Swimming Across the Pacific: A Novel Swimming Interface for VR

Author One
Author Two
Some Address
Some City
Author Three

Abstract

Locomotion interfaces to virtual reality environments present many challenges as well as exciting opportunities. Many researchers have examined classes of human movement such as walking, flying, and bicycling as means of locomotion in VR. By contrast, little has been explored in swimming. We outline the current state of development of the Swimming Across the Pacific (SAP) project which aims to replicate the feel of swimming in a virtual environment. Unlike other explorations into virtual swimming, SAP centres on the locomotive aspect of swimming - staying afloat and moving on the surface of the water. The SAP system is comprised of the swimming harness and a virtual ocean environment. The harness suspends the swimmer in a prone position that allows for swimming motions, while the accompanying graphic system renders the scene of sky, sea waves and ocean floor. Sensors on the swimmer's wrists, legs, and head are used to synchronise the virtual counterpart seen from the first-person perspective through a head-mounted display. Initial user feedback suggests that our system is capable of providing a sensation of swimming without highly sophisticated hardware.

Key words: Virtual reality, swimming, locomotion interface.

1 Introduction

In 1982 an artist performed the great feat of swimming across the Atlantic Ocean. This artistic endeavour was accomplished by swimming in the pool of the ocean liner, Queen Elizabeth II, travelling from South Hampton to New York. Almost twenty years later, the next stage of this performance art will be bigger and more ambitious: swimming across the Pacific, from San Francisco to Tokyo, in an airplane. This presents the problem: How does one swim in an airplane?

One solution is to swim in virtual reality (VR). The plan is to have the performance artist suspended in a swimming apparatus affixed inside an airplane. While he swims in a virtual Pacific Ocean environment, his audience can participate through virtual reality as spectating birds, fish and other creatures. To implement this solution requires a novel swimming interface to a virtual aquatic world.

Virtual reality has been demonstrated to be a powerful tool which can apply to many work-related applications in distance education, hands-on training, navigation, orientation, visualisation, and entertainment [2, 8, 15]. The fact that it permits users to experience and interact with synthetic worlds in a controlled environment provides the possibility to safely experiment in simulated real-life situations. It provides immersive experience through convincing visualisations and other sensations and being able to experience these in a confined space makes it an invaluable tool of discovery.

Figure 1: Swimmer in the SAP apparatus.

A new swimming interface provides new ways to explore VR. Locomotion interfaces such as virtual walking, virtual hang-gliding and others are closely tied to virtual reality. Hollerbach defines in [5]: "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". Researchers in VR, such as Durlach and Mavor, particularly advocate in [8] the development of locomotion interfaces because with their improvement come many more unrealised applications.

Virtual swimming requires the implementation of a new locomotion interface, which introduces the possibility of new virtual reality applications. One interesting aspect of our swimming system is that it occurs at the water 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 data spaces that use liquid as a metaphor. A picture of a user in the SAP apparatus is shown in Figure 1

2 Background

Previous locomotion interfaces have involved walking, bicycling and flying but little has been implemented relating to swimming.

Sarcos Treadport [5, 12] is a well-developed example of a walking interface. It comprises a large tilting treadmill placed in front of a CAVE-like visual display [7]. The walker is attached by a mechanical tether that exerts appropriate force to add to the user's walking experience on a slope. The visual simulation depicts outdoor terrain. Footstep sounds are in the process of being developed for additional realism.

Bicycling interfaces include the Peloton Bicycling Simulator and Trike. The Peloton Bicycling Simulator [4] includes a stationary bike, a computer, a fan and a sensor control unit. It provides users with visual and audio effects. Moreover, users feel pedalling resistance, bicycle tilt, and wind effects synchronised 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 world wide web. Another bicycle example is a "rideable computer" called Trike [1]. It consists a tricycle with an onboard computer. The visual display is derived from a head tracker on the rider and a potentiometer connected to the steering axis of the tricycle. The video output of the computer is fed to the cyclist's head-mounted display. The vehicle does not have to be stationary; in fact, it is thought that by combining visual display with non-visual cues generated by real cycling, the subject is less likely to get motion sickness. The idea of generating one's path based on one's earlier positions is also a focus of Trike research.

