Virtual Locomotion Concepts and Metrics Study: Experimentation and Results

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ABSTRACT

The U.S. Army Research Laboratory Simulation and Training Technology Center has been performing research in the field of virtual locomotion for multiple years with the main goal of finding the most naturalistic virtual locomotion design. This paper extends the results of a previous study which categorized and defined virtual locomotion technologies for use in immersive dismounted training into an experimentation phase. For the live experimentation baseline, a live Military Operations in Urban Training facility was used. At this facility, data were collected to support metrics provided in the previous study. In order to collect this data, site instrumentation and measurement apparatus were installed for a baseline system reference experiment. For position and accuracy measurements, the instrumentation included a surveyed path with time, space, position indicator sensors and other devices (live video). For fatigue measurement, a heart monitor was used to measure rate before and after the course was exercised. Using this live reference as a baseline, a subset of the key categories defined from the previous virtual locomotion technology study were tested, compared and contrasted to the absolute measurements and metrics collected. The virtual locomotion technology experiments were performed in a controlled indoor facility over a course which technically matches the live experiment. Desktop gaming systems and hybrid capture techniques were chosen as the virtual locomotion systems categories to compare to the baseline. This paper discusses the experimental set-up of each case, the metrics and measurements used to compare and contrast the systems, the results of the experiments, lessons learned, and a summary of results.

KEYWORDS

Dismounted Soldier, Locomotion, Mission Rehearsal, Virtual Environment, Immersion

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INTRODUCTION

Locomotion is defined as "the act or power of moving from place to place". Natural human locomotion is the self-propelled movement of a person through the real world, typically performed on foot (Templeman, Denbrook and Sibert, 1999). When associated with a Virtual Environment (VE), such as those for military training and commercial retail video games, the term is referred to as 'virtual locomotion'. Virtual locomotion is described as a control technique for allowing a person to move in a natural way over long distances in the VE, while remaining within a relatively small physical space (Templeman, Denbrook and Sibert, 1999). Virtual locomotion should also closely mimic natural human locomotion as realistically as possible. This idea has been the main goal of researchers for many, many years, yet still a viable virtual locomotion system has not been developed.

The U.S. Army Research Laboratory's Simulation and Training Technology Center (STTC) has been researching and developing virtual locomotion concepts and prototypes with the main goal of finding a naturalistic virtual locomotion controller. The ideal virtual locomotion system must be as close to live human locomotion, natural and intuitive so that the presence of immersion is not broken. In a previous paper (Roberts, Saffold and Garrity, 2010), researchers reviewed multiple locomotion concepts and systems that have been developed by multiple companies and agencies. In this paper, the results of a live locomotion versus virtual locomotion experiment will be discussed. For the live experimentation baseline, a live training facility was used. At this facility, data was collected on the sets of locomotion metrics provided in the previous study (Roberts, Saffold and Garrity, 2010). To collect these metrics, site instrumentation and measurement apparatus were used to form a baseline for the experiments. For position and accuracy measurements, the instrumentation would include a surveyed path with time, space, position indicator sensors and other devices (live video). For fatigue measurement, a heart monitor was used to measure rate before and after the course was exercised on a minimum of five trials. From there, three virtual locomotion devices from main virtual locomotion categories defined in the previous study were tested, compared and contrasted to the absolute measurements and metrics taken. A desktop gaming system with two controller variations (mouse/keyboard and joystick), and a hybrid capture system were chosen as the virtual locomotion systems to compare to the baseline. This paper discusses the experimental set-up of each case, the metrics and measurements used to compare and contrast the systems, the implementation plan for procedural data collection, the data acquisition system(s), and analysis of the experiments and results.

BACKGROUND

The STTC has been performing work in the area of virtual locomotion for several years, researching various virtual locomotion systems for use in dismounted Soldier virtual locomotion. In 2010, a study was performed to research past and current virtual locomotion systems that have been designed and developed to allow an avatar to perform virtual locomotion. The researchers wanted to define the true key pieces that are necessary in developing a realistic and natural virtual locomotion system; including all the different motion gestures a real human requires to perform natural human locomotion. In addition, the researchers wanted to define, categorize, apply metrics and summarize the multiple virtual locomotion concepts that had been researched. The study covers multiple concepts for virtual locomotion systems, but does not choose a "perfect" system as different applications require different solutions. Each system was defined, researched, categorized by type of locomotion concept and summarized based off of the information that was gathered for each system. Metrics were also developed and implemented to help define the specifications of each system. Three virtual locomotion controllers were chosen for an experiment to see which system provided the most naturalistic representation of live locomotion in a virtual environment.

