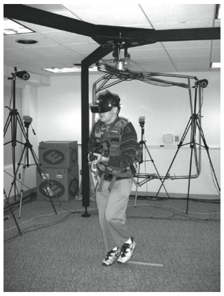


Figure 10 "Pringle" harness with sliding compliance system.

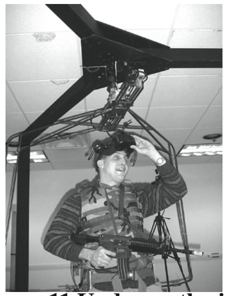


Figure 11 Underneath view of "Pringle" harness.

Figure 12 Overhead sliding compliance system with independently tunable fore and aft compliance.

could jog in place feeling a reassuring tug holding him or her centered and giving a fairly natural substitute sense of actually running in the virtual environment. A "pringle"- shaped tubular steel frame coupled to a set of adjustable length swinging control arms gave ample clearance for the user to move about in the harness without interfering with his or her arms or a weapon or other object he or she might be holding. The arms allowed vertical jogging motions to occur easily without impact on the rest of the system. Quick-release pins allowed rapid adjustment to accommodate different users.

5 INTERIM GO-PRONE TEST BEDS

Engineering is an iterative process. A number of unique go-prone systems were designed in the process of sifting through perceived requirements to find out what was really necessary in a deployable system. We experimented with many trade-offs such as cost, complexity, performance, portability, reliability, and stiffness. Packaging considerations played a large role, since the harness needed to

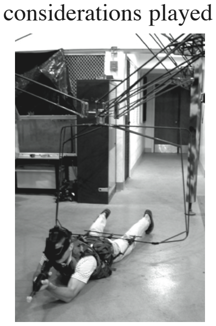


Figure 13 Early "Sarrus style" harness in prone position.

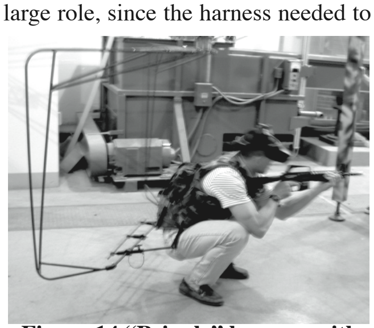


Figure 14 "Pringle" harness with uncoupled small perturbation spatial linkage on belt.

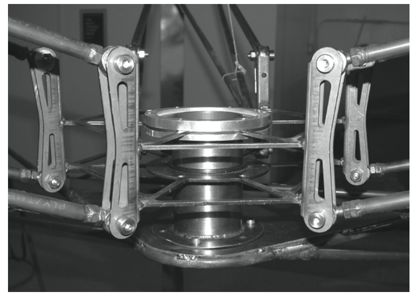


Figure 15 Primary vertical motion spatial mechanism is deliberately overconstrained for light weight and stiffness.

Figure 16 Compliant steel "Pringle" harness.

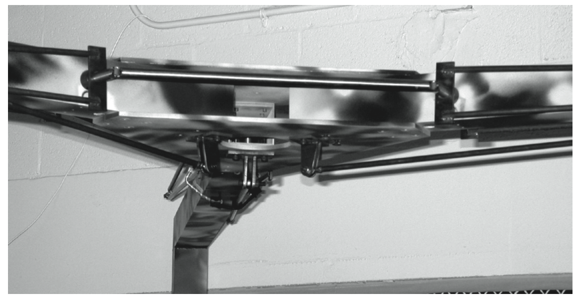


Figure 17 Overconstrained spatial loop of Hooke joints which provides supplementary stiffness and synchronization for the three 120º "Sarrus style" arms.

fit in a small space such as a classroom or on shipboard and it still needed to provide an unobstructed field of view for the sensors. It was also important to minimize chances for the user to collide with the hardware or head mount cables while immersed and swinging a weapon or other object. Each device taught us a great deal and played an important role in learning what the optimum solution would be. Many of our favorite ideas needed to be surgically and ruthlessly eliminated in the search for a simple, rugged, cheap solution. Here are some of the noteworthy yet abandoned prototypes we built:

Figures 13 through 17 show a first-generation steel go-prone configuration. It used three lightweight tubular arm pairs in a "stacked" vertical configuration to provide stiffness to the central pivot shown in Figure 15. These arms were synchronized by a unique closed-loop of six Cardan or Hooke joints as shown in Figure 17. This highly overconstrained spatial mechanism deliberately violated almost all traditional rules for mechanism design by effectively utilizing redundant force paths flowing through the strained flexing members to create a stable, lightweight central pivot platform. This pivot-carrying platform could be subjected to fairly high sideways loads from the immersed user while still moving up and down in a substantially straight-line vertical motion.