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 [14]. There are some low-end flight simulators available commercially usually for entertainment, such as Dreamality's DreamGlider, JetPack, and SkyExplorer, all in [15], and Ars Electronica's Birdman [10]. They include a head-mounted display or monitor for visual cues. Sound, wind, and movement also enrich the flying experience. Since these systems were built for entertainment, the visual displays are game-like: good flying performance scores points and poor flying results in point deduction. 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 [11], such therapy is reported to have had some success with patients.

Some examples of swimming interfaces include Aquacave [9], which allows virtual interaction with cartoon fish characters, and Virtual Diver [3], which is used for artificial reef study. Both appear to be in early stages of development. The Aquacave uses a paragliding harness and a pulley system to suspend the diver in a CAVE, wherein a virtual underwater environment is displayed. The Virtual Diver explores methods of mapping photographs of artificial reefs onto a 3-D reef model which is then explored using a 3-D joystick. There are also many high-end hardware and software systems that use virtual reality for undersea exploration; case studies of today's marine navigation and positioning technology may be found in [2]. In all of the above examples, the focus is on the underwater environment itself rather than on a locomotion interface based on surface swimming.

3 Design and Implementation

Our goal is to create an environment that feels as close to swimming as possible. Our current design has two major components: the swimming apparatus which suspends the swimmer in a harness, and the graphic system which depicts the synthetic Pacific Ocean.

3.1 The Swimming Apparatus

The swimming apparatus centres around a harness that suspends the swimmer in a prone position. Pulleys are used to allow rolling of the torso and vertical kicking of the legs. In keeping with the fact that swimming quickly depends more on effective streamlining of the swimmer's body in the water than it does on rapid stroking [6], the arms are left free to allow a smooth stroke. The following design parameters were also considered:

- The apparatus should provide a general research platform. It should be configurable and expandable as much as possible.
- The apparatus should be adjustable. It must accommodate swimmers of a range of heights and body measurements.
- The swimmer should be able to stroke with ease of movement during swimming.
- The swimmer should feel comfortable when suspended in the harness.

- The system should be robust. It must be capable of supporting heavy swimmers.

We also restrict the swimmer's motions to those of the front crawl and butterfly stroke, both of which use only vertical kicking motions and only from a prone position.

To meet these specifications, an 8ft x 8ft x 8ft wooden box frame was built to support the harness in which the swimmer is suspended (Figure 2). Its dimensions are enough to allow most tall people to make wide arm strokes without hitting the frame. It has five horizontal beams on top and two at the base, all of which are movable, on which pulleys can be mounted. Currently only three top beams and one bottom beam are used.

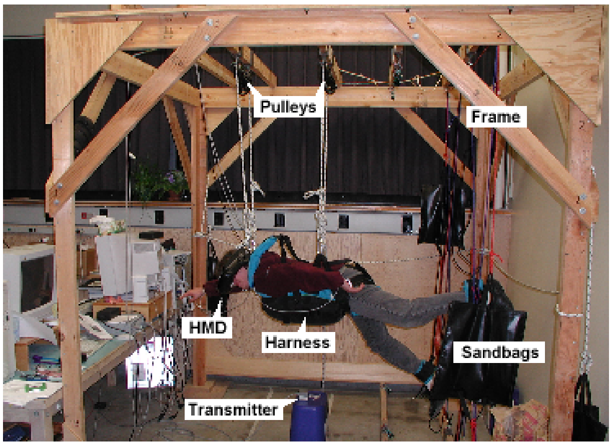

Figure 2: A profile view of the swimming apparatus.

The harness is a modified hang-gliding harness with additional padding for comfort. Two large pulleys on each of two upper beams support the harness at the swimmer's hips and shoulders; the pulleys allow torso roll during the swimming stroke and can be adjusted for width to match the swimmer, just as the beams themselves can be adjusted to the swimmer's height. The harness attaches to half-inch static cord with carabiners.