METRICS

The metrics focused on were derived to help meet the research goals. The metrics used in the live/virtual locomotion experiment were presented in the 2010 paper (Roberts, Saffold, and Garrity, 2010) as (a) Cost, (b) Accuracy, (c) Mission Time and Effectiveness, (d) Latency, (e) Installation, (f) Portability, (g) Human Factors, and (h) Fatigue. Each of these metrics are described from a computational standpoint later in the paper.

MOTION GESTURES

Motion gestures consist of all the different poses and movements a human must perform to achieve locomotion. Any virtual locomotion must also account for the many types of motion postures and movements required to successfully navigate through and around solids and obstacles placed in the virtual environment. A realistic, human-like virtual locomotion system should contain a capability to allow for each of the following types of poses and movements: scanning and steering, walking, jogging, running, sprinting, turning, jumping, climbing, crouching, crawling and swimming (note swimming was not used in this study as the researchers were only interested in human locomotion performed on land). The following figure illustrates these motion gestures.

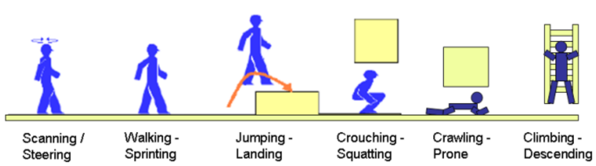

Figure 1. Motion Gestures and Modes

TEST COURSES

The live instrumented test course was designed to test all forms of motion gestures at a Military Operations in Urban Training (MOUT) facility. The course introduced seven motion gestures to be performed at various locations throughout the live course. Cameras were used to track all areas of the course indoors and outside while the subjects performed the various motion gestures. The course required users to acquire a total of five targets. Three of these targets were to be acquired only with a simple query - did the subject see or not see the target? Two targets required the subject to acquire the target and also to scan, steer and shoot the target. The subject was not scored on the accuracy of the shot, but a simple query as to whether they did or they did not shoot at the target.

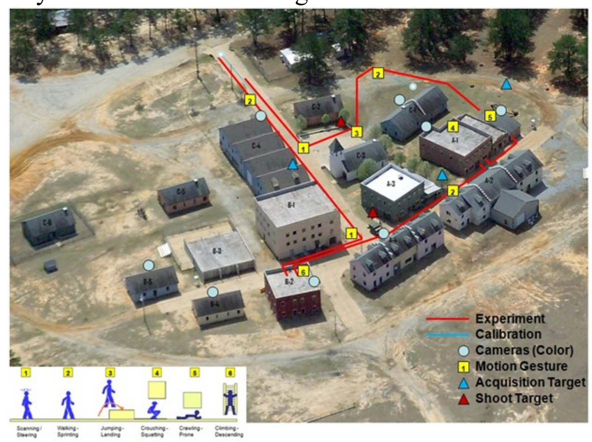

Figure 2. Live Locomotion Test Course Overview

Some general statistics on the course are summarized here. The total course length (main trials) was approximately 956 feet and contained over 150 discrete waypoint markers. The course included the following key stressors and characteristics:

- 2 stairways
- 1 Prone/Crawl Space
- 1 Crouch Space
- 1 Ladder
- 2 Shoot Locations (Acquire in unburdened trials)
- 3 Additional Acquire Locations
- 20 turn points
- Grass and Concrete Movement Surfaces
- 15 Camera Points (including 3 handhelds)
- 956 Feet – total course length

Figure 3. Virtual Representation of Locomotion Course

In addition to the live locomotion test course, an existing virtual representation of the test course was used in a game engine environment. The virtual locomotion course is designed to realistically represent the live course in a virtual environment, allowing subjects to traverse the same course in both the live and virtual environments.

The virtual representation, while technically correct, did not specifically match the live location dimensionally. To account for these dimensional differences, the extreme case was used to match the waypoint distances between the live and virtual courses to allow valid speed metric calculations. Comparisons of the differences in total course length between the live and virtual implementations are summarized below.

Table 1. Comparison of Course Statistics

Description	Live	Virtual	Notes
Total Course Length	956 Feet	1534 Feet	Scale differences related to game "unit" of measure and routes setup
Number of Waypoints	150	155	The live course missed a few around the church area

All speed and time calculations for the virtual trials were appropriately scaled with the live course to allow data to be directly compared in the analysis.