A need to lower the overhead clearance requirements to obtain more headroom and still fit within an 8' room height constraint led to the "folded" follow-on configuration shown in Figures 18 through 22. It used a vertical motion system that "tucked" into itself in the raised position, thereby saving about six inches of vertical height. This spatial linkage doubled up on the lateral supports expanding on the earlier concept of utilizing redundant force paths to provide still more stiffness while maintaining a light weight, low inertia configuration.

Figures 18 and 21 show an implementation that used a light weight laser-cut box truss welded up from chrome-molly steel as the central arm that coupled the user to the overhead linkage. This provided strength coupled with lightness and made the rotational

Figure 18 Laser-cut welded steel box arm harness.

Figure 19 Welded tubular chrome-molly arm harness.

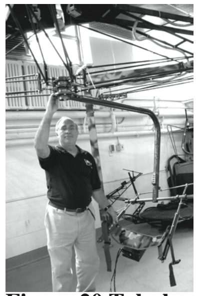


Figure 20 Tubular steel arm harness.

Figure 21 Laser-cut welded chrome-molly steel box arm harness.

Figure 22 Composite graphite arm, pivot and counterbalance components.

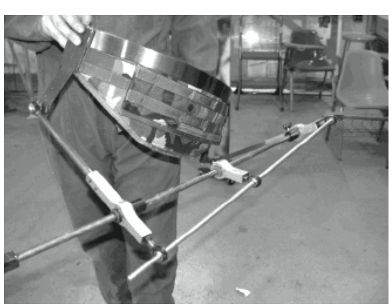
inertia experienced by the user a minimum.

A stiffer cheaper configuration that was far easier to fabricate is shown in Figures 19 and 20. This used a chrome-molly tubular arm that provided far better sideways strength at a minimal increase in weight. (Numerous other carbon/graphite composite arm configurations were also tried. Getting the right “feel” proved to be a difficult task of juggling springiness, strength, weight, and geometry.) In fact, none of the early systems really provided quite the right stiffness and restraint. Too much restraint felt unnatural and too little restraint allowed the user to get off-center and into a configuration similar to “gimbal lock”.

In the next version of the harness, the chrome-molly steel arm was eliminated. It was replaced by a strong but lightweight carbon fiber composite tubular arm. Part of this arm is partially shown in Figure 22. This detail also shows the central pivot with the slip rings mounted inside, the “double deck” central portion of the straight-line vertical motion mechanism, the constant force counterbalance springs, and quick release pins which allowed the system to be easily disassembled for moving.

A subtle point that the casual observer might not notice is that the overall vertical motion system needs to move up and down only when the average height of the user’s hips changes. It shouldn’t bounce up and down trying to respond to small vertical perturbations encountered in walking or jogging in place. A unique spatial linkage was designed for this task. One early version of this synchronization linkage is shown in Figure 23. This linkage utilizes nine links (one flexing), five ball joints, three sliding cylindrical joints, and three rotational joints to provide exactly the necessary degrees-of-freedom needed to perform its task without jamming. (One degree-of-freedom is passive.) Two of the ball joints couple the system to a flexing leaf spring on a belt/backpack system worn by the user and are ergonomically mounted so as to be approximately aligned with the user’s hip joints.

Figure 23 Vertical motion synchronization linkage.



All of these prototype harness mechanisms were built in the lab with a custom engineered overall three-legged frame. However they were designed in such a way that this stationary frame could be eliminated when used in a permanent installation. The central stationary harness member was designed to be ceiling mounted, thereby freeing up sight lines for the cameras or sensors, eliminating interference with a rifle or other weapon, adding to the overall stiffness of the entire system, and reducing costs in a production system.

