Swimming Across the Pacific: A VR Swimming Interface

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A locomotion interface for swimming and floating in a virtual ocean is part of the interactive installation of the *Swimming Across the Pacific* artwork.

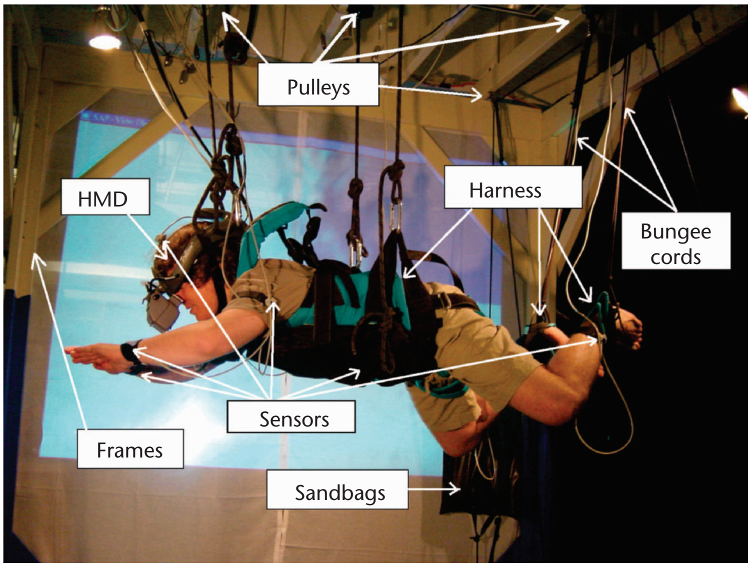
Swimming Across the Pacific takes inspiration from the performance art piece *Swimming Across the Atlantic*.[1] *Swimming Across the Atlantic* was performed by the artist Alzek Misheff, who accomplished the endeavor by swimming in the pool of the Queen Elizabeth II ocean liner while it traveled from South Hampton to New York. More than 20 years later, we intend to accomplish the next stage of this performance piece by swimming across the Pacific Ocean, from Los Angeles to Tokyo, in an airplane. We have created a virtual swimming apparatus to fit inside a large passenger airplane.

In our *Swimming Across the Pacific* artwork, we create a space for collaborative artwork in the airplane by having a swimmer swim while flying across the Pacific Ocean. The swimmer's swimming represents a transformation of the airplane into an art gallery where the medium is the airplane, much as Misheff transformed the Queen Elizabeth II while he swam during her journey. By using elements such as the AV system, food, and clothing in the airplane for expression, fellow artists, scientists, engineers, musicians, media, and other passengers participate together to create artwork.

We decided to use virtual swimming rather than put actual water in the plane to represent the role technology plays in contemporary society and its role in transforming individuals and cultures to work together. To create this special space, we plan to fly west near sunset so that the passengers see a constant setting sun. The plane flies at approximately the speed that the sun sets. Time appears fluid as each time zone is passed, shifting the clock back and forth. Likewise, there is no actual place on the ground that the plane exists. We think of this scenario as a bubble in which collaborative work can occur. The bubble is created by the swimmer in the apparatus. In contrast to Snow's work on the cultural divide between art and science,[2] we see our bubble as supporting a multicultural and multidisciplinary mosaic woven with the dynamic relations between people, space, and time encapsulated in the fuselage.

At this stage in our creation, we have built the virtual swimming apparatus described here. As part of our artistic process, we are using the virtual swimming apparatus as an interactive installation exhibit based on the theme of *Swimming Across the Pacific*. In the exhibit, participants try the swimming apparatus and experience the feeling of swimming in air and being part of a collective group of swimmers trying to swim across the Pacific Ocean.