The legs are supported by a counter-weighted pulley system as shown in Figure 3. Sandbags provide a feeling of neutral buoyancy, and can be filled to the appropriate weight of the swimmer's legs. 5mm static cords through low-friction ball-bearing pulleys on the upper and lower beams complete a loop between the leg and the counterweight, while further static cords on the diagonals provide stability. In addition, elastic shock cords are incorporated to restore kicking energy, adding to the buoyant feeling of kicking in water. Originally, this setup was arranged at the swimmer's knees and ankles, but user testing showed that only the ankle system was required.

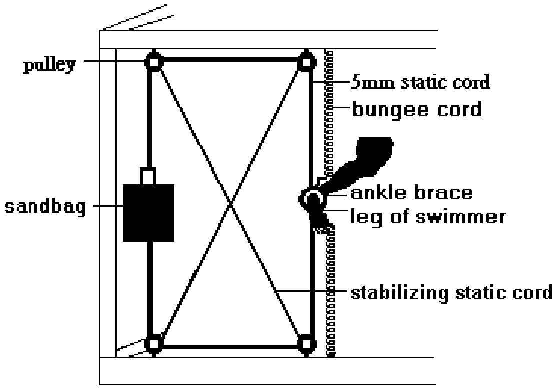

Figure 3: A rear view of the counter-weighted leg support system.

3.2 The Virtual Ocean Environment

The virtual Pacific Ocean environment is generated in OpenGL. Since the swimmer is swimming on the water surface, the environment must show sky, waves and ocean floor. Figures 4 and 5 illustrate views from above and below the sea surface, respectively. The graphics are intended to show a direct representation of swimming; the use of other virtual environments could allow this interface to be used as a more general purpose locomotion device. Swimming above or along reefs, shipwrecks, or aquatic caves are all direct interpretations of a swimming locomotion interface. Other interpretations include the exploration of human anatomy for medical education, in which the subject swims through the bloodstream, or more abstract environments composed of statistical data or based on network topology.

The environment is modelled as a sphere encompassing the viewpoint. A horizontal cutting plane splits the sphere in half, and the top hemisphere is texture-mapped with clouds, while the bottom is texture-mapped with rocks. The plane in between is texture-mapped with wave patterns representing the surface of the water. Because the performance of SAP is intended to take place in an airplane flying from San Francisco to Tokyo, the expectation is that the plane will be flying toward the sunset. This effect is accomplished by two light sources: one directional light to simulate the sun and one positional light to illuminate the sky hemisphere.

To create the impression of water, the sea surface is coloured using the OpenGL fog technique. The caustics effect developed by Stam in [13] is also utilised to render the scene more realistically.

The avatar is fixed in the centre of the sphere. By an-

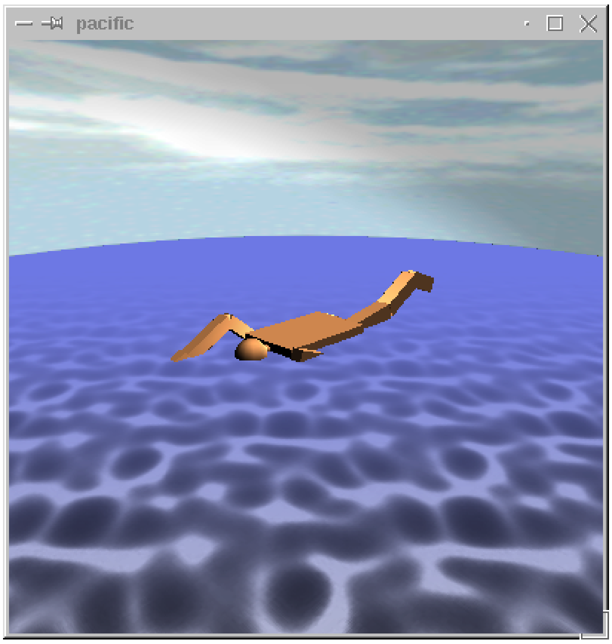

Figure 4: Aerial view of the SAP environment.