6 A GENERAL SYNTHESIS APPROACH TO DESIGNING FULL-BODY VIRTUAL REALITY HARNESS MECHANISMS

One could generalize the design of virtual reality harnesses by breaking the overall system down into a set of needed subsystems. The needed subsystems are:

- A frame subsystem
- A pivot subsystem
- A cable management subsystem
- A vertical motion subsystem
- A centering adjustment subsystem
- A compliance subsystem
- A support arm subsystem
- A human restraint subsystem

All of these subsystems must work in unison for the purpose of constraining the user within the volumetric field of view of the cameras or sensors while permitting a wide range of body motions

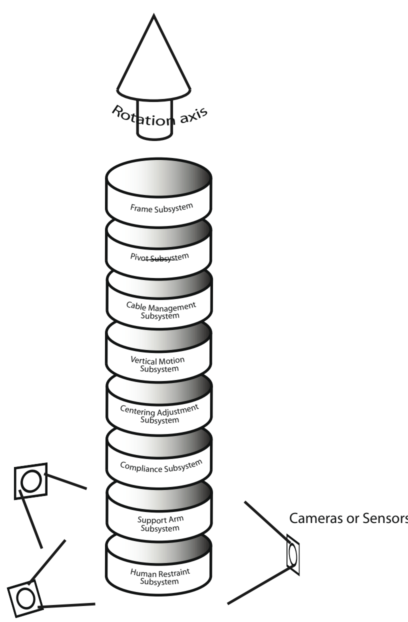


Figure 24 Different conceptual harness embodiments can be created by varying the stacking order of the component subsystems.

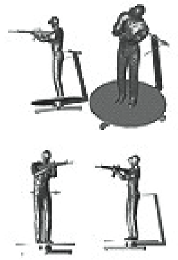


Figure 25 Inverted harness without kneeling or go-prone capabilities.

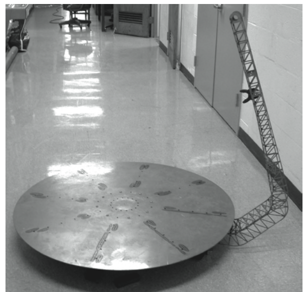


Figure 26 Prototype low cost inverted harness.

such as were described earlier. They must constrain the user to remain substantially aligned with a central axis. At the same time, the overall device must be cost effective, rugged, and practical. Ideally it should work in a transparent, unobtrusive fashion. It should be invisible to the immersed user, providing no spurious dynamic or static loads to the user but being able to apply significant loads in the direction of pedagogically useful force cues. In other words, it should be an invisible demon, doing the impossible in a marvelous fashion.

Contemplating this set of subsystems for four or five years while standing in the shower or lying awake all night one soon realizes that a whole family of topologically distinct devices can be realized by stacking these elements in different orders or by distributing their functions across multiple levels in the structure. For instance, Figure 24 shows one such theoretical topological embodiment of a potential harness. Different permutations of the subsystems will result in different unique embodiments for consideration. Also, one can consider leaving off some subsystems in certain applications or adding others to the stack for added features.

7 LOW-COST INVERTED HARNESS SYSTEMS

Figure 27 Inverted small harness.

Figure 28 Inverted small harness in kneeling position.

Figure 29 Inverted small harness showing synchronization linkage above the straight line four-bar.

Figure 30 Immersed user in inverted small harness.

If go-prone capability isn't required, a small, low-cost low-profile harness system could be created. To do this one would invert the stacking order of the subsystems and abandon the unused vertical motion subsystem. This would result in a system comparable in size to some of the small "pod" systems currently commercially available for VR but with greater freedom of motion and unlimited rotational capabilities due to the slip rings. The user would stand on a circular platform with the arm pivoted around a central column. The slip rings would also surround that column. Figure 25 is a sketch of such a system and Figure 26 shows the prototype we built when it was still under construction.

Figure 31 Inverted full "go-prone" system with a single composite strut arm.

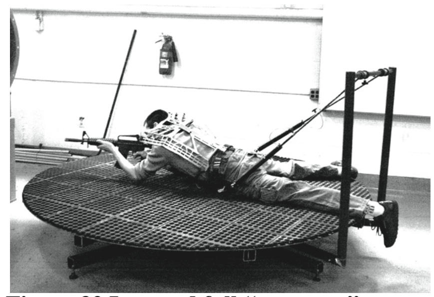


Figure 32 Inverted full "go-prone" system with a dual composite carbon fiber arm.

8 INVERTED HARNESS SYSTEMS WITH KNEELING CAPABILITY

By adding an approximate straight-line vertical motion four-bar linkage to the preceding structure we created a small inverted system which allows kneeling or standing, turning, jogging in place, squatting, etcetera. This configuration also utilizes a unique synchronization mechanism similar in principle to that shown in Figure 23. This is needed to prevent small independent vertical hip motions from driving the overall vertical motion four-bar. It makes the system more responsive and less ponderous. Light, laser-cut chrome-molly weldments are used for the truss-like four-bar links to keep the reflected inertias felt by the user to a minimum. There is also a set of compliant plungers within the swinging arms that provides the desired springiness as the user tugs against the harness

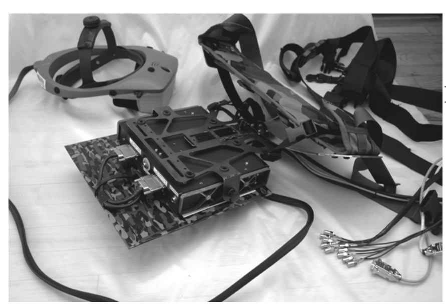


Figure 33 Backpack carries low voltage display electronics and provides flexural bracing for the harness.

while jogging. Figures 27 through 30 show this system in use.

