Level-Ups: Motorized Stilts that Simulate Stair Steps in Virtual Reality

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ABSTRACT
We present "Level-Ups", computer-controlled stilts that allow virtual reality users to experience walking up and down steps. Each Level-Up unit is a self-contained device worn like a boot. Its main functional element is a vertical actuation mechanism mounted to the bottom of the boot that extends vertically. Unlike traditional solutions that are integrated with locomotion devices, Level-Ups allow users to walk around freely ("real-walking"). We present Level-Ups in a demo environment based on a head-mounted display, optical motion capture, and integrated with two different game engines. In a user study, participants rated the realism of stepping onto objects 6.0 out of 7.0 when wearing Level-Ups compared to 3.5 without.

Author Keywords: Virtual Reality; Real-Walking; Head-Mounted Display.

ACM Classification Keywords: H.5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies, Interaction Styles.

INTRODUCTION
Ever since its conception in the 1960's, head-mounted virtual reality systems have been primarily concerned with the user's visual senses [10] and optionally spatial audio [1]. As the next step towards realism and immersion, however, many researchers argue that such systems should also provide a physical/haptic experience [2].

In this paper, we focus on one particular aspect of the physical experience, which is walking up and down steps and stepping onto objects in the virtual world.

Traditional solutions to stepping up and down build on the concept of a locomotion device, i.e., devices that simulate the experience of walking. These devices keep users in the same overall location, for example, by containing each of the user's feet in a motion platform [9] or by positioning platforms where the user is expected to step next [6]. While locomotion devices are space efficient, some researchers argue that allowing users to walk around freely ("real-walking") covers more of the user's senses [12].

In this paper, we present a device that allows users to experience elevation in real-walking environments.

THE LEVEL-UP MOTORIZED STILTS
Level-Ups are computer-controlled stilts that allow users to physically experience elevation.

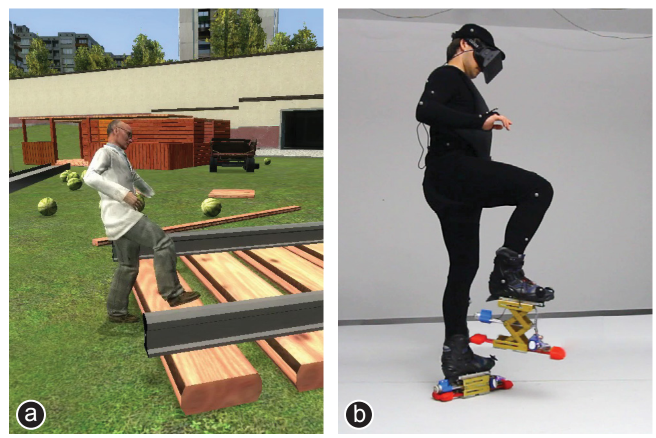

Figure 1: The Level-Up motorized stilts allow users walking in a spatial VR environment to experience physical elevation.

Figure 1 shows the devices in use. (a) The user is walking in a virtual world, here containing rubble and various obstacles (Garry's Mod: garrysmod.com). To get across obstacles, the user has to physically lift his foot and climb across. (b) In the physical reality, we see that the physical elevation is rendered using our Level-Up motorized stilts. These operate in the context of a typical VR environment with the user wearing a head-mounted display (Oculus Rift: oculusvr.com) tracked by an optical motion capture system (OptiTrack: naturalpoint.com).

Figure 2 gives an overview of Level-Ups' hardware design. Every device consists of a boot, mounted onto a lift table, which in turn is mounted onto a simple artificial foot. The lift table is actuated by a motor, which is observed by an encoder and controlled by a microcontroller. The entire unit is self-contained (3 kg) and wireless: via Bluetooth each unit talks to a remote computer system that runs the VR simulation.

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Figure 2: The Level-Up device

Level-Ups' main hardware element, the lift table, is based on a scissor mechanism. Figure 3 shows the mechanism extending by 12.5 cm. Level-Ups perform this while the user's foot is in mid-air and thus does not bear a load, allowing a compact motor (ca. 40 W) to fully extend or contract the device quickly (ca. 500 ms).

Figure 3: A Level-Up actuating its scissor mechanism

While this design allows users to experience stepping onto and off objects, it cannot simulate uneven terrain or texture.