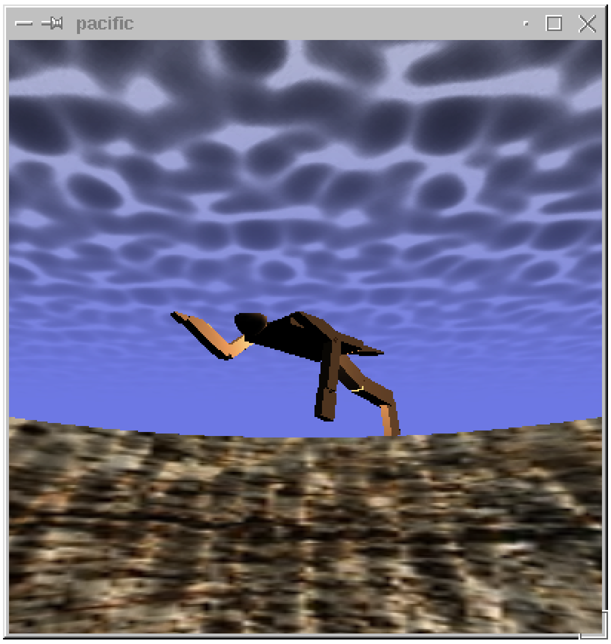

Figure 5: Aquatic view of the SAP environment.

imating the sea-texture so that it moves backward, the avatar appears to be moving forward. The speed of the ocean's movement also depends on the swimmer's stroking speed, so the harder the subject swims, the faster the waves are moving. We are in the process of animating the ocean floor.

3.3 Synchronising the Real World and the Virtual World

In order to synchronise the movement of the swimmer to that of the avatar, we utilise Polhemus Fastrack sensors for the limbs, head, and body, a head-mounted display for the swimmer, and a tcl/tk user interface for calibration and adjustment of various environment and avatar parameters. Figure 6 shows the placement of the sensors on the swimmer's limbs, torso, and head, as well as the position of the transmitter with respect to the swimmer. The hemisphere shown indicates the range in which the signals of the transmitter can be picked up by the sensors.

The mapping of sensor data to the avatar involves calculating the camera view, and the leg and arm positions. This is a similar problem to that of motion capture in animation. The restriction of swimming stroke to front crawl and butterfly simplifies the sensor interpretation for the legs because only vertical motion needs to be considered. We will see, however, that the arm positions are more complex.

The data from the head-mounted sensor is mapped to the avatar's view using OpenGL's convenient functions for setting the camera parameters. Once the position and orientation of the head sensor is obtained, the position and the orientation of the camera can be easily determined to create the viewing perspective. The scene is then rendered to the head mounted display worn by the swimmer. Since audience participation is desirable during the performance of SAP, the tcl/tk interface also provides selection of different perspectives of the scene.

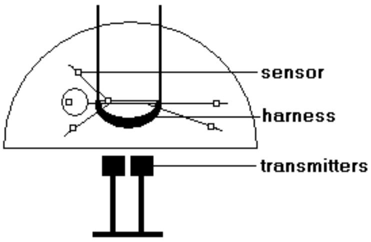

Figure 6: Locations of the sensors and transmitter on the swimmer.

Inverse kinematics is used to determine the leg positions based on data from sensors located at the swimmer's ankles. The vertical restriction of the kick allows us to assume only one degree of freedom at each of the hip and knee. This allows the legs to be mapped using just a straightforward application of the cosine rule to find the angle of rotation at the hip with respect to sea level. The angle of the knee is interpolated from the angle of the hip, which dictates how deep the leg is in the water.

The arm has much more mobility than the hip, effectively having three degrees of freedom at the shoulder and two at the elbow[1]. The arm is also very important in swimming: Counsilman explains in [6] that arm strokes are the main propelling component, whereas kicking only serves to keep the body afloat. This shows how important the arm strokes are in swimming.

The position of the swimmer's arms is determined with a sensor at each wrist and a sensor on the torso between the shoulders. Our original algorithm used inverse kinematics, as with the legs, to calculate the angle associated with each the five degrees of freedom of the arm. However, though theoretically sound, the calculations are underdetermined and even with simplification proved to be too sensitive to minor inaccuracies in calibration and sensor values to create a realistic impression.