A highly desirable feature of the inverted harness systems is that there is absolutely no overhead hardware. There is unlimited clearance for the head mount or for objects such as rifles that the immersed user might hold. There is also nothing to interfere with the virtual reality camera system's sight lines.

Figure 34 Latest dual arm inverted system offers full go-prone capability, superior centering control, minimal inertia, and strength.

Figure 35 A common backpack system is used in all the new harness systems. It resists inertial effects during sudden motions, acting like an exoskeleton mechanically supporting and stabilizing the harness on the user.

Figure 36 The backpack also provides a calibrated mounting surface for the vision marker system and a case for the headmount video and audio electronics whose high bandwidth signals are transmitted through the slip rings.

Figure 37 Latest dual diagonal arm overhead harness system offers full go-prone capability, strength, minimal inertia, and superior centering control.

Figure 38 Integrated backpack is part of the cable management, compliance, and human restraint subsystems.

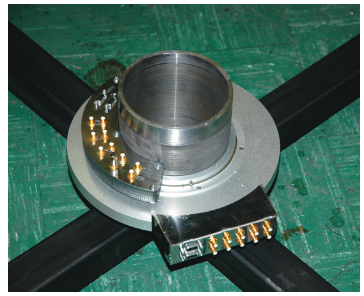


Figure 39 Slip ring system in inverted pod harness system.

Figure 40 Slip ring system in overhead pivot harness system.

Figure 41 Rigid surfaces on the backpack components provide reference locations for the VR markers for the torso and pelvis.

Figure 42 Immersed user can tug against flexural hip supports to enhance simulation of running in place.

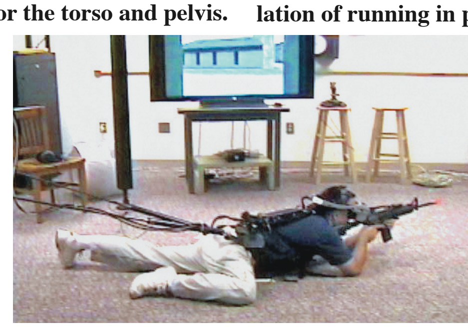


Figure 43 Immersed Army Ranger using the new overhead harness in the NRL's Gaiter Lab.

9 FULL "GO PRONE" INVERTED HARNESS SYTEMS—THE LATEST GENERATION

By using a large disk base and a new vertical motion concept we created an inverted system that permits full go-prone capability and with no overhead obstructions. This system has gone through several iterations, the latest of which are shown in Figures 31 through 34. These mechanisms accomplish the approximate straight-line vertical motion needed for "go-prone" motion by making use of long radius swinging arms. By carefully choosing proportions, the vertical arcs described by the pair of swinging arms is a close-enough approximation to a vertical straight line chord of the arc to make it "good enough for government work" since human users (our main clients!) aren't sensitive to such small discrepencies.

Figures 32 and 34 show the most recent system that we are ready to deliver to the Warfighter Human System Integration Laboratory (WHSIL) at the NRL. It incorporates a new backpack system (Figures 33, 35 and 36) which carries the markers for the cameras and which provides better control for the harness through the use of leaf springs and ergonomically designed straps. It also provides a covered mount for the head mount display electronics needed to carry the high bandwidth signals through the slip rings. Another feature of this latest inverted pedestal system is that rotational inertia effects have been minimized through redesign of the swinging arms and the horizontal compliance subsystem. Carbon fiber tubes have been added for stiffness coupled with low rotational inertia. This extra rigidity helps to center the user and to avoid possible "gimbal lock".

10 THE LATEST GENERATION GO-PRONE OVERHEAD HAR- NESS SYSTEMS

The most recent system we delivered to the Gaiter lab at NRL is shown in Figures 37 through 43. It offers powerful capabilities that they never had before and has stood up well during extensive experiments with test subjects since May, 2006. It utilizes diagonal composite carbon fiber arms for strength and minimal rotational inertia. It also incorporates the long radius vertical motion system used in the latest large inverted go-prone harness. In a permanent installation it could be ceiling mounted, lowering production costs and freeing up sight lines for the camera system.