CATEGORIZATION AND CONCEPTS

While reviewing the published information on virtual locomotion concepts a need for categorization emerged; there were so many different locomotion systems and concepts and many with only small variations from others. In the study, an initial set of categories were proposed but by no means were meant to fully encapsulate the novelty of any particular approach. In this section, the specific controller categories used in the metrics computations are described.

Desktop

The desktop category had to be included as the basic interface for humans to navigate and pose in virtual environments. This is the standard interface for gamers and can include a combination of common human interface devices (mouse, keyboard, joystick, gamepad) for moving and interacting with the virtual environment. Desktop controllers can use mice and keyboards to perform locomotion. Most commercial gaming systems include either a single pole joystick with buttons or a double pole joystick with multiple buttons. The double pole allows one pole for translation and one for rotation of the avatar.

Figure 4. Desktop/Mouse Controller

The main limitation of desktop systems is typically the subject is seated playing the game, their feet would not be moving or helping to perform locomotion in any way. Joysticks and buttons are still used in most First Person Shooter action games to perform all of the actions of the avatar which is unrealistic in matching human locomotion. Joysticks and buttons also provide users with tools and methods that compensate for motion gestures and poses not directly measured form the human subject (such as jumping, crouching, crawling, scanning, etc). These are put into games for fun, but these "aides" do not exist in the real world.

Figure 5. Desktop/Joystick (Gamepad) Controller

Commercial gaming companies may also increase the range of the weapon or the kill radius which may be different for actual combat weapons. Most games include "negative training aspects" such as having access to weapons that do not exist in the real world, joysticks and buttons that allow you to perform actions that do not exist in the real world or increased physics allowing you to run faster, jump higher or longer, etc…(Roberts, Saffold and Garrity, 2010). These actions are quite different between desktop training games and actual combat training.

Hybrid Capture/Controller Systems

A hybrid capture/controller system is one that uses a variety of different methods to allow a user to perform virtual locomotion. Many of these hybrid systems use partial sensors, partial meaning on one leg, thigh, or foot, with a combination of joysticks and buttons to perform locomotion. These systems do not create a large amount of fatigue as most users use joysticks with a desktop system, but usually wear dismounted Soldier man-wearable suits so they can stand up as they would in natural human locomotion. The limitations on human locomotion with hybrid systems are that many still use joysticks and buttons to perform translational locomotion without using their feet or hands as they would in the real world. This type of navigation/locomotion control interface can also encumber the maneuverability of Soldiers during critical combat tasks such as looking around corners, moving through buildings and stacking on walls (Lane, Marshall and Roberts, 2006). Because a Soldier's decision-making focus is taken off of the scenario to artificially engage a simulation button, there are tasks introduced that are not present in actual combat (Marshall, H., Garrity, P. et. al., 2008). The buttons and joysticks bring in negative training aspects as they are new devices added to a weapon for training that are not on the Soldier's weapon during battle.

Figure 6. Hybrid Controller

The other issue with Hybrid Capture/Controller Systems is that most trainees have a limited amount of space available for them to train in (Sibert, L.E., Templeman, J.N. and Page, R.P., 2004). A person must be able to move naturally through the VE while, in fact, remaining within the bounded physical space of the tracking system. Therefore many of the locomotion systems are tied to the fact that the trainee has to stay within the tracking area of the system while performing virtual locomotion. Due to the fact that there is limited area to perform locomotion, a trainee may have to perform a "proxied" style of interaction to perform in the real world which is then translated into realistic locomotion while in the VE.

RESULTS

In this section the results for each metric are summarized across the comparative subjects between the live and virtual trials along with the data acquisition systems used for both the live and virtual tests. The same subjects (two male and one female) were exposed to common stressors under the live and virtual conditions. Subject 3 was a male with a four year background in Army infantry and airborne with a workout regimen of 10 minutes per day with little to no gaming experience. Subject 5 was a female secretary with an exercise regimen of walking 30 minutes, twice weekly with no gaming experience. Subject 6 was a software developer with an exercise regimen of working out 3-4 days a week and has extensive commercial gaming experience, but no military training. In all trials both burdened (with a weapon in hand) and unburdened (nothing to carry) modes were performed. The data for each metric are illustrated along with the controller mode used.