Our swimming apparatus provides an exciting and interesting experience for the expert performer



1 Profile view of a swimmer in the swimming apparatus.

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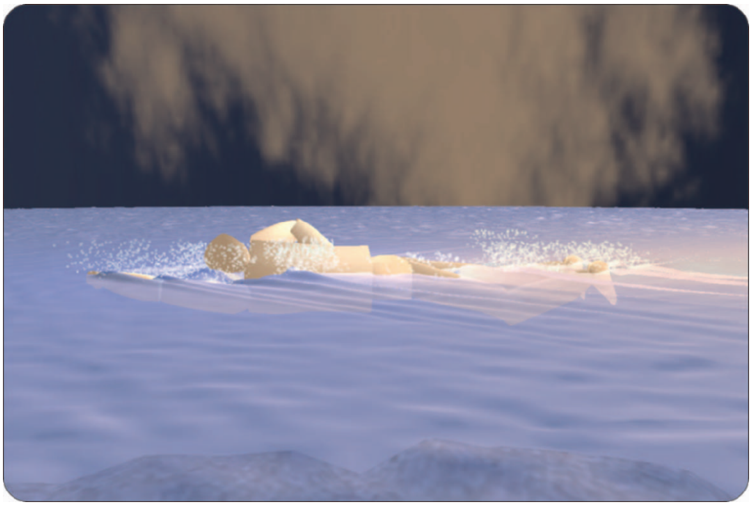
and the novice. The swimmer is suspended in a real swimming apparatus, but navigates in a virtual Pacific Ocean environment. The swimmer is suspended using a hang gliding harness and a leg harness in an 8 × 8 × 8 foot wooden frame, as shown in Figure 1. We use bungee cords to mimic buoyancy, while sandbags act as counterweights to the participants' legs. Friction in the system adds resistance to the swimmer's kicking actions. Swimmers wear a head-mounted display (HMD) with an attached tracking sensor, plus wrist and ankle bands for securing sensors so that he or she is hindered as little as possible during virtual swimming.

Technical innovations

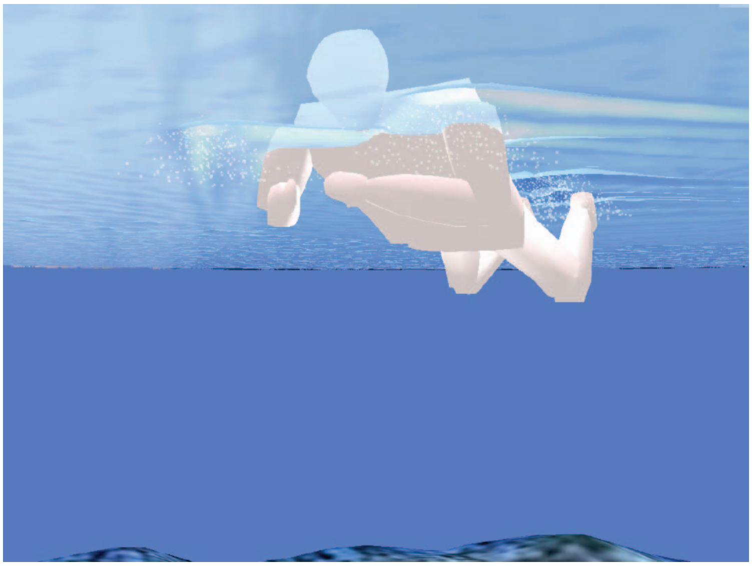
VR is a powerful tool suited to many work-related applications in distance education, hands-on training, navigation, orientation, visualization, and entertainment.[3] It permits users to experience and interact with synthetic worlds in a controlled environment, allowing safe experimentation in simulated, real-life situations. It provides an immersive experience through convincing visualizations and other sensations; experiencing these in a confined space makes it an invaluable tool of discovery.

Locomotion interfaces, such as virtual walking, virtual hang gliding, and others, are closely tied to VR. In an artificial reality, where the users have a presence in a 3D space and use their bodies as natural input devices, development of locomotion interfaces is vital for immersive VR experiences. "Locomotion interfaces are energy-extractive interfaces to virtual environments and fill needs that are not met by conventional position-tracking approaches or whole-body motion platforms."[4] Researchers in VR advocate the development of locomotion interfaces because their improvement will bring many more unforeseen applications.[3]