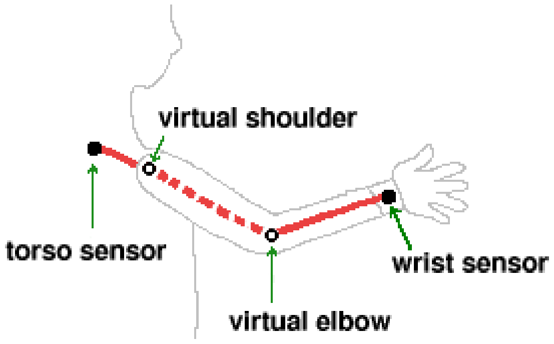

Figure 7: Sensor positions on swimmer's arm, along with extrapolated shoulder and elbow positions. The dotted line depicts the interpolated upper arm.

A simpler, though less accurate, method was chosen to display the arms; it just connects the positions of shoulder, elbow, and wrist with links. The wrist position is known from the wrist sensor, and the shoulder is known to be a certain offset from the torso sensor. The elbow is calculated simply as an offset from the wrist, making it effectively disconnected from the shoulder, as shown in Figure 7. With the three positions known, links are drawn between the shoulder and elbow and between the elbow and wrist; no joint angles need to be calculated. The inaccuracy lies in the fact that the upper arm can change length if the shoulder and elbow offsets are incorrectly calibrated. Careful calibration can overcome this difficulty.

The avatar itself is of simple construction, being implemented with rectangular prisms and spheres. It is modelled in a hierarchical fashion that includes the torso, head, legs, and feet. When the inverse kinematics problem of the arms is solved, the arms will be added to the hierarchy.

We are looking at better sensor placement to make the inverse kinematics simpler and more appropriate for swimming. This will facilitate the use of the swimming interface as a general purpose interface.

4 User Testing

Thus far, only informal testing has been done to evaluate the swimming apparatus. The subjects included seven lab mates, two of the three main SAP performance artists, and several volunteering lab guests, all of whom had various levels of swimming experience. The majority of users responded that they experienced the feel of swimming when suspended in the swimming apparatus. The rope-pulley system provides appropriate resistance as well as buoyancy during kicking, and the harness is comfortable to wear, although a little heavy. In terms of the graphics environment, users suggested having more objects in the scene to make the swimming environment more interactive and engaging. Although the head-mounted display in use was unreliable due to hardware driver difficulties on our Linux machine, users using the monitor felt that environmental objects serving as landmarks would help navigation.

5 Discussion and Future Work

The SAP project has been well-received by those who have tried it. The harness is comfortable if worn correctly, though rolling is not as easy as it could be. The leg system is sufficient in its current state. Haptic feedback is desirable on the arms, which are currently unencumbered. The graphics are good as a starting point, but certainly need improvement for SAP to be used as a general VR interface. Other possible improvements involve the engagement of the swimmer's other senses, such as hearing or taste.

The harness required very little modification from its original form as a hang-gliding harness. Some of the straps and support points required adjustment, and padding was added to improve comfort, but otherwise the harness serves very well. Unfortunately, the harness doesn't allow as much rolling motion as we would like; a solution for torso roll needs to be found. Improving the quality of the pulleys supporting the torso helped the roll, but the harness could still be improved.

The leg rig provides a close approximation to the sensation of kicking in water, though we were surprised to

---

[1] The rotation of the forearm can be considered to be a rotation at the elbow.

find that no support was required at the knees as we had initially implemented. With the sandbags properly weighted for the user, the passive feedback of the leg system needed improvement from our initial implementation. The first pulleys that were used didn't have fast enough bearings, so the response was sluggish; the inertia of the sandbags was noticeable as well. Faster pulleys, stabilised by diagonal cords, improved the response, while the addition of bungees overcame the inertia problem. The resulting passive system proved adequate in approximating the swimming feeling. The greatest improvement that could be made to the leg system is to add active feedback to simulate the legs' exit from the water when the swimmer kicked high enough, but as this rarely happens during normal prone swimming it wasn't a priority.

Some sort of haptic feedback is certainly required for the arms, but remains a research question. Improving the sensor locations for the arms is also important, as this will allow us to properly calculate the hierarchical model of the avatar. Additional sensors may be required to accurately determine the joint angles of the arm.