Figure 4 shows the motor actuating the lift table. In order to minimize friction, the motor is mounted directly onto the lift table's axle. In order to prevent the motor from spinning, we wrapped it in a 3D-printed cuff that holds on to two aluminum tubes. When the motor actuates, these tubes slide in and out of two holes drilled into the center bar of the lift table. This allows the motor to drive the axle, but prevents it from rotating as a whole.

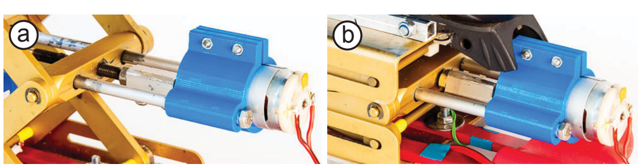

Figure 4: Level-Up's Motor and carriage in one piece

The additional height of the device increases the forces that apply to the user's ankle. We address this by stabilizing the user's ankle with a boot. Experimentation showed that the ankle is sensitive to left-right tilt, but that the foot is still able to handle forward-backward tilt. By using a boot with a rotary joint at the ankle (Figure 5), we accommodate this, resulting in more realistic walking.

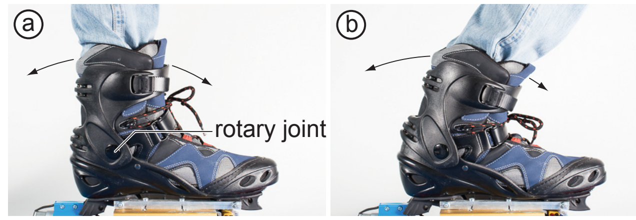

Figure 5: Level-up's boot supports the user's foot in the left-right direction while still allowing for front-back tilt action

To provide users with the springiness of a realistic walking experience we added a simple artificial foot (42 cm × 13 cm) made from three strands of fiberglass held together by 3D printed toes and heels. Figure 6 shows how the ball and heel segments flex when the user sets the foot down or lifts the foot off. Videos recorded during our user study (see below) showed that while walking participants had their feet tilted backwards most of the times causing the flexible heels to bend and to dampen the steps' impact as intended.

Figure 6: Fiberglass gives the artificial foot its flexibility

To better approximate the experience of walking on elevated terrain (in contrast to walking on stilts) we made the artificial foot longer than the user's actual foot to allow it to attack at the correct angle (Figure 7).

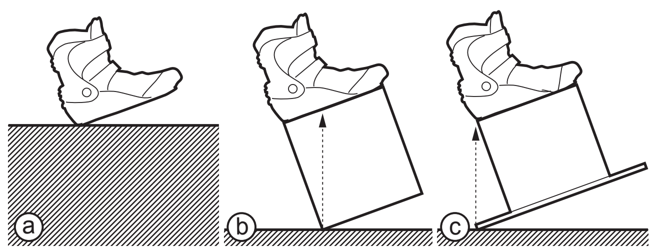

Figure 7: (a) The experience we want to simulate. (b) Setting down an artificial foot of regular length creates a force too far forward. (c) We compensate by elongating the foot.

Figure 8 shows the board that controls the unit. It consists of an Arduino nano, a motor driver with H–bridge, a serial Bluetooth interface, and a voltage regulator.

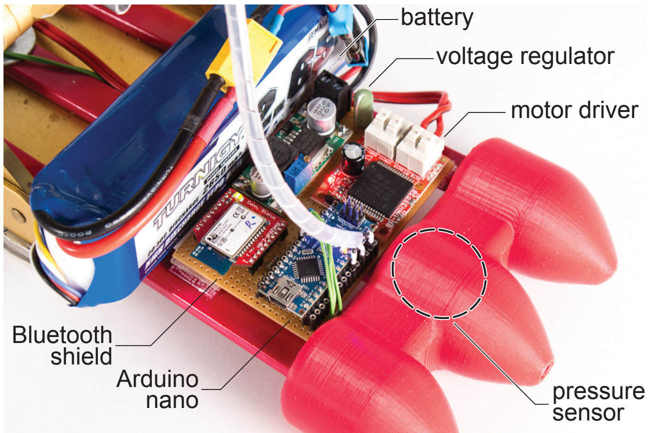

Figure 8: Level-Ups' circuitry consists of an Arduino controller, Bluetooth shield, voltage regulator, motor driver, and pressure sensors.