2 Side view of the swimmer at daybreak in the *Swimming Across the Pacific* environment.

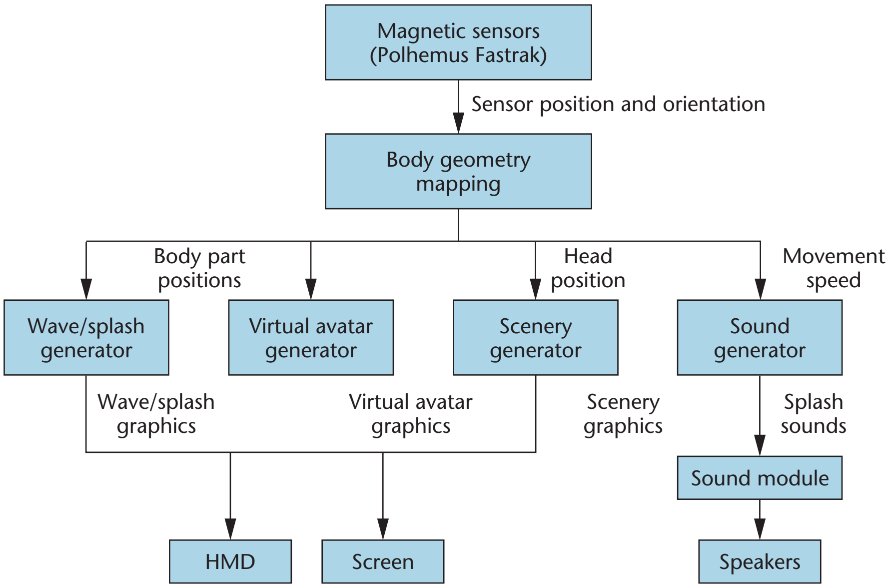
3 Aerial view of the swimmer at sunset in the *Swimming Across the Pacific* environment.



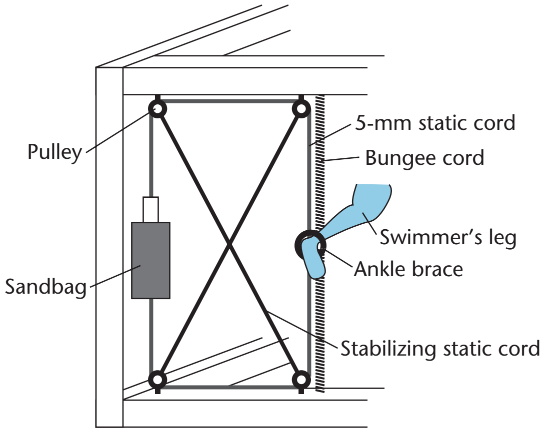
4 Underwater view of the swimmer at midday in the *Swimming Across the Pacific* environment.

One unique aspect of our swimming system is that it occurs at the water's surface, requiring the simulation of the boundary between air and water. This is one of the key issues we address in our system. While we use our swimming apparatus to move in virtual water, it could be used more generally to move in any virtual space that uses liquid as a metaphor. Typical images of the virtual environment are shown in Figures 2, 3, and 4.

We have implemented dynamic waves and splash action (described later) so that both the participant and the viewer experience water like scenery as the participant moves. Our scenery is currently simplistic. But it's a relatively straightforward effort to improve realism using caustics, fog effects, and texture to achieve a dif-



5 System diagram of the virtual swimming system for *Swimming Across the Pacific.*



6 Rear view of the counter-weighted leg support system.

ferent representation of sea, sky, sun, and swimmer. Our approach to exploration and navigation could make this project part of an emerging trend toward novel VR technologies.

System architecture

Our current design consists of a physical swimming apparatus and a virtual ocean environment. Figure 5 depicts a block diagram of the overall system design. The swimmer wears eight Polhemus Fastrak sensors and an HMD. The software program processes the movement data captured by the sensors so that the virtual swimmer mimics the real swimmer in the virtual environment. The system translates the sensor readings by the mapping function that determines the elbow, shoulder, and knee positions and orientations to derive the avatar figure geometry.

The mapping function determines the swimmer's speed. The body positions are then fed to the wave–splash generator, virtual avatar generator, scenery generator, and sound generator. The system then presents the graphics to the HMD for the swimmer and a rear projection screen for the audience. The sound generator mapping converts the swimmer's movements in the water using a MIDI sound module to produce splash sounds. Normally, the system does not perform calibration because the correspondence between the real and virtual swimming is adequate for a large range of people. When required, we can calibrate the system by adjusting external controls or a configuration file to specify the geometry of the avatar with respect to the actual swimmer. Calibration usually takes a few minutes.

