Indoor Skydiving in Immersive Virtual Reality with Embedded Storytelling

Horst Eidenberger*, Annette Mossel†
Interactive Media Systems Group, Vienna University of Technology, Austria

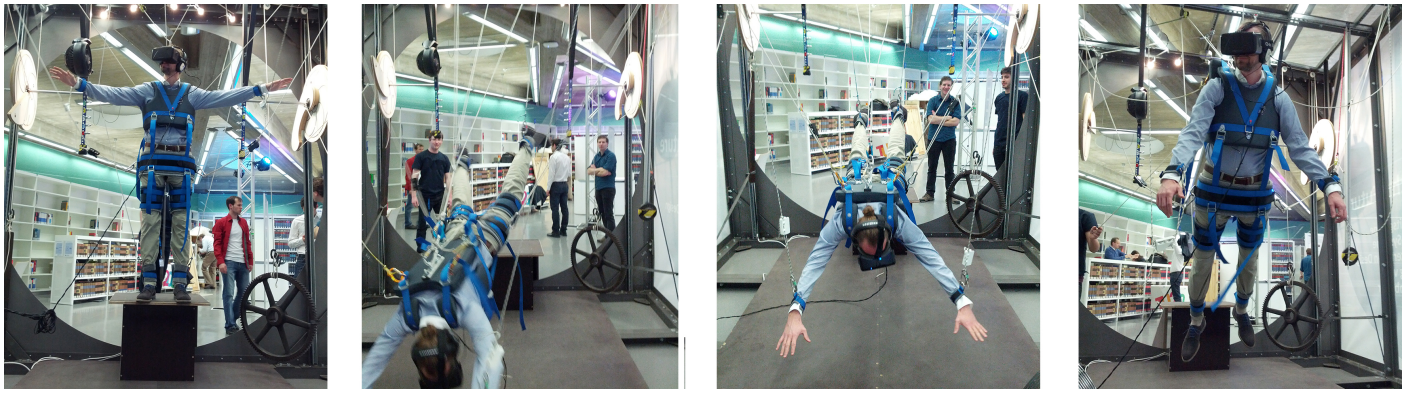


Figure 1: *Indoor skydiving with the Virtual Jump Simulator.*

Abstract

We describe the Virtual Jump Simulator, which allows subjects to perform an indoor parachute jump in a virtual environment. The necessity to jump physically off a platform combined with immersive virtual reality and tactile feedback creates an experience with a high amount of presence, as the evaluation of the prototype confirms. The system consists of a steel cube, a mechanical absorber system with stacked eccentric wheels and counterweights that allows subjects in the weight range from 35 to 150kg to jump without the need for individual calibration, a virtual reality setup with high-quality 3D content and tactile stimuli. In the immersive virtual jump experience, we embed a story using rich multimedia content, such as images and sound. We iteratively tested the entire system with users of different backgrounds. Thereby, we gathered user feedback from the very beginning to create a novel virtual reality system that allows for actual physical jumping and flying with free body movement.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

Keywords: Immersive Virtual Reality, Hybrid Physical Digital Installation, Model of Interactivity, Entertainment

*e-mail:hme@ims.tuwien.ac.at
†e-mail:mossel@ims.tuwien.ac.at

1 Introduction

The Virtual Jump Simulator (VJS) is an installation that allows the user to perform a parachute jump in a safe environment just one meter above the ground. The illusion is created by a physical jump off a ramp, stabilization in a horizontal flight position during free fall, mechanical simulation of the opening parachute, and virtual reality (VR) as well as audiovisual content for embedded story telling. The different jump phases are illustrated in Figure 1. The installation as well as the embedded story spans an umbrella over the 200 years of history of the Vienna University of Technology (1815-2015, in German: *TU Wien*). This contextualization is achieved by 1) associating the trajectory of the jump through the virtual content with the time axis of the university's history and tell the story of the university's evolution by media objects (e.g. sound, images) that cross the path of the jumper, and 2) by combining state of the art VR hardware with a mechanical system that could – at least, in theory – already have been built in 1815. The installation consists of a number of components – described in the consecutive chapters. It is important to note that the particular character of the VJS comes largely from the interlock between the mechanical hardware, the immersive VR setup and the high-quality 3D content. The hardware alone without VR it would hardly have constituted a hot medium in McLuhan's sense and would not be as exciting without the VR setup and the content. Nor could the VR setup or the content alone create the "highly emotional experience," as it was described by almost all users. The presented system can be employed to enable novel ways of first responder training, it can be used for interactive edutainment and tourism.