Cost

The specific cost of additional equipment necessary for human locomotion in a virtual environment was compared. Since a virtual environment requires a basic computer with peripherals as a host, a generic cost of a modern computer with display and mouse/keyboard of $2000 was presumed and not included as an "additional cost" for the locomotion controller. Cost factors were based on a proportional cost (*Pcost*) of the baseline computer system. Controllers costing less that this baseline were given the lowest cost rating. In each controller case the *Pcost* rating was also provided which is simply a ratio of the additional controller cost to the baseline computer system. The results related to this metric across all controllers and live baseline are summarized in the following table.

Table 2. Cost Metric Summary

Controller	Rating	Pcost
Live	1	0
Desktop / Mouse	1	0
Desktop / Joystick (Gamepad)	1	0
Hybrid	5	25

Accuracy – Locomotion

The virtual course included both real-time display markers and Game Distributed Interactive System (GDIS) software that outputted a variety of information on the "player" in real-time with an update rate of 0.030 seconds and a precision of 3 decimal places. Accuracy was computed as the deviation from the marked path in cross range at each waypoint marker. The average value for each statistic across all subjects was taken. Since the live data offsets were collected with a direction sign, this data was converted to magnitude before summarizing here.

The results related to this metric across all controllers and live baseline are summarized in the following tables.

Table 3. Accuracy/Locomotion - Unburdened

Accuracy Metric	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Mean (ft)	0.26	1.65	1.79	
Median (ft)	0.02	0.98	1.22	
Variance (ft)	0.73	1.94	1.84	
Max (ft)	5.87	12.44	11.47	
Min (ft)	0.00	0.04	0.10	
RMS Accuracy (ft)	0.73	1.94	1.84	

Table 4. Accuracy/Locomotion – Burdened

Accuracy Metric	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Mean (ft)	0.17	1.80	1.93	2.22
Median (ft)	0.00	1.03	1.26	1.45
Variance (ft)	0.54	2.15	1.97	1.95
Max (ft)	4.03	14.85	11.70	9.45
Min (ft)	0.00	0.08	0.04	0.05
RMS Accuracy (ft)	0.54	2.15	1.97	1.95

Locomotion accuracy was very good for the live course as well as the desktop mouse variations. Subjects using joystick based locomotion systems often overcompensated turns and maneuvers producing a "sine wave" type effect as shown in Figure 7.

Accuracy – Acquisition

During acquisition points the subject is required to scan and steer according to the course target locations which in general were to the sides of the main path. For the live and virtual tests acquisition accuracy was assessed on a simple "did I look or shoot while moving" or "was I unable to look or shoot while moving".

The results related to this metric across all controllers and live baseline are summarized in tables 5 and 6. The average value for each statistic across all subjects was taken. Since the original data were yes/no, this information was converted to equivalent 1/0. As with all metrics like this, missed items due to subject forgetting instructions were not included in the summary data.

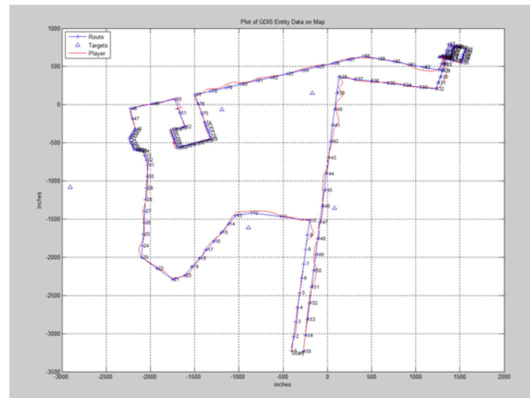

Figure 7. Sine-Wave Effect - Subject 6 Unburdened (Desktop/Joystick)

Table 5. Accuracy/Acquisition - Unburdened

Target	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Shoot 1	1	1	1	
Acquistion 1	1	0.5	1	
Acquistion 2	1	0.5	1	
Shoot 2	1	1	1	
Acquistion 3	1	1	0.5	

Table 6. Accuracy/Acquisition - Burdened

Target	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Shoot 1	1	0.5	1	0
Acquistion 1	1	1	0.5	0.5
Acquistion 2	1	0.5	0.5	0
Shoot 2	1	1	1	0.5
Acquistion 3	1	1	1	0.5

Mission/Waypoint Time and Speed

At key waypoints the time difference (speed) was measured to ensure the subject was completing the course with all best effort and this speed should represent key samples of the different linear motion types (walk, run, sprint, crouch walk, prone).

