Using Your Own Muscles: Realistic physical experiences in VR

Leveraging the user’s own muscles to simulate impact and forces from a virtual reality world allows us to create more immersive experiences without bulky equipment.

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CONSUMER VIRTUAL REALITY HEADSETS (SUCH AS THE OCULUS RIFT, SAMSUNG GEAR VR, OR GOOGLE’S CARDBOARD) PROVIDE AN EXCITING PEEK THROUGH THE WINDOW OF VIRTUAL REALITY (VR), BUT THAT IS WHERE OUR EXPERIENCE ENDS. AS WE REACH OUT TO TOUCH THESE NOVEL REALITIES WE ARE LEFT WITH A SENSE OF DISILLUSION, BECAUSE ALL WE SEE ARE 3-D GHOSTS WITHOUT ANY MASS. TO GIVE VR USERS A SENSE OF AN OBJECT WITH MASS, TRADITIONALLY LARGE ROBOTS ARE USED THAT CAN, FOR INSTANCE, MOVE THE USER OR SIMULATE VIRTUAL TERRAIN. HOWEVER, THESE LARGE AND STATIONARY ROBOTS ARE OUT OF PLACE IN THE MOBILE AGE: WE ARE USED TO SMALL AND LIGHT, YET POWERFUL, DEVICES IN OUR POCKETS. AFTER ALL, CONSUMER-READY VR BECAME A REALITY WHEN THE HEADSETS FINALLY MET THE SIZE AND PORTABILITY REQUIREMENTS OF OUR MOBILE TIMES.

At the Hasso Plattner Institute’s HCI Lab, our research has focused primarily on bringing a physical component to mobile VR experiences. Users can reach out and feel what is, virtually, there. Because we have engineered these devices to be wearable, they leave the user unconstrained to freely move in space and enjoy the virtual experience to its fullest. In this article we describe a new world of VR, in which users feel forces from the virtual world through their fingers, arms, and even the terrain under their feet. This is our contribution to making virtual reality physical.

MOBILE TERRAIN SIMULATION

From the inception of VR in the 1960s [1], through the industry hype of the 1980s, up until today, many efforts have been geared toward helping users to “feel” virtual worlds. Industry and research labs responded to this challenge by using motion platforms, such as Lufthansa’s flight simulator. These motion platforms are heavy stationary machinery that are too impractical to ever reach our homes—even if you could afford a large motion platform, space is sacred these days. This technology was acceptable when VR was a specialist product, and these machines shone through their precision rather than their form factor. In fact, the biggest players in VR were not gam-

1 http://www.virtual-fly.com
with just a headset, you encounter various obstacles that you cannot interact with using your physical senses. However, with Level-Ups you can actually step on these objects as depicted in Figure 1. To get across obstacles, you physically lift your foot and climb across. In the physical reality, we see physical elevation is rendered using our Level-Up motorized stilts. Depicted here, Level-Ups provide the physical sensation of an elevated ground to a user wearing a head-mounted display tracked by an optical motion capture system. Every Level-Up 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 that communicates via bluetooth with VR applications. Each boot can render an elevation of up to 12.5 centimeters. Because Level-Ups only extend while the user’s foot is in mid-air, they can be fully extended or contracted with a compact 40W motor in half a second, yielding a wearable free-walking physical feedback device.

**THE CHALLENGE OF MOBILE FORCE FEEDBACK**

Level-Ups was, for us, a clear step in the right direction toward mobile physical VR, but is it what sci-fi had us dreaming about for years? What about feeling forces from the virtual world? These dreams of a physically believable virtual reality aren’t new, but so far they required heavy gear, such as exoskeletons. These are large mechanical contraptions mounted onto users; a motor is placed at every joint of their limbs and thus users are able to manipulate their limbs while they experience VR. Think of motion platforms that you carry around. The human is rather powerful, and therefore the motors required to move our limbs must be powerful, too. And powerful motors are large. Now if you look at Google Cardboard, Oculus Rift, or any other headset on the market, you realize their form factor is orders of magnitude smaller than the actuator systems that would allow us to bring some physicality to virtual experiences. So how can we produce enough power to actually move a human limb, but in a very concise form factor?
At first this sounded as contradictory as Newton’s Third Law, which demands a counter force to every force you want to apply; this is why an exoskeleton has to be a certain size—it must attach to your arm and apply a counter force (called force feedback) to your muscle motion. The same applies if you want to play virtual soccer: A robotic contraption would need to apply a force to your foot every time you hit the massless virtual ball you see on the headset. So how do you keep the required amount of force feedback, but scale down the hardware? Our approach has been to simply take all the mechanics out of the equation and replace them with our own muscles. Because our technique uses human muscles to create the force sensation, we called it “muscle-propelled force feedback.”

LEVERAGING THE USER’S MUSCLES
Muscle-propelled force feedback brings force feedback to mobile devices. It explores the user’s own muscle power as a replacement for motors. To achieve this, we actuate the user’s muscles using electrical muscle stimulation (EMS), a technique first explored in physical rehabilitation in the 1960s and 1970s [4], and more recently in the research of Tamaki, Miyaki, and Rekimoto [5].

