Gait Master: A Versatile Locomotion Interface for Uneven Virtual Terrain

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Abstract

The Gait Master is a locomotion interface that creates sense of walking on uneven surface. The device employs a turntable on which two motion platforms are mounted. The motion platforms trace the feet and carry them back to the neutral position. The user can physically walk in a virtual space while the position is maintained. The motion platforms move vertically, which simulates uneven surface. The walker can climb up or go down a virtual staircase while the position is maintained. The turntable rotates the motion platforms, so that the walker can walk in any direction. We have developed two prototypes and evaluated them through user studies.

1. Introduction

Advanced applications of virtual reality technology often require good sense of locomotion. Traveling on foot is the most intuitive style of locomotion. One of the major research issues in locomotion interface is presentation of uneven surface. Locomotion interfaces are often applied for simulation of buildings or urban spaces. Those spaces usually include stairs. A walker should be provided sense of climbing up or going down those stairs. Some applications of locomotion interface, such as training simulators or entertainment facility, rough terrain should be presented.

Typical locomotion interface employs a treadmill. However, the device has difficulty in presentation of uneven surface. We solved the problem using two motion platforms that independently move according to the position of the feet. The motion platforms trace the feet and carry them back to the neutral position. The user can physically walk in a virtual space while the position is maintained. The motion platforms move vertically, which simulates uneven surface. The walker can climb up or go down a virtual staircase while the position is maintained. These motion platforms are mounted on a turntable, which trace the orientation of the walker. The turntable enables the walker to go in any direction.

We have developed tow prototypes of the GaitMaster. Effectiveness and limitations are studied using these prototypes.

2. Previous works on simulation of uneven surfaces

There are two methods for simulation of uneven surface:

(1) Treadmill

A simple device for virtual walking is a treadmill, ordinary used for physical fitness. An application of this device to virtual building simulator was developed at UNC[1]. Their treadmill has a steering bar similar to that of a bicycle. A treadmill equipped with a series of linear actuators underneath the belt is developed at ATR[2]. The device is named GSS, which simulates slope of virtual terrain. The Treadport developed at University of Utah is a treadmill that is combined with a large manipulator connected to a walker[3]. The manipulator provides gravitational force while the walker is passing a slope.

The Omni-directional Treadmill employs two perpendicular treadmills, one inside of the other. Each belt is made from approximately 3400 separate rollers, woven together into a mechanical fabric. Motion of the lower belt is transmitted by the rollers to a walker. This mechanism enables omni-directional walking[4].

(2) Foot pad

Foot pad applied to each foot is an alternative of implementation of locomotion interface. Two large manipulators driven by hydraulic actuators are developed at University of Utah and applied to a locomotion interface. These manipulators are attached to feet of a walker. The device is named BiPort[5]. The manipulators can present viscosity of virtual ground. A similar device has been developed at the Cybernet Systems Corporation, which uses two 3 DOF motion platform for the feet[6].

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These devices, however, have not been evaluated or applied to VE.

We have been developing prototypes of locomotion interfaces for virtual environments since 1989. The project was named Virtual Perambulator[7] A walker of the first prototype wore parachute-like harness and omni-directional roller skates. The trunk of the walker was fixed to the framework of the system by the harness.

We tried presentation of virtual staircase at the early stage of the Virtual Perambulator project [8]. A string is connected to the roller skate of each foot. The string is pulled by a motor. When the walker climbing up stairs, the forward feet is pulled up. When the walker goes down stairs, the backward foot is pulled up. However, this method was not successful because of instability.

Later we applied a 6 DOF motion platform to final version of the Virtual Perambulator, where a user walks in a hoop frame. The walker stood on the top plate of the motion platform. We used pitch and heave motion of the platform. When the walker stepped forward to climb up a stair, the pitch angle and vertical position of the floor increased. After finishing climbing motion, the floor went back to the neutral position. When the walker stepped forward to go down a stair, the pitch angle and vertical position of the floor decreases. This inclination of the floor is intended to present height difference between the feet. The heave motion is intended to simulate vertical acceleration. However, this method failed in simulation of stairs. The major reason was that the floor was flat.

