Designing Extreme 3D User Interfaces for Augmented Live Performances

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ABSTRACT

This paper presents a proof-of-concept system that enables the integrated virtual and physical traversal of a space through locomotion, automatic treadmill, and stage based flying system. The automatic treadmill enables the user to walk or run without manual intervention while the flying system enables the user to control their height above the stage using a gesture-based control scheme. The system is showcased through a live performance event that demonstrates the ability to put the actor in active control of the performance. This approach enables a new performance methodology with exciting new options for theatrical storytelling, educational training, and interactive entertainment.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 INTRODUCTION

Three dimensional and spatial user interfaces are generally designed to enable more effective and efficient modes of user operation; however, live performance events offer an interesting and under-explored area of investigation. In typical stage-based performance, the actors react to the technology around them, which means that they need to adjust to the projected scenery or automation effects.

The presented system alters this dynamic to allow performers to directly manipulate their "world" through a novel 3D User Interface. Performers are able to virtually interact with projected media in ways that would not be possible traditionally, such as moving projected media, walking through spaces larger than the physical environment, and interacting with virtual characters. The projections are rendered from the audience's point of view, making it seem as though the projected world and physical world are one and the same. In the presented approach, motion capture technology is integrated with an automation control system to allow performer-initiated stage automation movements. The automation system enables virtual exploration through the modalities of both walking and flying. In the walking modality, the user walks on an interactive treadmill, which determines the users speed and moves the user backwards while the virtual world moves accordingly. In the flying modality, the user is able to control the height above the stage using a gesture-based control scheme. Performer flying effects initiated by predetermined actor movements provide smoother operation during take-off and landing, as well as the opportunity for dynamic control during flight. To ensure the safety of the performers, audience, and crew, all motions are checked by an industrial functional safety system in real time to limit hazardous conditions (i.e., over-speed, collision detection, over-travel).

The major contribution of this paper is the creation of a system that enables virtual world traversal through physical locomotion, an automatic treadmill, and a flying system in a unified space. This integration of technology and a 3D user interface enables the actor to be in control of the entire performance, including the traversal of space, lighting, and sound. The project is demonstrated through a series of proof-of-concept live performances.

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2 RELATED WORK

This work is motivated by three different categories of research: augmented reality live performance events, automatic treadmill systems, and flying-based modes of interaction. As our work is the first to combine these different areas, we will discuss each of these areas individually.

Augmented Reality Performance Events: There is a long history of researchers exploring the combination of live performance and augmented reality. Researchers have developed virtual sets [5], platforms for dance and theater events [1, 15] and the combination of actors and robots [9]. More recently, Marner et al. presented *Half Real*, which demonstrated a theater production that featured projected environments, actor tracking, and audience interactivity [8]. Lee et al. have have also demonstrated projection-based augmented reality for dynamic objects in live performance events [7]. While the motivation for the presented work is similar to these projects in the sense that they augment the stage performance, the presented work's aim is to enable new modes of stage based interaction.

Automatic Treadmill Systems: Methods for automatic treadmills have been tested for a variety of systems including training and rehabilitation [17]. This has also been integrated into virtual environments in which the world moves around the user [3, 10, 18]. Unfortunately, these previous systems used specialized equipment and tracking mechanisms that are not suitable for live performance events. Fortunately, Kim et al. recently demonstrated that while consumer-grade tracking sensors had significantly worse precision and sampling rates compared to professional motion capture systems, when controlling an interactive treadmill system, the resulting performance remained unchanged [6]. The authors also suggested that the Microsoft Kinect V2 may help to improve the robustness of the tracking algorithms. This work demonstrated the feasibility of this selected approach for an interactive treadmill system.

Flying Systems: Flying systems have been demonstrated in both live entertainment and simulated environments. The most dramatic uses of stage automation have generally been seen in high-end productions of performance events such as *Le Reve: Diving the Dream*, at the Wynn Casino in Las Vegas. While the concept of flying is common to virtual world interaction, it is generally only applied to virtual world traversal while subjects are rooted on the ground in the physical world [13]. A few examples that remove this constraint include a suspended swimming system shown by [4], an instrumented table based flying system [12] and a virtual skydiving simulator [2]. We note that these previous approaches have all been very tailored to a single action. For example, the skydiving system proposed by [2] could not be used to traverse the virtual world by walking. Combining these modalities together poses unique challenges for system designers. The proposed approach utilizes concepts from stage-based automation alongside the concepts from user interface design and augmented and virtual reality to develop a new and unique interface modality.