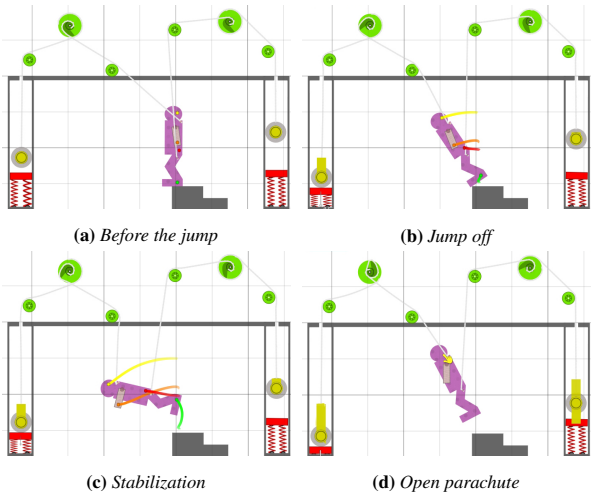
A variety of research has been done in the past to investigate physical body movements in VR, ranging from omni directional treadmills, bicycle simulators, flying or floating platforms. The Virtual Swimming interface [Fels et al. 2005] is a locomotion device that allows the users to physically perform swimming gestures while being hold in a horizontal body position, and Birdly [Rheiner 2014], an installation for virtual bird flight come closest. However, both environments do not allow the user to perform a jump from high altitudes – with the jump being real, allowing a wider field of possible simulations and training. Humphrey II [Ars-Electronica-Center 1998] is also a related project that – like Birdly – allowed the user to fly through a 3D world. However, this world showed hardly

any interesting virtual artifacts. Furthermore, the hardware used for flotation created a latency that limited the experience considerably. Eventually, vertical wind tunnels allow the user to perform jumps from relatively high altitudes (up to 15 meters). A semi-immersive system has been presented in [Kitchen and Bird 1997] that provides a vertical air chamber combined with a video projection. To our best knowledge, there are no truly immersive VR installations in theme parks available that employ stereoscopic viewing with a head mounted display combined with the intended sensations. We are aware of multi-user screen-based installations that are combined with haptic and/or force feedback (i.e. rollercoaster ride). However, these installations lack the dynamics that are at the core of the VJS experience. Up till now, no projects have been demonstrated that match to the functionality and experience of VJS, providing physical jumping and free body movement combined with high quality 3D visualization.

To summarize, the main contributions of the presented VJS are 1) A novel system for immersive Virtual Reality that allows physical jumping and subsequent free body movement in air that can be used as the fundamental component for a wide range of immersive simulations, 2) A flexible mechanical absorber system that does not require calibration of body weights. This is achieved by a novel jump suit and by introducing eccentric absorber discs that can be programmed in stacks in order to solve almost arbitrary impulse problems.

2 Setup & Requirements

The virtual jump is – like a real parachute jump – a sequence of phases. We explain the choreography in this chapter and derive the requirements from the general picture, which leads us to the major components, here visualized in form of the floor plan of the physical appearance, the jump cube. Before the accurate 3D CAD simulation, a simplified 2D physcial simulation was done in Algodoo [da Silva et al. 2014].