Swimming apparatus

Running static cords through the pulleys mounted on the beams and attaching the cords to the harness with carabiners supports the user at the shoulders and hips in a prone position. The rope-pulley system (see Figure 6) for the legs conforms to several swimming styles, including front crawl, breast stroke, butterfly stroke, and dog paddle.

For each ankle, we run 5-mm static cords through two ball-bearing pulleys mounted on one of the top beams, with another pair of pulleys on the bottom beam. This configuration forms a rectangle where the diagonally opposing pulleys are connected with additional cords for stability. Between the inner pair of the top and bottom pulleys, an ankle brace secures the swimmer's leg. Between the outer pair of top and bottom pulleys, the static cords hold a sandbag that counterweights the swimmer's leg so that only resistance is provided during kicking. Bungee cords connecting the inner pair of pulleys further help restore the kicking energy, adding the feeling of buoyancy. Currently, there are no mechanics designed for the arms so that they are left free to allow smooth movements.

We use straps for attaching the Polhemus Fastrak sensors to the participant. Each strap is made of nylon material and Velcro. In all, there are six straps that are adjustable to fit each swimmer while being tight enough to stay on during motion. In addition, we route the wires from above to minimize interference with the swimmer's movements.

Virtual ocean environment

We use OpenGL to generate the computer graphics for a sky hemisphere, sea surface plane, ocean floor plane, virtual avatar, and various lighting effects for different times of the day, as shown in Figures 2, 3, and 4. The sky hemisphere is texture-mapped with moving clouds, and the ocean floor plane has a rugged plane, texture-mapped with rocks. Both planes are animated to move past the virtual swimmer, making it appear as if the virtual avatar is swimming forward.

We created the sense of time passage through providing sunrise, day, sunset, and night by moving the sky and lighting effects. We wanted to present different times to alter the user's sense of reality and timing in the virtual world, both for aesthetic and conceptual reasons. We can adjust the virtual avatar so that the arms, legs, and torso match every participant. We perform this calibration—which is not usually needed—through known measurements of participant configurations combined with the eight measured points from the trackers.

We use physically based methods to approximate the water splashing and waves. Making physically based computer graphics for simulating water requires considerable computation time, but it needs to be done in real time to be realistic and engaging. In contrast, many movies, such as *The Perfect Storm*, have photorealistic water waves and splashes. These computer graphics are costly, both in computational time and money, because many developers often revise them manually. Because they are not interactive, they are inappropriate for use in VR systems requiring low latency for quick response times.

We based our water simulation on the method in which the water surface is modeled as a thin film, transformed and visualized.[5] This method is usually used in video games. For the sea surface plane waves, we use recurrence relations to solve the partial differential equation for the 2D wave equation. In this method, the sea surface is modeled as a mesh. The height of the grid at point $[i][j]$ at time $t+\Delta t$ on the sea surface is $h[i][j][t+\Delta t]$ and is calculated with the relation shown in Figure 7.

$$h[i][j][t+\Delta t] = \frac{\left(h[i-1][j][t]+h[i+1][j][t]+h[i][j-1][t]+h[i][j+1][t]\right)}{2-h[i][j][t-\Delta t]}$$

7 **Relation used to calculate the sea surface grid's height.**

We approximate the volume of the swimmers with bounding boxes to improve performance and determine when they intersect any of the water grids when they move. When they intersect, they cause the height of the water grids to be set to the same as the bounding box. There are two conditions that we consider:

- When the bounding box goes into a water grid, the height of the grid is increased with a predefined value.
- When the bounding box goes out from the water surface, the height of the grid is decreased with a predefined value.

When these two conditions occur, the system makes waves and propagates them. If the height is over a predefined threshold value or the swimming avatar's motion interferes with waves, the system generates particles in the air to simulate splashing.

Splashing water is quite difficult for an interactive simulation. Computer graphics used in movies typically rely on particle system methods. In our system, we use a simplified particle system simulation to achieve interactive response times. The splashing water particles fall down according to a simple gravity model. When the particles reach the water surface, the surface grids are set to the appropriate height according to the wave model.