The results related to this metric across all controllers and live baseline are summarized in the following tables. The average value for each statistic across all subjects was taken. The mean speed was based on waypoint reached time differences. The average speed indicated used the total course time. The additional course length associated with scaling of the virtual environment to the live environment is included in the virtual controller results.

Table 7. Speed - Unburdened

Speed Metric	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Mean (ft/sec)	5.40	7.51	7.34	
Median (ft/sec)	5.40	8.91	8.93	
Standard Dev (ft/sec)	1.99	2.52	2.76	
Time to Complete (sec)	175.67	235.89	262.73	
Average Speed (ft/sec)	5.61	6.64	6.05	

Table 8. Speed - Burdened

Speed Metric	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Mean (ft/sec)	5.41	7.39	7.17	5.52
Median (ft/sec)	5.53	8.73	8.77	5.69
Standard Dev (ft/sec)	1.97	2.58	2.79	2.92
Time to Complete (sec)	179.65	237.87	291.89	325.03
Average Speed (ft/sec)	5.43	6.57	5.54	4.94

The speed results were interesting in that for desktop systems there seemed to be little intermediate speeds between stop and run. This is due to the inability of the controller to support the range of speeds available to a live human. The lack of fatigue using this controller also allowed the subjects to move through the entire course without slowing down or resting. The following figure illustrates this phenomenon on Subject 3.

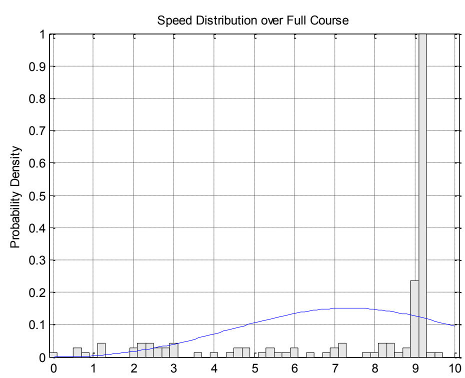

Figure 8. Subject 3 - Unburdened Speed (Desktop/Mouse)

The team noted that the hybrid controller speed control (joystick on the gun) prevented doing an unburdened trial. It was also noted that while the joystick included acceleration proportional to the deflection of the stick, most subjects did not use that feature on the course.

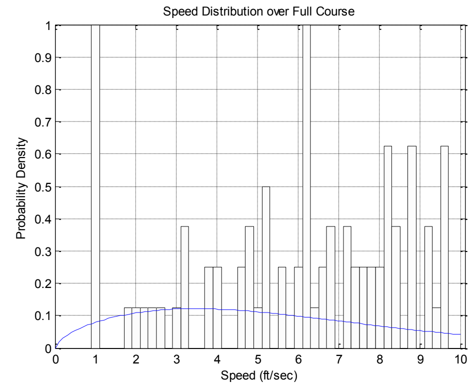

Figure 9. Subject 3 - Unburdened Speed (Live)

Latency

For the virtual tests, the latency relates to the time delay between pressing a controller option and the perceived effect of motion. This is also impacted by the sample rate of the data collection software in GDIS with the additional latency of video presentation updates (frame rate) to the user and of course the time it takes for the human brain to process the video data. For the data acquisition and display systems, the latency was fixed to about 30 frames per second or < 0.030 seconds update rate from the time the motion was performed to the time the motion written to the data acquisition file. For the live trials, latency only related to the frame rate of the data capture system. In both tests, the latency associated with brain command to muscle reaction time was neglected as it was very small compared to the data acquisition systems. The results related to this metric across all controllers and live baseline are summarized in the following table.

Table 9. Latency Summary

Controller	Latency (ms)
Live	< 30
Desktop / Mouse	< 30
Desktop / Joystick (Gamepad)	< 30
Hybrid	< 30

Installation

For the virtual tests different levels of human subject installation was needed other than wearing a heart rate monitor (watch and chest strap) which was not specific to locomotion. The typical time to install these devices was estimated from time to start install to ready to run experiment on each subject. The results related to this metric across all controllers and live baseline as summarized in the following table.

Table 10. Installation Summary

Controller	Rating	Time (min)
Live	1	0
Desktop / Mouse	1	0
Desktop / Joystick (Gamepad)	1	0
Hybrid	2	5

Portability

Similar to the installation metric the subjects wore a heart rate monitor (watch and chest strap) in addition to any equipment needed to achieve locomotion. The heart rate monitor added less than one pound of weight and provided no observed stiction or hindrance of motion. Portability was estimated based on subject after action reviews and overall size and weight of the controller relative to fitting into a carry-on luggage container. The results related to this metric across all controllers and live baseline as summarized in the following table.