3 System Hardware

The system was constructed using both physical and digital components. The stage environment was approximately 7.5 meters wide by 3.6 meters deep. The projection screen was 6.1 meters wide and 4.2 meters tall. Two WUXGA projectors were used to project on the rearside of the projection screen, creating an image that was 2052x1920 in resolution. Two HD projectors were used to project on the floor as well, mounted directly above stage center at a height of 5.4 meters while the second projector, also mounted 5.4 meters high, was positioned approximately 3.0 meters between the stage center. Based on the suggestions of [6], an array of Microsoft Kinect v2 sensors were used to determine the position and gestures of the actor on stage. These sensors enabled the actor to be in costume, as opposed to using external trackers while at the same time providing the needed level of tracking fidelity. As the Kinect sensor works best when the user faces the device, one device was positioned on house right (the right side of the stage from the audience's point of view), 3.8 meters right of stage center and one was positioned stage down, 3.8 meters between the audience and stage center. The Kinect sensors were hidden from view of the audience using custom built podiums. Two computer nodes were responsible for acquiring data from the Kinect devices. Using the Kinect SDK, each joint position and confidence value were sent to the Application and Automation Control nodes via UDP protocol.

The *Automation Control Node* was responsible for controlling the stage automation equipment. The node utilized TwinCat, a low latency architecture for controlling external control equipment. The system received input through the Kinect Nodes and the Application Node via UDP transport streams. This data was used to set the user interaction mode, determine the position of actor in order to ensure the proper alignment of the actor, run the treadmill system and determine the height of the actor for the flying system. The Automation Control Node utilized a Beckoff control system to interface with a custom treadmill system. The treadmill system was constructed using a standard treadmill system, 1.6 m long by .7 m long. The treadmill was capable of a maximum of 2.4 m/s linear travel velocity. This velocity was sent to the Application Node in order to coordinate virtual world traversal.

The flying system was created using a stage-based automation hoist system. The actor was custom fitted with a harness to alleviate slack in the system. The flying system used a single connection point placed at the actor's upper back. The hoist was capable of accelerating a 100 kg performer to a speed of 2.9 m/s in 0.75 seconds but we limited the speed to 1.2 m/s for safety reasons.

The *Theater Control Node* was used to control the lighting and sound for the performance event. To enable the ease of integration, the Open Sound Protocol was used to send packets to the MAX/MSP programming language. These packets were parsed into lighting- and sound-based events with sound events being routed to the QLab application. The Theater Control Node interfaced with the lighting and sound equipment through a Motu 828 mkII audio interface. The sound system consisted of two EV Sx300 loudspeakers and one EV 12 sub-woofer. The lighting equipment utilized an ETC Element console to control arrays of the ETC Source 4 ERS and Par lighting instruments.

The Application Node was used to manage all virtual interactions and projections. One of the node's responsibilities was to maintain the state of the story and subsequent user interaction mode, as described in Section 4. This information was forwarded to the Automation Node in order to maintain the correct user interaction paradigm. The Application Node was also responsible for the coordination of the multiple Kinect devices into an integrated virtual model of the actor.

The Unity game engine was used to build all virtual world content and interactions. Asymmetric viewing frustums were used with the center of projection put in the middle of audience to create the illusion that virtual and projected were intertwined. To minimize the offset from this center of projection and the audience members, the audience was arranged using stadium seating with the width of of the rows approximately equal to that of stage.

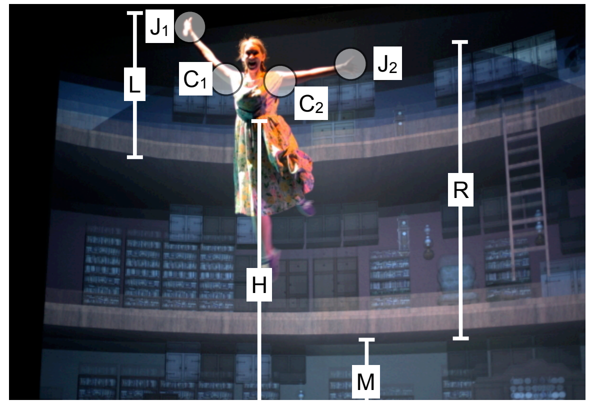

Figure 1: The actor is able to control the physical flying height using a gesture-based control scheme. The tracked joints and positions from Equation 1 are labeled.

4 User Interaction

The developed system supported three different types of user interactions in a single environment. Each of these methods combined physical actions with virtual projected effects. These methods are further described below.