A possible method of creation of height difference between the feet is application of two large manipulators. The BiPort is a typical example. A 4 DOF manipulator driven by hydraulic actuators is connected to each foot. The major problem of this method is that how the manipulators trace the turning motion of the walker. When the walker turns around, two manipulators interfere each other.

We developed the Torus Treadmill for providing natural turning motion[9]. The walker on the Torus Treadmill can physically turn about on the active floor. Turning motion using the feet has major contribution to human spatial recognition performance. Vestibular and proprioceptive feedback is essential to the sense of orientation [10]. The Torus Treadmill can be modified for simulation of uneven surface. If we install an array of linear actuators on each treadmill, uneven floor can be realized by controlling the length of each linear actuator. However, this method is almost impossible to implement, because a very large number of linear actuators are required to cover the surface of the torus-shaped treadmills and control signal for each actuator must be transmitted wirelessly.

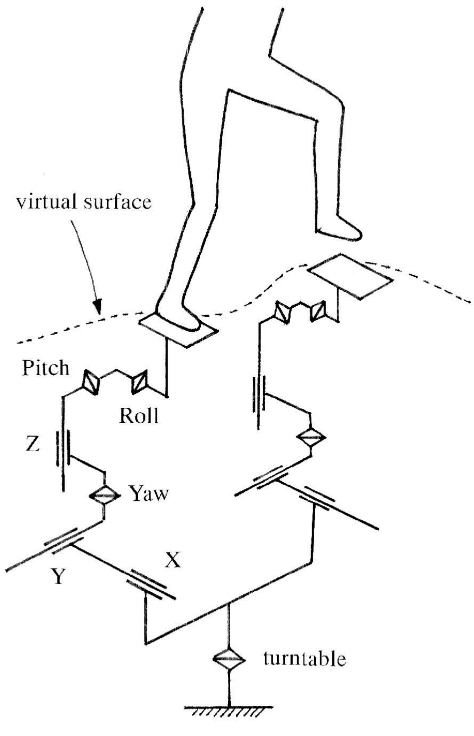


Figure 1 Basic design of the GaitMaster

3 Basic Design of the Gait Master

3.1 Physical configuration

A new locomotion interface that simulates omni-directional uneven surface has been designed. The device is named "GaitMaster." The core elements of the device are two 6 DOF motion platforms mounted on a turntable. Figure 1 illustrates basic configuration of the GaitMaster.

A walker stands on the top plate of the motion platforms. Each motion platform is controlled to trace the position of the foot. The turntable is controlled to trace the orientation of the walker. The motion of the turntable removes interference between the two motion platforms.

The X and Y motion of the motion platform traces horizontal position of the feet and cancel its motion by moving to the opposite direction. The rotation around the yaw axis traces the horizontal orientation of the feet. The Z motion traces vertical position of the feet and cancels its motion. The rotation around the roll and pitch axis simulates inclination of a virtual surface.

3.2 Control algorithm

The control algorithm must keep the position of the walker at the neutral position of the GaitMaster. In order to keep the position maintained the motion platforms have to cancel the motion of the feet. The principal of the cancellation is:

1) Suppose the right foot is at the forward position and left foot is at the backward position while walking.
2) When the walker steps forward the left foot, the weight of the walker is laid on the right foot (Figure 2 left).
3) The motion-platform of the right foot goes backward in accordance with the displacement of the left foot, so that the central position of the walker is maintained.
4) The motion-platform of the left foot follows the position of the left foot. When the walker finishes stepping forward, the motion-platform supports the left foot (Figure 2 right).

If the walker climbs up or goes down stairs, a similar procedure can be applied. The vertical motion of the feet is canceled using the same principal.

Figure 3 illustrates the method of canceling climb-up motion:

1) Suppose the right foot is on the upper stair and left foot is on the lower stair while climbing.
2) When the walker lifts up the left foot, the weight of the walker is laid on the right foot.
3) The motion-platform of the right foot goes down and backward in accordance with the displacement of the left foot, so that the central position of the walker is maintained.
4) The motion platform of the left foot follows the position of the left foot. When the walker finishes stepping up, the motion platform supports the left foot.

In this way, the vertical displacement of the forward foot is canceled in accordance with the motion of the backward foot. The central position of the walker is maintained at the neutral height so that infinite sitars can be simulated.