(a) *Before the jump* **(b)** *Jump off* **(c)** *Stabilization* **(d)** *Open parachute*

Figure 2: *The mechanical absorber system during the jump. The green disks, roller bearings and the counterweights represent a simplified version of the real setup. The tracers visualize the movement of certain points during the jump process.*

Figure 2 shows keyframes of this simulation, the green discs indicate the eccentric discs for impulse absorption, the colored points along the body of the jumper indicate its rotation. The actual jump is the major adrenalin kick of the installation since the fall is real and visualized in the virtual environment as a jump out of the plane. After that, the mechanical system absorbs the jump energy and stabilizes the jumper in horizontal position. In the horizontal position the user is able to move the body quite freely – in fact, an experienced user is even able to stand up. During the free fall phase, the actual story of the jump is told and additional special effects create unexpected (tactile) sensations. The opening of the parachute is performed manually with the aid of the safety rope, a double redundant steel rope (as required by norm [German-Standardization-Institute 2012]), connected to an independent counterweight. Since the safety rope does not contribute to jump and absorption, it is tailor-made for setting the jumper into vertical position. In the vertical position, the last elements of the story are presented before the jumper flies over the virtual city and lands in the university's main building by lowering the security ropes. From the phases of the virtual jump, we can derive the major requirements of the project:

- The installation has to be *visually perceivable* safe. There is only little time in before the jump during the configuration phase to build up the confidence of the jumper. As soon as the VR equipment is mounted, the jumper is outside the physical reality.
- The second requirement is to provide a thrilling story that is stringent and keeps up the excitement during the horizontal flight (in comparison to the highly exciting jump).
- Eventually, the installation has to be robust and the design has to be appealing.

2.1 Bearing Structures

The bearing structures consist of the jump cube, the jump suit and the start ramp. The jump cube was implemented as a 3x3x3m steel structure, as shown in Figure 1. The requirements for the jump suit were that it had to (1) be as comfortable as possible both in horizontal and vertical position, (2) absorb part of the shock of the jump as well as the opening of the parachute, (3) be designed visibly safe and (4) are suitable for varying body types. Testing existing belts for industrial climbers, parachute jumpers, pilots and rally drivers as well as bullet-proof jackets proved that none of these systems could fulfill all requirements.

Hence, we developed with our project partners a tailored-made jump suit depicted in Figure 1. It consists of elements for breast, hips, thighs, wrists and ankles. All elements are connected by straps so that the entire suit can be put on by simply pulling the breast element over the head and fastening the straps. Furthermore, it allows to serve for a wide range of varying body types (from 35 to 150kg).

2.2 Mechanical System

This section describes all moving parts of the virtual jump simulator that are required to stabilize the user after the jump in horizontal position, to maximize the flexibility of movement during the flight, to simulate the opening parachute and stabilize the jumper vertically and, eventually, to land her in virtu-physical reality. The starting points of the mechanical system are karabiner hooks at the ends of the ropes that connect to the eyelets of the jump suit. We employ high quality sailing (Dyneema 6mm ropes) and mountaineering equipment (Mammut karabiner) for this purpose. The requirement for the mechanical system are:

1. The mechanism should be independent of the weight of the jumper in a range from 35 to 150kg.
2. Like the bearing structures, the mechanical system has to be visually safe. We provide the redundant steel cables requested

by the standard [German-Standardization-Institute 2012].

3. The jump and the flight experience have to be pleasant. Therefore, the absorption process – independent of the weight – has to be smooth and progressive. During horizontal flight, the position of arms and legs has to be supported in a way that restricts free movement of the extremities as little as possible.

The majority of these requirements is met by a stack of eccentric absorber discs, as shown in Figure 3 where a test setup made of wood is illustrated. The final discs are sandwiches of laser-cut steel discs. As the figure shows, the minimum configuration consists of two discs mounted together. One disc is connected to the jump suit, the other to the counterweight. The disc runs over a high-quality roller bearing. The fundamental idea of the absorber discs is that while one disc carries a linear force (e.g. the counterweight), the other has the form of a spiral. With the rope starting in the center, it effects that the further the rope is dragged from the disc, the larger the difference in the relative strength of the weights at the ends of the ropes becomes. With no force on the jump belt, the ratio is – in the visualized example – roughly 1:1; with a very heavy test subject it might go down to 1:10 – and in theory to infinity. Practically, this means that the difference in horizontal positioning of two jumpers with 100kg weight difference is – depending on the shape of the discs – just a few centimeters.