Our feeling is that the biggest improvements for SAP will come from better graphics. A full 3D environment should be implemented using a 3D rendering engine such as Quake. More environmental elements, such as fish, boats, and underwater terrain should be modelled; landmarks for San Francisco and Tokyo should certainly be included. 3D wave and water splashing effects will create essential visual stimulation, and the avatar should be rendered in a more sophisticated fashion. When the system is developed substantially, we plan to investigate the swimming cage in a CAVE to see if we can achieve a more immersive experience.

Audio feedback will likely provide additional realism if synchronised properly, though the synchronisation is not a simple task. Finally, olfactory and gustatory feedback will allow the swimmer to feel wetness and the urge to breath in through the mouth and out through the nose when engaged in virtual swimming.

6 Summary

Swimming Across the Pacific introduces surface swimming as a new locomotion interface. It allows common swimming movements to be translated into movement through a 3D virtual environment and provides some realistic swimming sensations to the swimmer. The SAP interface has great potential as a general locomotion interface for a variety of educational and entertaining 3D environments.

Acknowledgements

The people and organisations we would like to thank are left out to preserve anonymity. They will be included in the final version.

References

[1] R. S. Allison, L. R. Harris, M. Jenkin, G. Pintilie, F. Redlick, and D. C. Zikovitz. First steps with a rideable computer. In *Proceedings of the Second IEEE International Conference on Virtual Reality*, 2000.

[2] Case studies in navigation and positioning. *Underwater Magazine*, Fall 1999.

[3] M. Buffa, F. Diard, M. Persson, and P. Sander. The Virtual Diver, an architectural "swim-around" system incorporating real imagery. In *Proceedings of the Computer Graphics Technology for the Exploration of the Sea*, Rostock, Germany, May 1995.

[4] G. U. Carraro, M. Cortes, J. T. Edmark, and J.R. Ensor. The Peloton bicycling simulator. In *Proceedings of the Third Symposium on Virtual Reality Modeling Language*, pages 63–70, New York, 1998. SIGGRAPH, SIGCOMM, ACM Press.

[5] R. Christensen, J. M. Hollerbach, Y. Xu, and S. Meek. Inertial force feedback for the Treadport locomotion interface. In *Presence: Teleoperators and Virtual Environments*, volume 9, pages 1–4, 2000.

[6] J. E. Counsilman. *The Science of Swimming*. Prentice Hall, New Jersey, 1968.

[7] C. Cruz-Neira, D. Sandin, and T.A. DeFanti. Surround-screen projection-based virtual reality: the design and implementation of the CAVE. In *ACM SIGGRAPH Proceedings*, pages 135–142, 1993.

[8] N. I. Durlach and A. S. Mavor, editors. *Virtual Reality: Scientific and Technological Challenges*. National Academy Press, Washington, D. C., 1994.

[9] The Fraunhofer-Institute for Industrial Engineering IAO. About Aquacave, 1996. http://www.iao.fhg.de/VR/information/Equipment/CAVEEE/aquacave5.html (Accessed Jun 30, 2001).

[10] Ars Electronica Futurelab. The birdman, 2000. http://www.aec.at/center2/english/exhibit/archiv/hump/hump/hump_1.htm. (Accessed Nov 18, 2001).

[11] L. F. Hodges, B. O. Rothbaum, B. Watson, G. D. Kessler, and D. Opdyke. A virtual airplane for fear

of flying therapy. In *IEEE Virtual reality Annual International Symposium Proceedings*, pages 86–93, 1996.

[12] J. M. Hollerbach, Y. Xu, R. Christensen, and S. C. Jacobsen. Design specications for the second generation SarcosTreadport locomotion interface. In *Proceedings of ASME Dynamic Systems and Control Division*, volume 69, pages 1293–1298, 2000.

[13] J. Stam. Random caustics: Natural textures and wave theory revisited. In *ACM SIGGRAPH Proceedings*, page 150, 1996.

[14] D. Stewart. A platform with six degrees of freedom. volume 180, pages 371–386, 1965-1966.

[15] Dreamality Technologies. Dreamality technologies, 2001. http://www.dreamalitytechnologies.com. (Accessed Nov 17, 2001).