This procedure is similar to climbing up a downward escalator. However, different from an escalator, the GaitMaster doesn't move until the walker lifts up the downward foot. The center of mass of the walker rises up during the motion, so that the GaitMaster provides exertion to the walker. Figure 4. Illustrates the rising up procedure.

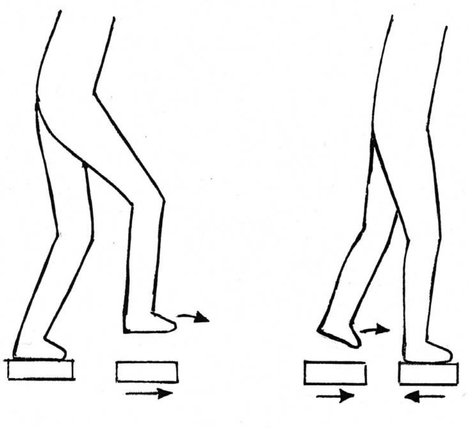


Figure 2. Cancellation of forward motion

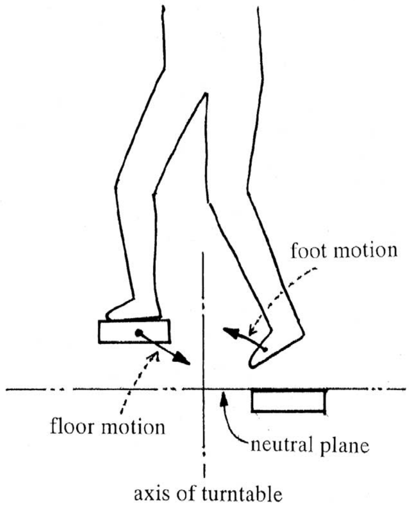


Figure 3. Cancellation of upward motion

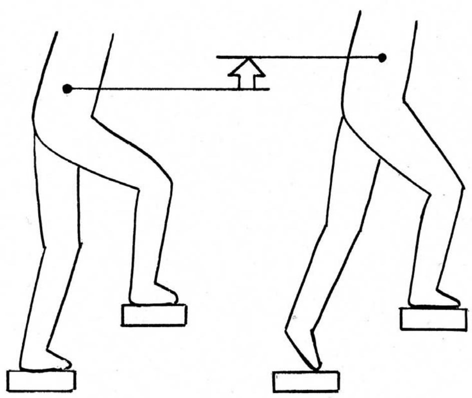


Figure 4. Rising up motion of the center of mass

When the walker goes down stairs, vertical motion of the GaitMaster is reversed. Figure 5 illustrates the method of canceling go- down motion;

1) Suppose the right foot is on the lower stair and left foot is on the upper stair while going down.
2) When the walker lifts up the left foot, the weight of the walker is laid on the right foot.
3) The motion platform of the right foot rises up and backward in accordance with the displacement of the left foot, so that the central position of the walker is

maintained.

4) The motion platform of the left foot follows the position of the left foot. When the walker finishes stepping down, the motion platform supports the left foot.

The turntable rotates so that the two motion-platforms can follow the rotational motion of the walker. If the walker changes direction of walking, the turntable rotates to trace the orientation of the walker. The orientation of the turntable is determined according to direction of the feet. The turntable rotates so that its orientation is at the middle of the feet (Figure 6). The walker can physically turn around on the GaitMaster using this control algorithm of the turntable.