Figure 3: *The stack of eccentric absorber discs.*

The configuration requirement is met by stacking absorber discs into arrays and connecting them to one lever (in Figure 3, one is visible in the upper left corner) that are on the other side connected to the ropes that lead to the jump belt. By that, we can create any trajectory of forces required by a certain power curve of human movement. In fact, the disc configuration represents a cybernetic gravity-based analogous computer.

3 Virtual Reality Development

To allow for a fully immersive simulation of a parachute jump, we firstly developed a VR hard- and software prototype. Based on that, the 3D jump application was subsequently implemented.

3.1 Hardware and Software Setup

The VR hardware setup consists of a head mounted display (HMD), two full-body motion capture devices and a headphone set. As HMD, we used the Oculus Rift Development Kit 2 that offers low persistence displays with a $960x1080px$ per eye resolution, $100°$ nominal field-of-view (FOV) and a built-in inertial measurement unit to estimate the user's head orientation. Over USB 2.0 and HDMI 1.4b, the HMD is connected to the workstation, allowing for low-latency tracking and visualization. The Sennheiser HD 201 headphones provide high quality stereo sound. To track the user's full body, two *Microsoft Kinect for Windows* are used that are connected over USB 2.0 to the workstation. Our overall hardware installation requires long cables lengths (approx. $10m$) between the peripheral devices and the workstation. Therefore, we used a $8m$ extension cable with integrated repeater to extend the HMD's $2m$ HMDI cable as well as $8m$ USB extension cables for both Rift and the Kinects. At the current state of implementation, motion capturing is solely employed for visualization purposes. Therefore, the captured data is mapped to a virtual avatar to provide the user with means of self-awareness in the virtual environment. That is, the avatar is a virtual representation of the jumper's body.

The proposed VR hardware setup achieves a high level of immersion by providing egocentric 3D scene viewing with a large FOV and full body motion capturing to animate the virtual avatar interactively. Combined with the sensation of the physical jump, our installation is capable of stereoscopic viewing, 3D sound, tactile stimuli [Dinh et al. 1999] virtual self-awareness, proprioception and vestibular feedback. These factors have been found particularly important [Usoh et al. 1999] to enhance the level of presence, enabling our system to be perceived by the user as highly convincing. For 3D application development, the game engine Unity 3D is used as core technology. By default, it offers powerful 3D rendering, scene authoring, model import and deployment to various platforms, such as Windows, Android and iOS. To provide the required VR support in Unity, we integrated the Oculus Rift Unity plug-in to feed the orientation head tracking to the application and to enable stereoscopic scene viewing. Furthermore, the Unity Asset *Kinect with MS-SDK*[1] was used to provide the motion capturing data to the application. The 3D jump application was developed with the described hard- and software prototype.

We deployed the application on a workstation, running Windows 7 64bit, equipped with a 3,3 GHz quadcore CPU, 8GB RAM and a NVIDIA GeForce GTX 980, featuring 4GB memory. The current hard- and software prototype runs with 40 frames per second, allowing to interactively explore the virtual 3D scene that has an overall size of 120 GB.

3.2 Immersive 3D Jump Application

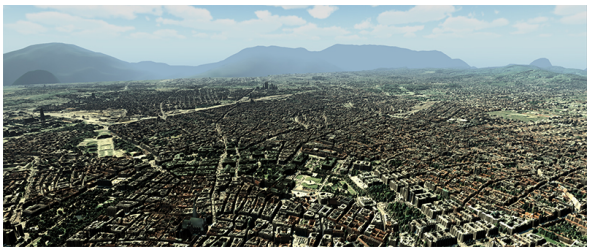
For the implementation of the virtual jump application, it was of major importance to provide a compelling, high-quality rendering of the virtual scene objects, especially of the 3D city model. To achieve this goal, we firstly used a publicly available 3D city model, provided by *Vienna City Map*[2] consisting of 3D models and high-resolution textures. The data was exported to the *raw*-format to prepare it for Unity3D import. Secondly, we used high-quality 3D models of prominent landmarks in *fbx*-format that were made available through Vienna's *Land Surveying Office*[3]. Next, we replaced parts of the 3D city model by adding the high-quality 3D building models to combine the heterogeneous data sources. To reduce the computational burden for scene rendering at run-time, the 3D model was manually edited by removing data that is out-of-sight during the flight. This reduction was strictly necessary to allow for interactive frame rates. Furthermore, we employed several level-of-details (LOD) of the 3D model, with the highest LOD at the area of the virtual landing zone. The virtual jump application was implemented as one 3D scene.