The microcontroller monitors the height of the stilts by reading a linear potentiometer mounted to the underbelly of the top of the lift table (Figure 9).

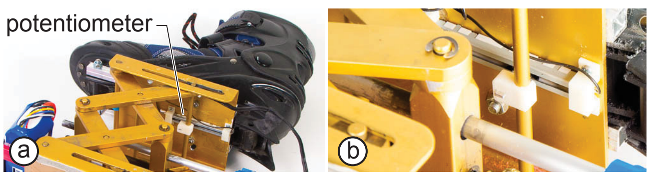

Figure 9: This potentiometer serves as linear transducer to determine the unit's current height

Pressure sensors inside the toe and the heel of the artificial foot determine when the unit is in the air and thus can be actuated. A current limit algorithm stops the motor in case of overload to prevent physical damage to the unit.

System Integration

Figure 10 shows the VR environment we created to test our Level-Up devices. The user is wearing a head-mounted display (Oculus Rift) and is tracked using an optical motion capture system (OptiTrack). A MacBook Pro in the user's backpack (carried on the front) runs the VR game engine.

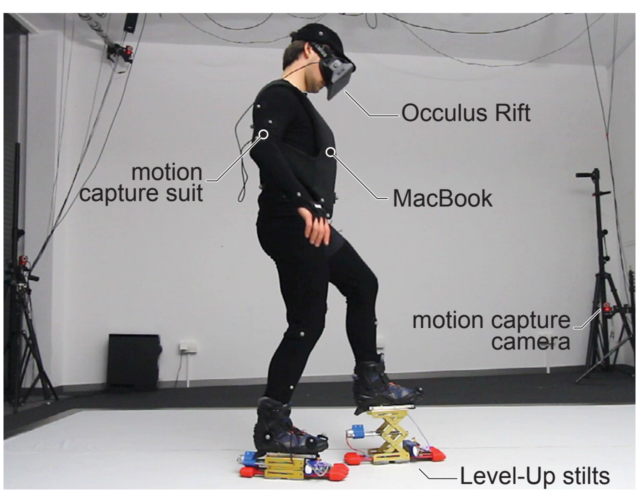

Figure 10: Our VR test environment for the Level-Up stilts

There are no wired connections to or from the user, allowing the user to walk around freely. During operation, the motion capture system's tracking software (Arena) sends position data to the game engine via UDP, which in turn sends commands to the Level-Up units via Bluetooth.

A simple program running inside of the game engine determines where the user's next step in the virtual world is expected to come down. By casting a ray downwards at this location, our program determines the height of the terrain, which it sends to the Level-Up units.

To demonstrate our design, we have integrated Level-Ups with two game engines: Unity (unity3D.com)—which we used to create levels for our user study (see below, Figure 12) and Garry's Mod using the Source engine (Figure 1).

The latency from detecting an obstacle in the game engine to the start of device actuation is below 100ms. We measured this by recording audio and letting our program emit a beep on obstacle detection (both beep and the stilts' motors are clearly identifiable in the audio recordings).

CONTRIBUTION

Our main contribution is the concept of motorized stilts for virtual reality, as well as the particular mechanical design we have created. The main benefit of our approach is its applicability to real-walking in virtual worlds and the simple self-contained design of our device.

The main limitation of our approach is the limited vertical range. When steps are sparse, we can extend that range by unobtrusively slowly resetting the stilts with every step the user takes on flat terrain, so they can actuate again in full when the user reaches the next step.

RELATED WORK

Level-Ups are related to software and hardware systems that give users the impression of walking in terrain and in particular of walking up and down steps.

Simulating Terrain. In HCI, CabBoots guide pedestrians by simulating a well-trodden path. They achieve the effect using servo motors that tilt the user's shoes inwards [3].

In virtual reality, a range of hardware projects simulates terrain texture. The ground surface simulator, for example, is a treadmill equipped with individually height-adjustable elements of up to 6 cm that simulate bumpy terrain and virtual slopes [8]. Torso force feedback pulls users walking on a treadmill using an active mechanical link, simulating a slope [4].

Simulating Steps: Marchal et al. proposed a purely *virtual* solution to walking up and down by modifying the subjective camera [7].