The system draws splash particles with transparent squares. The color, transparency, and size of the square are changed randomly for a natural spray without much computational overhead. We have chosen each default value mentioned above empirically. To save computational time, we only calculate the interaction with the waves in a small bounding box that encloses the whole swimmer and the immediate area. We use a second sea mesh that has a natural waving pattern spread over the whole sea plane for the large plane representing the rest of the sea. As seen in Figures 2 and 3, the interactive waves near the swimmer merge with the background waves for a smooth transition on the sea.

Synchronizing the real and VR worlds

We track the swimmer's movements to calculate the avatar's position to synchronize the real and virtual movements. We use two Polhemus Fastraks, each running at different transmitter frequencies, with four receivers each to provide eight tracked positions:

- Tracking the swimmer's head: The orientation of this sensor determines the position and orientation of the head and how we adjust the scene camera to update the swimmer's view in the HMD.
- Tracking the swimmer's wrists and biceps: Arm movements are determined using vectors formed by approximated shoulder and elbow positions.
- Tracking the swimmer's ankles: We approximate knee positions and leg positions algorithmically.
- Tracking the swimmer's abdomen: The abdomen and approximated shoulder positions let us approximate the orientation and size of the torso.

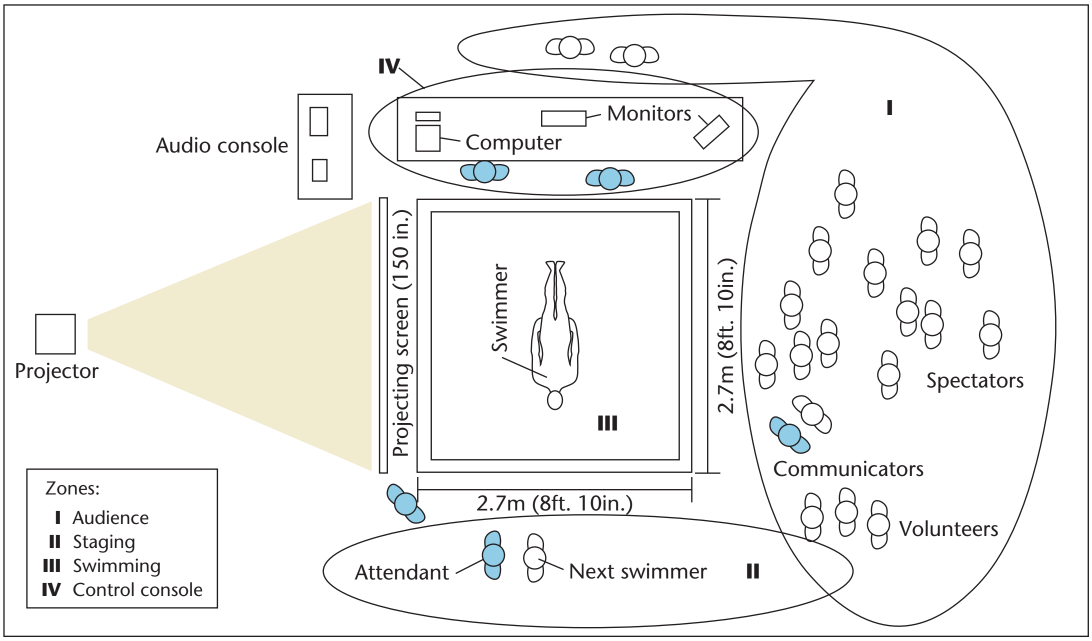
The *Swimming Across the Pacific* system requires tracking head, neck, shoulder, elbow, wrist, lumbar, knee, and ankle positions to map the swimmer geometry. For example, biceps are determined by shoulder and elbow positions. The sensors track some required positions—head, wrist, and ankle—while the system uses tracked positions and orientations to calculate other positions.

The system calculates shoulder positions using the distance between the bicep sensor and swimmer's shoulder by a rotation matrix. We based the method we use on the following formulation: The sensor position is (x, y, z), and a point P on the x-axis is d inches away from the sensor position and can be expressed as $(x+d, y, z)$. The x-y-z rotation matrix $\mathbf{r}$ can be expressed as follows:

$$\mathbf{r} = \begin{pmatrix} C\alpha\, C\beta & C\alpha\, S\beta\, S\gamma - S\alpha\, C\gamma & C\alpha\, S\beta\, C\gamma + S\alpha\, S\gamma \\ S\alpha\, C\beta & S\alpha\, S\beta\, S\gamma + C\alpha\, C\gamma & S\alpha\, S\beta\, C\gamma - C\alpha\, S\gamma \\ -S\beta & C\beta\, S\gamma & C\beta\, C\gamma \end{pmatrix}$$

where α, β, and γ are the rotation angles about the x-, y-, and z-axes, respectively, and $C = \cos$ and $S = \sin$. Thus, the rotation of the point P can be expressed as $(x + d(\cos\alpha \cos\beta), y + d(\sin\alpha \cos\beta), z + d(-\sin\beta))$.