11 SUMMARY

One of the hardest tasks in engineering is giving up your neatest, most ingenious ideas in deference to simpler, cheaper, more practical concepts. The earlier harness systems developed during this investigation utilized intriguing, innovative linkages and clever concepts such as uncoupling the rotational and translational inertias. The final systems threw away most of that complexity and resulted in rugged, practical, inexpensive configurations. Incremental improvements will continue to improve these devices but they have already reached a level suited to many VR applications such as the training of the military or first responders or for high-end arcade use. They might also be employed in other human-computer interactions or situations such as biomechanical studies. A provisional international patent application has been submitted covering the inventions described in this paper.

The purpose of this paper was to provide a case study of the development of a family of new full body virtual reality harness systems which were tailored to the unique needs of the VIRTE program of the Office of Naval Research. None of the devices described in this paper has been previously published in the technical literature.

The author recognizes that a great deal of prior work has been done by other researchers on harness mechanisms for other applications. Due to space limitations no effort has been made to discuss harness systems which lacked the features required by this ONR project. Many of the existing harness devices are extremely ingenious but they are not pertinent to the present investigation. In some cases they are intended for use with alternative simulation technologies such as caves. In other cases they involve expensive servocontrol systems, motorized floors, skates, omni directional treadmills, robotic devices, and other technologies better suited to use in the lab than on shipboard. In contrast, the devices described herein are purely passive and can be deployed in a relatively small confined area.

None of the previously existing harness systems offered the combination of elements required for a low-cost simulator that could be deployed in the fleet for training Marines in close-quarter combat. Most systems lacked the capability to provide simulation fidelity in gestural locomotion activities such as running, twisting, and turning in place.

A fundamental law of physics shows it is impossible to reproduce the dynamic loads experienced by a moving user in a static device. The best one can hope to do is provide subtle force cues that imply the dynamic effects that would be experienced in reality. Slippery floors or moving supports of the types employed in some other harness technologies provide an unrealistic sense of trying to stand or move on an ice skating rink and are a distraction from the training task being simulated. The mere act of standing up or moving in a simulator should not be a distraction or a task requiring training!

Existing systems also lacked the range of motion required to simulate actions such as dropping to the knees, squatting, or dropping to a prone position while simultaneously constraining the user to a small training volume within the field of view of the cameras and compact enough to fit within the confines of a compartment on shipboard. These motions by an immersed user can produce incredible loads on the harness system. Ruggedizing the harness so as to withstand those loads comes at a cost in terms of rotational inertia and "simulator claustrophobia" on the part of the user. Over constraining users feels unnatural and limits their ability to perform important training tasks. Under constraining users allows them to leave the field of view of the cameras and to get into configurations of "gimble lock". Force cues are easily overlooked if one is in the heat of a simulated battle! A satisfactory compromise must be chosen even though it seems there is an impossible set of trade-offs to satisfy and no happy medium.

Cost and reliability considerations were also important, since the goal was to develop a system that could be deployed in the fleet and used for realistically training Marines who are deeply immersed in a battle simulation and not concerned with the breakability of the harness in which they are confined. Ideally, the harness should be "invisible" and simply be a natural and unobtrusive part of their battle gear. All training should be directed to the simulated task and not to an artificial skill such as learning to use the simulator. That type of misdirected learning to "be gentle with the computer equipment" could be counterproductive and dangerous once the user was out of the simulator and confronted with a real battle situation requiring aggresive action.

This investigator was primarily involved in the design and construction of the mechanical hardware. The Gaiter lab and the WHSIL lab at the Naval Research Laboratory are working extensively with the hardware and performing the user studies which will validate the utility of the hardware. The results of those studies will no doubt be published by those investigators. Since this author is not involved in those studies, some of which are classified, and is not privy to those results, no effort was made to cover that aspect of this work in the limited space allotted for this paper.

12 ACKNOWLEDGMENTS

The author would like to express his appreciation to Dr. Jim Templeman of the NRL for his many ideas and support of this project and to Mr. Carl Behnke, of The George Washington University's Mechanical and Aerospace Engineering Department, for his invaluable help with the construction of these devices. He is also appreciative of the support of this work through the VIRTE (Virtual Technologies and Environments) Future Manpower Capability Program of the Office of Naval Research, grant number N00014-04-1-0068, and by the NRL through contract number N00173-05-P-0983.

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