Table 11. Portability Summary

Controller	Rating
Live	1
Desktop / Mouse	1
Desktop / Joystick (Gamepad)	1
Hybrid	3

Human Factors

Human factors questionnaires were completed by the subjects for each locomotion controller (live and virtual). Since human factors are subjective, the results for each controller are presented as discussed in the body of the report for the virtual locomotion controllers only. Comments with a "(#)" tag at the end indicate the number of subjects with the same comment on the controller.

Desktop/Mouse

The following were positive comments made on the controller:

- The controller was very easy to use. There were not many controls to operate
- The mouse made tight corners easy to navigate
- The mouse was easy for fine view control as well as quick turns

The following were negative comments or improvement suggestions made on the controller:

- The "X" button for prone I didn't like because I had to tap it twice for engagement and disengagement (aka didn't hold it down like crouch button)
- Using the "A" [strafe] button [to scan/steer] was difficult to do
- A useful feature would be speed control (2)

Desktop/Joystick

The following were positive comments made on the controller:

- The controller was very easy to use with simple instructions (3)
- The joystick was more familiar than the mouse and reminded me of a Playstation controller
- Analog movement control and all controls on a single device

The following were negative comments or improvement suggestions made on the controller:

- The right thumb button operated more slowly than the mouse
- The joysticks were very sensitive [making it difficult to control]
- It was difficult to walk and look [with two joysticks at the same time]
- Turning was a hassle due to the sensitivity of the joystick (2)
- Dynamic sensitivity [speed control] on the move stick would be useful for quick turns with fine control

Hybrid

The following were positive comments made on the controller:

- The system was very easy to operate and let me utilize more of my body to locomote (2)
- I liked using my head to turn and look (2)

The following were negative comments or improvement suggestions made on the controller:

- The joystick was not consistent and I would have to trouble shoot it several times to get it working (2)
- The joystick was difficult to push and the vest extremely heavy (2).
- It was difficult to go to the prone gesture [due to inconsistent thigh pad sensing] and also with the gun and helmet on (2)

Motion Gestures

Each motion gesture was included at least once in the live course and the metric was generally assessed according to "can do it" or "cannot do it" criteria based on a difficulty scale of 1 – 5 where 5 is the highest difficulty and 1 was the lowest difficultly.

The results related to this metric (rating) across all controllers and live baseline are summarized in the following table. The average value for each gesture across all subjects was taken. Samples that were simply missed due to subject forgetting to perform the gesture were not included in the average.

Table 12. Motion Gesture Summary - Unburdened

Gesture	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Scanning/Steering	1.00	3.67	3.00	
Walking – Sprinting	1.00	1.00	1.00	
Jumping – Landing	1.17	1.00	1.00	
Crouching	1.00	1.00	1.00	
Crawling	1.17	1.00	1.00	
Climbing	1.67	1.33	1.33	

Table 13. Motion Gesture Summary – Burdened

Gesture	Live	Desktop / Mouse	Desktop / Joystick	Hybrid
Scanning/Steering	1.00	3.67	3.33	3.67
Walking – Sprinting	1.00	1.00	1.00	2.00
Jumping – Landing	1.25	1.00	1.00	2.00
Crouching	1.00	1.00	1.00	2.00
Crawling	1.25	1.00	1.00	4.00
Climbing	1.75	1.33	1.33	2.67

Generally speaking, all three virtual controller configurations tests illustrated difficultly with the scanning and steering maneuver. For the dual joystick (gamepad) controller the user was required to manipulate the move joystick sideways while turning the look/weapon angle joystick in the opposite direction. For the mouse controller, the user was required to manipulate the keyboard W, A, S, D (where "W" is move forward, "A" is move left, "S" is move backward and "D" is move right) to strafing sideways while turning the look/weapon angle mouse location at the target of interest. For the hybrid controller, the user was required to manipulate the joystick sideways while turning the head (and or weapon to shoot targets) toward the acquisition target. The hybrid controller was the only one tested which allowed a true scanning and steering implementation (compared to a live subject). The desktop variations essentially rotate the whole body and walk sideways to implement scanning and steering. The course location data clearly showed this difficultly at the key acquisition target points.