Likewise, the wrist sensors calculate the elbow posi-



8 Top view of the swimming apparatus installation.

9 World flight map showing progress of accumulated swimming time of all swimmers during each day of the exhibit. The exhibit lasted 9 hours each day, which is approximately how long it would take to fly across the Pacific Ocean.

tions, and the ankle sensors calculate the knee positions. The abdomen sensor calculates a lumbar position, and the calculated two shoulder positions estimate a neck position. Every distance between a sensor and a target point is adjustable so that the system can specify the avatar's geometry with respect to the actual swimmer. Only some body part sizes, such as the hand or head, use fixed sizes.

Swimming Across the Pacific exhibit

Given the size of the swimming apparatus, plus the rear-projection video, we need a minimum of a 17 × 17 × 15-foot space for the interactive installation. The surrounding area of the swimming device must be kept free to avoid encumbering the swimmer's kicking movements during performance. The additional leeway is necessary as well because the sandbags protrude slightly. Figure 8 depicts a top view of the installation.

To make the interactive installation part of the *Swimming Across the Pacific* artwork, we show participants a map of an airplane's progress as swimmers collectively accumulate swimming time during the day. We display this map at the beginning and end of each swim, as Figure 9 shows. The map provides the context of each swimmer cooperating to reach the final destination across the Pacific Ocean.

When the swimmer gets into the apparatus, he or she sees the map in the HMD and the audience sees it on the projection screen. When the attendant switches the view, the swimmer sees either a first- or third-person perspective in the virtual ocean. The system automatically switches between first- and third-person views in the HMD every 30 seconds. The audience sees a side view of the swimmer oriented the same as the real swimmer in the rear projection system.

We identified four distinct user types whose needs we needed to address in making the exhibit run well and to provide a meaningful experience: the swimmer, the swimmer as a group, the attendant, and the audience. To ensure that the exhibit ran smoothly all day, we stress tested the code to make sure it would not crash. We automated all software settings but the switching of the map, so that attendees could spend as much time helping people get into and out of the swimming apparatus efficiently and as little time controlling the graphical user interface for the virtual reality simulation. We also use

Related Work

Previous locomotion interfaces have involved walking, bicycling, and flying, but little has been implemented relating to swimming. One well-developed example of a walking interface consists of a large tilting treadmill placed in front of a CAVE-like visual display.[1-3] The walker is attached by a mechanical tether that exerts appropriate force to the user's walking experience on a slope. The visual simulation depicts outdoor terrain.

Bicycling interfaces include the Peloton Bicycling Simulator[4] and Trike.[5] The Peloton Bicycling Simulator includes a stationary bike, a computer, a fan, and a sensor control unit. It provides users with visual and audio effects. Moreover, users feel pedaling resistance, bicycle tilt, and wind effects synchronized with their movements over the synthetic terrain of the virtual cycling course. The graphics were developed in VRML, allowing participants to join their friends in the virtual environment via the Web.

While not strictly a locomotion interface, high-end flight simulators have been used in the air force and pilot training schools for a long time. Their features often consist of a realistic visual display and a Stewart platform mount.[6] Historically, flight simulators have been available either publicly or commercially, usually for entertainment. These include Dreamality's DreamGlider, JetPack, and SkyExplorer, and the latest version of Ars Electronica's Humphrey that includes some force feedback (http://www.aec.at/en/center/project.asp?iProjectID=12280). These systems include a head-mounted display or monitor for visual cues. Sound, wind, and movement also enrich the flying experience. Because these systems were built for entertainment, the visual displays are like games. Another flight simulator of note simulates the flying experience from the passenger's point of view rather than that of the pilot. Built to treat fear of flying, this therapy is reported to have had some success with patients.[7]