Upon start of the application, the user – standing in an upright physical position – observes the open air plane door and below, the virtual city through its HMD. Multiple fans simulate wind streams of the flying plane. After the physical jump, the virtual free fall starts by changing the avatar's roll orientation and subsequently updating its position. To enhance the level of presence, the fans' revolution is increased to simulate a free fall wind situation. While the user is

[1] http://rfilkov.com/2013/12/16/kinect-with-ms-sdk/
[2] https://www.wien.gv.at/ma41datenviewer/public/
[3] https://www.wien.gv.at/stadtentwicklung/stadtvermessung/

flying towards the city, the large landscape is visualized (see Figure 4) at different LODs, and images and a narrator tell the history of the university. The visualization of these virtual storytelling objects is coupled to the flight trajectory. At a predefined altitude, the landing procedure is initiated by decreasing the free fall speed and the fans' number of revolution. A virtual parachute is opened and the user is manually pulled in a more upright physical position. Finally, the user lands in the university's celebration hall.

(a) *Storytelling during free fall.*



(b) *View before parachute opening.*

Figure 4: *The virtual 3D city model, visualized at different LODs.*

4 Evaluation

The virtual jump simulator was developed by rapid evolutionary prototyping in multiple parallel tracks. Cube and 3D landscape content were provided by sponsors while the mechanical system, story and VR setup were implemented by a hybrid team of computer scientists and mechanical engineers. Evaluation was part of this process from the beginning, thus development was physically test-driven.

One evaluation of paramount importance was early simulation of the physical forces that might occur during the jump. We found out that the maximum force during the jump acts on the roller bearing of the pulley between hip eyelet and the lever of the back absorber. For a person of 150kg a force of up to 1200N can appear. This value formed the starting point for the construction of the jump cube. Later, during physical testing of the acting forces it proved extraordinarily precise. Qualitative user feedback was almost invariant. Test subjects were – in particular after their fist jump – highly excited, which is possibly caused by to the loss of control during the physical jump combined with the high level of presence in the fully immersive VR system. All young and most other subjects showed a tendency to comment on audiovisual and tactile stimuli during the free fall. This might be due to the fact that they could not hear themselves. Oral feedback was highly positive. Almost all subjects liked the general flow of storytelling and in particular expert users were surprised by the quality of the landscaping content. In more than 200 test jumps only one male subject reported slight nausea after the jump. This surprisingly good result may be explained by the low latency of the VR system combined with the short duration of the jump (4:30 minutes). Neither body height, weight nor breast size were experienced as limiting by the test subjects.

5 Conclusions and Outlook

In this paper, we described the novel Virtual Jump Simulator that allows a physical jump within a virtual world and thus, creates a highly immersive environment by combining egocentric stereoscopic scene viewing with proprioception, vestibular, audio and tactile feedback. The most important potential improvements to optimize system performance and subjective jump experience are 1) Incorporate the user's body movement to allow for intuitive flight control, 2) Extended testing by quantitative methods but as well by biosignal analysis (EEG, EMG). The evaluation should serve two purposes: a) Quantitative evaluation for developing the installation into a product and b) Biosignal analysis for understanding precisely when, where and why excitement happens, 3) Use an alternative game engine to support high-quality landscape rendering at high update rates and apply further 3D model reduction. Besides using the installation as a jump simulator, it can be extended into a floatation simulator that allows for movement in air (bird flight), space and deep sea. And, of course, the authors will continue to perform at least one jump per day.

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