Flying: The flying system enabled the actor to control their physical height above stage as shown in Figure 1. The height of the actor was controlled using a common proportional control scheme. The target height for the actor was determined by the Application Node, which considered both the actor's gesture and virtual world state. Gestures were designed in a similar approach as shown in [16]. This information was then sent to the Automation Control Node via a UDP network stream. The Automation Control node then translated these desired height values into commands for the hoist system. The proportional control scheme was designed as:

$$P = K_p\left(\sum_{i=0}^{n}\left(\frac{J_i - C_i + L}{2Ln}\right)R + M\right) - H) \tag{1}$$

where K_p is the proportional gain, n is the number of tracking joints, J_i is the height of the joint position, C_i is the height of the comparison joint, L is the maximum length of travel of the joint, R is the maximum range of flight, M is the minimum flying height, and H is the height of the center of mass for the tracked individual as show in Figure 1.

For the purposes of the project, we analyzed the position of the hands above the shoulder resulting in two joints being tracked, with the left and right side being compared individually and the length of the arm being approximated by the length between the shoulder joint and hip joint when standing. Through empirical testing, it was found that K_p was set to 0.2 m/s. The values for R and M were altered depending on the flying mode as described below.

The takeoff action posed a potential hazardous situation for the user. If the user was not properly aligned under the hoist system, the user could be swung side-to-side like a pendulum. To ensure the user was in the correct space, the system ensured that the user was within a 0.5 m radius to the hoist location. When lifted, the actor was pulled into the air at 1.2 m/s, and the system was switched to flying mode.

In the flying mode, the user could control their height, as described above. In order to ensure the user was in a safe space, the height of the user was constrained between 3.5m and 2.2 m meters above the stage. Additionally, the actor's position relative to the center hoist location was also monitored in order to ensure the actor did not drift side-to-side. If problems were to occur, the system would stop all movement.

To get the actor safely back to the ground, the velocity of movement was first reduced from 1.2 m/s to 0.8 m/s. Next, the range of flight R and the minimum height above the stage M was eased to zero over the course of a 15 second window. This enabled the actor to either control the time of their landing through their gestures or to simply maintain a pose and have the system land them on the ground automatically.

Walking: The treadmill was used to support the use of walking interactions as shown in Figure 2. The treadmill was controlled using a simple proportional control scheme:

$$V = K_p(C - P) \tag{2}$$

where V is the treadmill velocity, C is the tracked center position at which no movement should occur, P is the current tracked position from the Kinect system of the shoulder center, K_p is the proportional gain. Through initial testing, it was found that a proportional gain value of 0.35 m/s enabled a user to walk, jog and run. To prevent the system from inadvertently triggering, if $(C - P) < 15mm$, the value was set to 0. While the treadmill was able to operate bidirectionally, due to the length of the device, it was decided to only operate in a single direction. The treadmill velocity value V was sent back to the Application Node in order to interface with the virtual environment.

Free Stage Interaction: The system was also built to enable the user to move around freely in the stage environment. The challenge of this setup was to support this type of interaction while enabling the flying mode (and to a lesser degree, the walking mode) of interaction. The harness system needed to support the user as she traversed the stage environment, thus releasing the cord as the user moved farther away from stage center so as to not impede movement; however, putting too much slack on the line created a dangerous situation when the user was to be transitioned into flying mode. In order to support this mode, the system constantly monitored the actor's position on stage, releasing slack given a triangulated position. This method also monitored the height of the user, enabling the user to sit, stand, and jump in an unimpeded fashion.

The amount of line to release L was determined by:

$$L = \|H - P\| + D \tag{3}$$

where H is the position of the pulley system, P is the position of the actor, and D is the distance from the hoist system to the pulley as shown in Figure 3.

Safety Considerations: Several systems were put in place to ensure the safety of the actor in accordance with the guidelines of

Figure 2: Shows the actor traversing the virtual scenery using the automatic treadmill system.

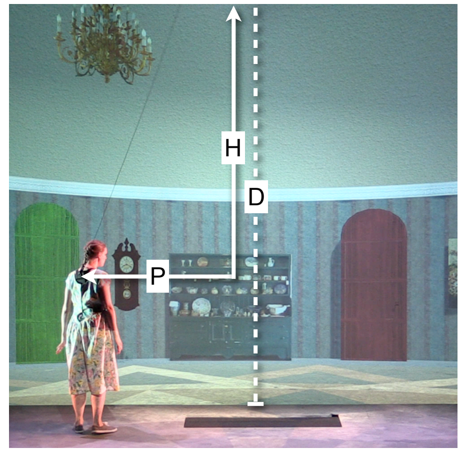

Figure 3: Shows the method for controlling the length of cable while the actor moves around freely on the stage. The position of the actor P, position of pulley system H, and distance from the pulley to the hoist system, D, are used as shown in Equation 3

[14]. Specifically, All equipment was constructed, tested, and monitored by professionals in the field of flying entertainment. For the system to be active, an external operator needed to press and hold a system enable button to enable the rapid termination of many potentially dangerous situations and prevented the system from triggering accidentally. The actor's position was tracked on stage with only certain regions enabling the system to be active and all values were verified to be within system limits before they were applied to the system.