Examples of swimming interfaces include Fraunhofer's Aquacave, which allows virtual interaction with cartoon fish characters, and Virtual Diver,[8] which is used for artificial reef study. The Aquacave uses a paragliding harness and a pulley system to suspend the diver in a cave where a virtual underwater environment is displayed. Virtual Diver explores methods of mapping photographs of artificial reefs onto a 3D reef model, which is then explored using a 3D joystick. There are also many high-end hardware and software systems that use VR for undersea exploration. One project called Osmose also suspends a user in a harness, but senses breath and torso movements to control diving action to navigate an aesthetically designed virtual space.[9] In all of the above examples, the focus is on the underwater environment itself, rather than on a locomotion interface based on surface swimming.

Virtual swimming offers some unique advantages over other forms of locomotion or VR interfaces. In comparison to flying interfaces, most people have experienced swimming in water. Flying in air is not such a common experience. Thus we expect people to understand and more easily explore the interface when moving in a virtual world. Bicycle and treadmill interfaces share this property as well. However, with swimming, there are many styles and personal techniques that provide means for people to develop complex behaviors and expertise with the apparatus. This leads to an increase in intimacy with the device,[10] providing more satisfaction and enjoyment than might be possible with typical flying, bicycling, and walking interfaces.

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two harnesses so that one person can be suiting up while the other is swimming to improve the throughput of the installation. We painted the cage and added lighting to attract people to participate in the swimming process. Finally, we created buttons with our logo to give to each swimmer to wear to signify their contribution to *Swimming Across the Pacific*.

Our system is robust and safe to use. The swimming cage is configurable, and we can adjust supporting point positions (such as the shoulders, hips, and ankles) according to a person's size. The cage's dimensions are large enough to allow taller people to make wide arm strokes without hitting the frame. The system can also support heavyweight swimmers. Each small ball-bearing pulley can support up to 2,000 pounds, while each large industrial pulley can support up to 1 ton. These pulleys allow rolling of the torso and vertical kicking of the legs. It's easy to remove the HMD in case a participant experiences sea or motion sickness. We supply a stepladder so that a participant can easily get down from the apparatus and out of the harness.

Future directions

The current state of *Swimming Across the Pacific* permits one person to experience the virtual swimming while fully immersed in the aquatic environment. We plan to further develop the graphics world to support audience participation, letting them watch birds or fish.

Naturally, we see this interface used in different types of aquatic worlds with multiple swimmers and spectators. But for the artwork it's only necessary that participants be able to join the swimmer during the flight. We continue to develop the *Swimming Across the Pacific* artwork with the goal of finding an airplane.

The exhibit at Siggraph 2004 was successful, allowing more than 400 people and thousands of spectators to experience the work. We collected numerous anecdotal reports as well as attendants' observations about how the exhibit worked and the experiences people had. Initial reports indicate that many swimmers enjoyed the experience. Interestingly, expert swimmers and larger people explored new body sensations and movements possible while being suspended in air. Novices tended to enjoy just floating in the water. Amateur swimmers were the main user group who sometimes commented negatively on the low-fidelity virtual environment. We are still analyzing the data from Siggraph and hope that it uncovers guidelines for creating a successful experience using locomotion interfaces in an exhibition setting.

For long-term applications, we see three potential directions for this locomotion interface: sports, education, and entertainment. One of the virtues of locomotion interfaces is that, regardless of the type of activity, they all promote physical fitness.[6] One's whole body becomes involved in the interaction. The ever-changing virtual environment can turn these interfaces into a sport simulator, which means the swimming interface has potential uses in water sports simulation.

While stand-alone virtual swimming is fun to use, creative use of such technology in an amusement park setting could provide experiences to people who might want to escape the ordinary. Whether it's swimming with dolphins and whales, or swimming to escape enemy pursuit, virtual swimming has the potential to address the human craving for an enjoyable, relaxing, educational, and safe way to spend leisure time. ■

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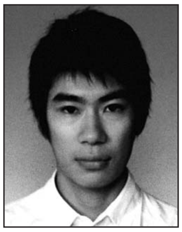

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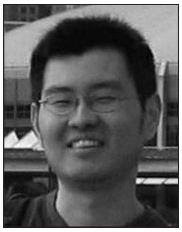

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