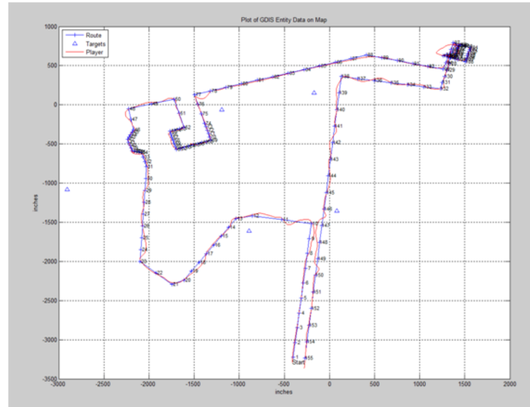

Figure 10. Subject 5 – Unburdened Course Locations (Desktop/Mouse)

Fatigue

Fatigue was measured by comparing the real time heart rate to the Lactose Threshold Heart Rate derived from the live calibration trials and associating those ratios to the Borg scale. The results related to this metric across all controllers and live baseline as summarized in the following tables. The Rating of Perceived Exertion (RPE) levels encompass the range of all subjects in the trials.

Table 14. Fatigue Summary – All Controllers - Unburdened

Controller	RPE	MAX LEVEL
Live	70% - 110%	Very Heavy
Desktop / Mouse	30% - 40%	< Very Light
Desktop / Joystick (Gamepad)	30% - 40%	< Very Light
Hybrid	NA	NA

Table 15. Fatigue Summary – Burdened

Controller	RPE	MAX LEVEL
Live	70% - 110%	Very Heavy
Desktop / Mouse	30% - 40%	< Very Light
Desktop / Joystick (Gamepad)	30% - 40%	< Very Light
Hybrid	30% - 70%	Very Light - Light

In general the fatigue estimates for all the tested virtual controllers did not match the live course data. A typical example is illustrated using the hybrid controller as compared to the live test. The hybrid controller, mostly due to its weight, did cause some spike in RPE when going into the prone and crouch positions. The desktop controller variations indicated little or no exertion over the full course.

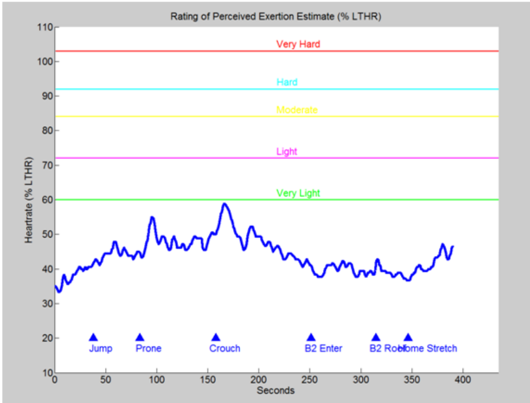

Figure 11. Subject 3 - Burdened RPE (Hybrid)

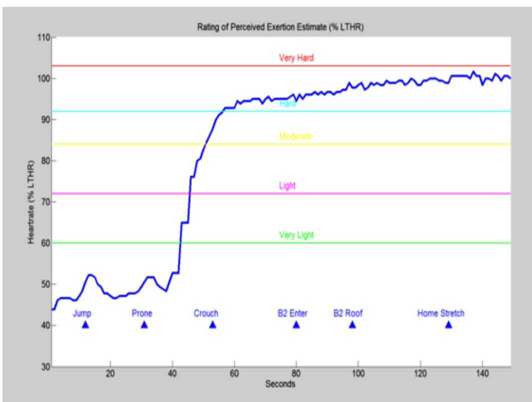

Figure 12. Subject 3 - Burdened RPE (Live)

DATA ACQUISITION SYSTEM DESCRIPTION

This section discusses how the collected data were used to extract quantifiable results for each of the proposed metrics related to locomotion.

For the live tests, strategically positioned cameras providing full course coverage were used to collect video on subjects as they passed surveyed waypoints in the area. This video was analyzed to produce many of the metrics presented.

For the virtual trials data was output from the GDIS on the player every 0.030 seconds after the start of the experiment and continued to do so until the operator stopped the experiment scenario. Scenario times were also displayed on the Heads Up Display (HUD) along with real-heart rate for each subject during the trials.

Figure 13. HUD Illustrating Heart Rate and Scenario Time (Burdened Trial)

At each data acquisition time sample, a complete set of position, orientation, stance, rate, and state information for players and player components (head, weapon, etc) were output from the GDIS system.

All plots and numerical results generated for this report used this analysis tool.