5 Results

As the major goal of this work is to put the actor in control of the entire performance, we created a proof-of-concept performance event based on the book *Alice's Adventures in Wonderland* by Charles Lutwidge Dodgson under the pseudonym Lewis Carroll. This story motivated the need for the unconventional user interfaces and projected display environments. As the performance was meant to be a proof-of-concept piece, only the first three chapters of the book were used. However, this story content was able to sufficiently motivate the types of virtual world interactions described in Section 4 including walking, flying, falling, growing, shrinking and grabbing and pushing virtual objects.

The performance piece was formally shown six times over a two-month period to nearly 300 individuals. Audience reaction to the project was overwhelmingly positive. As word of mouth spread, later shows were entirely sold out. Audience suggestions included the reduction of noise for the treadmill system, the enabling of horizontal flying movement, and the ability for audience participation (e.g., enabling the audience to create virtual objects in the scene). No actors, staff, or crew had any injuries during either a performance or rehearsal for the event. The actors felt confident enough in both the flying and treadmill systems to play with speeds and test the boundaries of the system. Issues with the gesture tracking during live performance events were infrequent and inconsequential to the overall performance. The emergency safety procedures were also never triggered outside of times when they were explicitly being tested. While the absence of accidents does not prove that the system is safe, it does help to show the system is behaving properly.

Unfortunately, deep analysis of the system is not a straight forward endeavor [1] and given the fitted harness system tailored for each of the two actors, a formal user evaluation was not informative. However, many other forms of evaluation demonstrated the success of the system. The latency of the tracked system was determined using a similar approach to that shown in [7, 11]. An actor held their arms to their side while a projected representation of their arm was shown behind them with the entire sequence recorded. For each movement of the arms, the number of video frames was counted until the projected arm position reached the same state repeated 10 times. The resulting mean latency for a single Kinect system to demonstrate change on screen was found to be 164 ms with a standard deviation of 16 ms with the resulting mean latency for creating the virtual model of the actor found to be 248 ms with a standard deviation of 35 ms. To measure the latency of the flying system, the actor maintained a stable flying position, then changed her arm position and measured the time until the actor's body position was also changed. This process was repeated 10 times. The resulting latency was found to be 344 ms with a standard deviation of 125 ms.

Measuring latency of the treadmill system proved to be most difficult of the three different interaction paradigms, as it was difficult to determine the exact point at which movement should occur. Measuring the latency from the lifting of foot in the first step of walking until the treadmill's first movement was shown to produce a mean latency of 204 ms with a standard deviation of 98 ms. It was found that the mean latency for the backdrop to move from the lifting of the foot was slightly longer at 227 ms with a standard deviation of 119 ms.

We also measured the quality of the alignment of the treadmill system and the virtual world by analyzing the difference between projected virtual markers and physical markers on the treadmill. It was found that when the actor walked on the treadmill at a speed of 1.6 m/s, an average error of 26% with a standard deviation of 10% occurred. We believe this was due to the belt slipping with the weight of the actor on the walking space, thus creating movement that was not accounted for. Future iterations of this project will compensate for these offsets.

6 Discussion

While reducing latency values is generally considered to be positive for 3D user interfaces, this may not be the case for mechanical systems, such as those described in this paper. For these systems, the trade-off between smoothness and responsiveness has ramifications beyond user perception as mechanical devices such as motors can not instantaneously change performance characteristics. In this regard, we feel that the demonstrated latencies are quite acceptable as they are similar to other systems which use similar technology [7, 11] and note that the actors did not have issues interfacing with the system.

While the Kinect system was capable of tracking multiple individuals, the system was designed for a single user, meaning these features were not utilized. Future work will explore adding multiple users and utilizing other interface modalities such as speech. Finally, as the performance was created as a proof-of-concept several items could be refrained in order in mask the underlying technology. For instance, to mask the sound of the treadmill, background audio was used while targeted lighting was used to help hide the sight of the wire. Both of these techniques could be further improved through the use of high-end custom professional grade technology that was beyond the scope of this project.

7 Conclusion

This project demonstrates a proof-of-concept system for the support of flying, walking, and physical locomotion interfaces in a unified environment showcased through a live performance event. This approach enables a new performance methodology with exciting new options for theatrical storytelling, educational training, and interactive entertainment. Future work will explore simulating other types of virtual world interactions, augmenting the actor's abilities for jumping and creating a training environment for theater events.

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