Building on the principle of locomotion devices, Schmidt et al. proposed simulating walking on slopes or stairs using motion platforms that hold the user's feet at all times [9]; this allows for simulating soft surfaces. In contrast, Iwata et al. use motion platforms that position themselves where the user is expected to step next [6]. CirculaFloor builds on the same concept, but uses four robot units that place themselves under the user's steps [5]. An extended version of CirculaFloor provides one step worth of elevation.

Level-Ups, in contrast, are designed for real-walking interfaces as these are believed to produce a higher sense of presence than the more space-efficient locomotion devices [11].

USER STUDY

To validate our design, we conducted a simple user study. We recruited 12 participants (3 female) between 18 and 26 years old (M = 21.5 yr, SD = 2.3 yr) from our institution. Every participant stepped on and off virtual boxes in a world created in Unity (Figure 12a). We compared a baseline VR condition (i.e., wearing normal shoes), a Level-Up/On condition that was identical to the baseline condition except that participants wore Level-Up stilts (Figure 12b), and a Level-Up/Off condition that was identical to the Level-Up/On condition except that we disabled the stilts' height actuation.

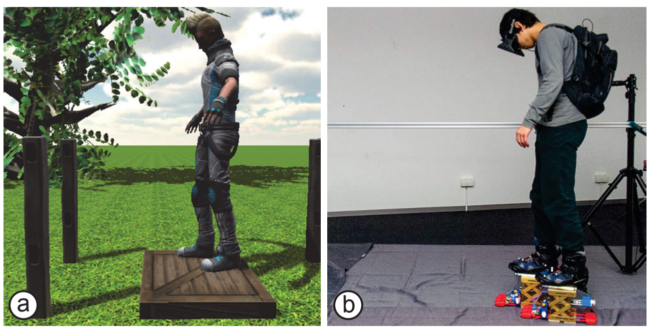

Figure 12: Participant walking study level

For safety reasons, we provided a handrail that participants could hold on to. To minimize setup time, we attached three markers to the participants' torso and feet instead of using the full-body suit. Participants filled in a questionnaire rating their overall enjoyment of the experience as well as the realism of their interaction with the boxes, each on a 7-point Likert scale.

Results

As shown in Figure 13, participants enjoyed the experience best when using (enabled) Level-Ups. Similarly, they rated the realism of stepping onto boxes the highest in this condition. Wilcoxon signed-rank tests found significant differences (*) for Level-Up/On vs. the two other conditions—except for the enjoyment rating of Level-Up/On vs. normal shoes (experience on vs. off: $z = -2.48$, $p = 0.13$; realism on vs. shoes: $z = -3.1$, $p = 0.002$; realism on vs. off: $z = -2.96$, $p = 0.003$).

In general, participants enjoyed the experience of stepping up and down using Level-Ups (e.g., "I felt like actually standing on a box", "pretty realistic", "worked well"). One said that stepping up felt particularly realistic due to the actual force that was required. In the regular shoe condition, in contrast, six participants commented on the lack of physical elevation (e.g., "I expected a step but there was none"). On the flipside, five participants commented that regular horizontal walking felt less natural when wearing the Level-Up units, as this, for example, caused them to make bigger steps. This is not surprising due to our current prototype being larger and heavier than regular shoes.

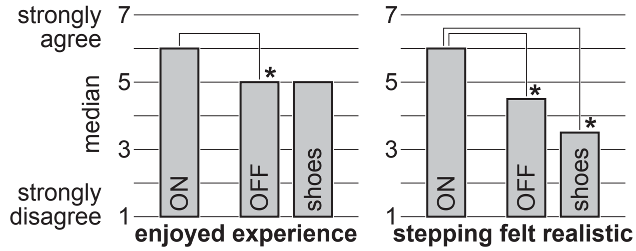

Figure 13: Participants enjoyed the experience best and rated the realism of stepping onto boxes the highest using Level-Ups

CONCLUSIONS

In this paper, we have presented Level-Up motorized stilts that simulate steps in virtual reality environments. Our main contribution was the concept and the specific mechanical design. Our study results suggest that Level-Ups improve the realism of stepping onto and off virtual steps, and that Level-Ups are sufficiently fast to simulate realistic stepping. As future work we plan to extend the height range of Level-Ups by stacking multiple units.

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