Figure 2 illustrates the use of our mobile force feedback prototype in a mobile gaming scenario. The muscle-propelled prototype is mounted on the back of a mobile phone. The player connects to it by attaching two electrodes to the flexor muscles on the forearm as depicted in Figure 3. The game requires the user to steer an airplane through strong side winds by tilting the device. The game renders the wind force by tilting the device against the user’s will. It achieves this by stimulating muscle tissue in the user’s arm though the electrodes, triggering an involuntary contraction. This causes the user’s arms to tilt sideways and thus the device to tilt. Since the airplane is controlled by tilt, the involuntary tilting threatens to derail the airplane. To stay on course, players counter the actuation using the force of their other arm. As we showed in a study, participants perceived the interaction between the involuntary and voluntary tilt as force feedback. In fact, these participants rated muscle-propelled force feedback as more exciting than vibration feedback, which is the standard feedback modality for mobile devices.

The great thing about not using motors is we were able to miniaturize the device to fit in a 133 mm × 70 mm × 20 mm casing, weighing only 163 grams. This simple prototype is comprised of an Arduino microcontroller, a Bluetooth modem, and an EMS unit (similar to muscle rehabilitation devices found in a doctor’s clinic), which outputs a maximum 50V/100mA. If you stop and think for a second about these numbers, you will realize the 100mA needed to actuate muscles is two orders of magnitude more efficient than actuating a conventional motor. This happens because, in reality, the electrical muscle stimulation is just a “control signal” to...
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After we demonstrated muscle-propelled force feedback at a few conferences (ACM’s Augmented Human’13, ACM CHI’13, and IEEE World Haptics’13), some of our peers were really excited about the idea of having mobile force feedback. While this type of force feedback works well for “invisible” forces like wind or magnetism, we started asking the next question: How would this feel in virtual reality when a visible object hits you? Can we create a believable physical sensation? Can we let the user feel the virtual world?

REALISTIC PHYSICAL EXPERIENCES IN VR

It turns out this is harder than it sounds. When somebody hits you in “real” physics-based reality, you feel the point of contact and you feel the impact transmitted onto your limbs. So how can we replicate that sensation? One possibility is to add a robotic arm that hits you in the “physical world” exactly when you get hit in the “virtual world.” Unfortunately that is (1) dangerous as it might break our bones into pieces, (2) expensive, and (3) requires large machinery that you likely don’t want to store in your basement.

This is why the most conventional way to emulate the sensation of impact is to use vibration. There are haptic suits out there, such as the Tesla Suit, which has embedded vibrotactile and electrotactile stimulators touching your skin. This is a great step forward, however Newton would certainly not be thrilled about it since vibration motors only stimulate the skin’s surface and will not make your arm move. An impact sensation is more complex than you might think. For instance, if someone pushes you, your skin detects pressure through its mechanoreceptors at the location you were touched, your muscles move and your proprioceptive sense will tell your brain your muscles are being moved. So the requirements for impact emulation pile up: We need to stimulate the skin, we need to apply pressure, and we need to inform the proprioceptive sense by moving your muscles. We need to do all of this, and keep the hardware smaller and less dangerous than a massive robotic arm. The answer is, again, your own muscles.

To tackle this challenge we built impacto, a device designed to render the haptic sensation of hitting or being hit in virtual reality as shown (see Figure 4). The key idea that allows our rather small device to simulate a massive hit is it decomposes the stimulus into two distinct components: tactile sensation and force feedback sensation. Tapping the skin with a solenoid renders the tactile sensation; the force of the impact is added by thrusting the user’s arm backwards using electrical muscle stimulation. In fact, because the EMS is able to move the arm at such a compact form factor, we can keep the solenoid component to a minimum size, because all it needs to do is tap the skin. As a matter of fact, participants of our study rated impacto’s combination of solenoid hits and electrical muscle stimulation as more realistic than either technique in isolation.

The sensation of impact plays a key role in many sports simulations such as boxing, fencing, football, etc. Imagine all the sport simulators, games, and digital experiences you had so far,
which enables a different VR experience: soccer juggling. This setup points out the solenoid component at the user’s instep (top of the foot) and the EMS unit to the calf muscles. The electrical muscle stimulation causes the foot to slightly bend backward at the moment the ball hits the foot. Also, by placing impacto units on arms and legs, users experience a Thai boxing simulator where they feel virtual punches and kicks. As in all our sport simulators, we use a Kinect camera to track the user’s body posture and an additional wireless accelerometer on the solenoid to determine the foot’s tilt. Lastly, we can actuate users, even while they operate objects. This allows impact sensation to happen in hand-held props that the user manipulates in a virtual world: Imagine hitting a baseball with your VR bat. Figure 5 shows a prop becoming animated; here a stick is a stand-in for a baseball bat. We mounted the solenoid onto the prop but the EMS unit, in contrast, stayed with the user; here it stimulated the wrist muscles exactly when the ball hits the virtual bat.

CONCLUSIONS

We are finally getting rid of the massless ghosts in VR and are sticking to the consumer form factor: mobile and wearable. This is the start of the end of virtual experiences with no physical sense of force, impact, and terrain elevation. Companies have been marketing their VR products as “experiences like you are actually there” (e.g., Google’s 360 camera rig) or “feel the sudden impact of a bullet” (e.g., the Tesla Suit), but these are ghost experiences without any strong physical sensations. However, by actuating the users’ own muscles we can provide strong physical sensations and fit all of this in a convenient mobile package that users have come to expect from technology. Our approach promises a future of physical VR without wearing bulky apparatus, such as large motion platforms or exoskeletons, an approach that leaves the user untangled and free to move.

Figure 5: By wearing impacto on the feet, the user experiences the impact of kicking a virtual soccer ball (left). He hits a virtual baseball with impacto’s solenoid on the prop and electrodes on the wrist extensor muscle (right).