SUMMARY AND CONCLUSIONS

In this paper, a study of multiple virtual locomotion systems of the past and of the present was extended to live and virtual trials in an attempt to quantify a concise set of metrics which could be used to define a controller's applicability for use in simulating natural human locomotion.

While the trial set presented is too low to draw any broad conclusions, the data indicated a number of trends that should be verified over a statistically valid set of trials, conditions, and controllers. Of course, the utility of a locomotion controller must also be weighed against the specific requirements associated with an application or training exercise. Based on the limited data set, the following key trends were noted:

- Subjects clearly navigated the virtual environment more precisely with a Desktop/Mouse configuration over the other controllers. Conversely said, the joystick controller caused most subjects higher difficultly when making tight turns and trying to enter narrow spaces such as halls, ladders, and doorways. The rollup data did show some inverse bias here based on the limited samples of subjects cutting a lot of corners in the course
- The dual joystick controller was difficult for subjects without console gaming experience
- Subjects had a natural tendency to follow the direction they are looking when wearing a Head Mounted Display which was not true in the real world live tests thus making scanning

and steering very difficult in these configurations

- The hybrid controller implementation allowed no provision for performing unburdened trials since the locomotion controller is embedded in a weapon prop
- A single "bad run" in a limited trial space can tend to bias rollup summaries

REFERENCES

Templeman, J.N., Denbrook, P.S. and Sibert, L.E. (1999), Virtual Locomotion: Walking in Place through Virtual Environments, *Presence, Vol. 8, No. 6,* pgs 598 - 617.

Davis, E., Techgnosis: myth, magic and mysticism in the information age, 1998.

Lane, S. H., Marshall, H. & Roberts, T., "Control Interface for Driving Interactive Characters in Immersive Virtual Environments", *Presented at the 2006 Army Science Conference, November 27-30th, Orlando, FL.*

Templeman, J.N., User Control of Simulated Locomotion, *US Patent 6,646,643, B2, November 11, 2003*

Williamson, B., Wingrave, C. and LaViola, J. J., (2010), RealNav: Exploring Natural User Interfaces for Locomotion in Video Games, *Presented at the 2010 IEEE Virtual Reality Conference, March 20-26, Waltham, MA.*

Marshall, H., Garrity, P., Stahl, J., Dean, F., Green, G., Dolezal, M., Hall, G., Bounker, P., and Mocnik, C., "Embedded Dismounted Simulation – Issues, and the way forward to a field capable embedded training and mission rehearsal system" 2008

Sibert, L. E., Templeman, J. N. and Page, R.C. "Initial Assessment of Human Performance Using the Gaiter Interaction Technique to Control Locomotion in Fully Immersive Virtual Environments", *NRL/FR/5510—04-10,086, July 30, 2004*

Youngblut, C., Johnson, R.E., Nash, S.H., Wienclaw, R.A., and Will, C.A. (1996), Review of Virtual Environment Interface Technology, *(Tech. Rep. No. IDA Paper P-3186, Log: H 96-001239). Alexandria, VA: Institute for Defense Analyses.*

Templeman, J. N., Sibert, L.E. and Page, R. C., "Immersive Simulation to Train Urban Infantry Combat", In *Virtual Media for Military Applications 2004 (pp. 23-1 – 23-16).*

Darken R., Cockayne W., & Carmein D. "The Omni-Directional treadmill: a locomotion device for virtual worlds" *Proc. of UIST'97. pp: 213-222, 1997*

Iwata H., & Fuji T. "Virtual perambulator: a novel interface device for locomotion in virtual environment". *Proc. of IEEE VRAIS'96, pp: 60-65, 1996*

Sibert, Templeman, Page, Denbrook, "Pointman – A Device-Based Control for Realistic Tactical Movement", IEEE Symposium on 3D User Interfaces 2007, March 10 - 11, Charlotte, North Carolina, USA, 1-4244-0907-1/07/$25.00 ©2007 IEEE

Ensor, J. R., Carraro, G. U., "Pelton: A VRML-based bicycling simulator" *In SIGGRAPH'97 Visual Proc., p.198. 1997*

W. Couvillion, R. Lopez, J. Ling, "The Pressure Mat: A New Device for Travering Virtual Environments Using Natural Motion," *Proc. of the Interservice/Industry Training Simulation and Education Conference, pp.199-211, 2001*

T. Roberts, J. Saffold, P. Garrity, "Virtual Locomotion Concepts and Metrics Study," *Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), 2010*