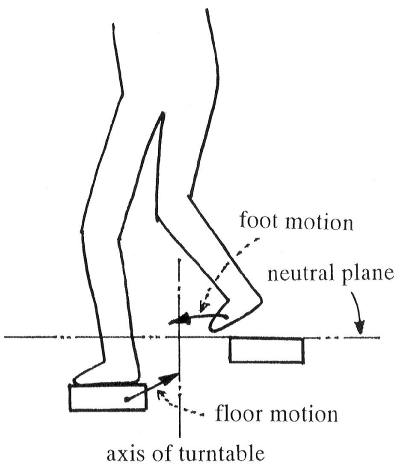


Figure 5. Cancellation of downward motion

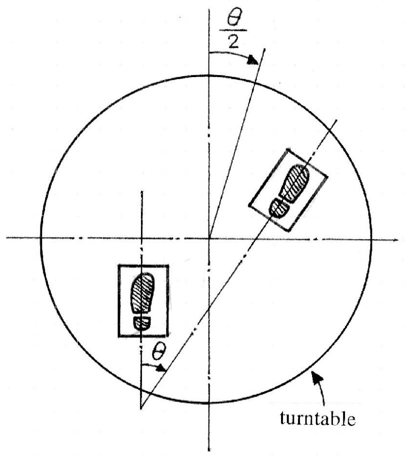


Figure 6. Method of following orientation of the walker

4. Implementation 1: Straight Forward Prototype

Basic function of the GaitMaster is that two foot pads follow walker's feet and provide uneven terrain. The simplest configuration of a motion platform is 2DOF that moves back-and-forth as well as up-and-down. We developed the motion platform using pantograph

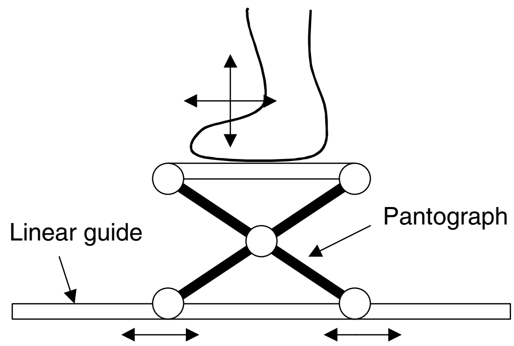


Figure 7. Pantograph mechanism

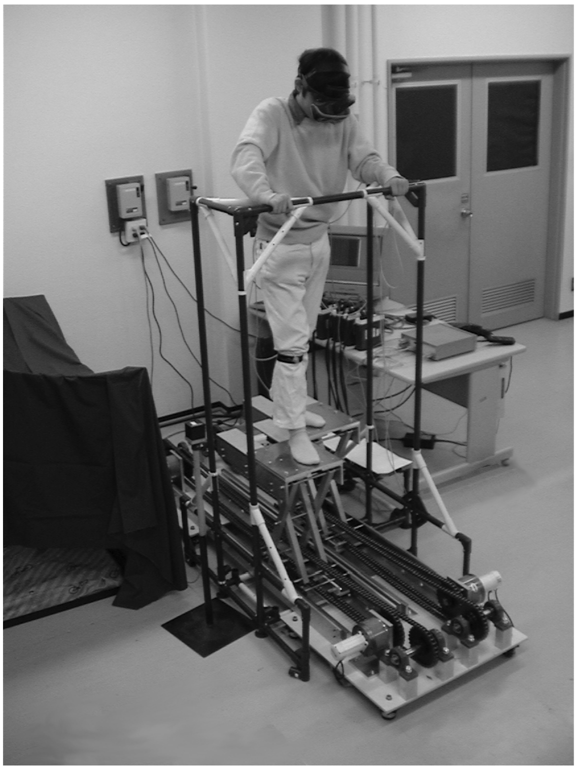


Figure 8. Overall view of the straight forward prototype

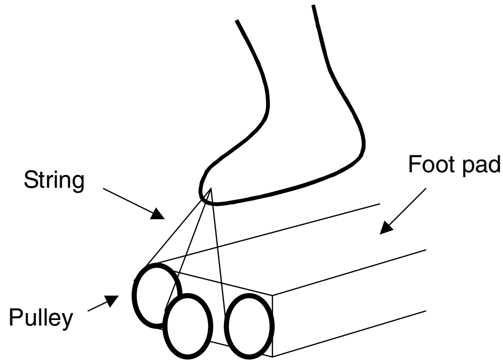


Figure 9. String sensor

mechanism. Figure 7 illustrates basic structure of the mechanism. Base joints of the pantograph move independently along a linear guide. These joints are actuated by two AC motors and chains. Horizontal working area of the motion platform is 80cm, which is designed to cover normal steps. Vertical working area is 20cm. The maximum horizontal speed of the foot pad at loaded state is 1.5m/s. Thus, the foot pads can follow the feet moving at normal walking speed. The maximum payload is 80Kg. Figure 8 shows overall view of the prototype.

Position of the foot is measured by Polhemous FASTRACK at first. However, FASTRACK suffered from magnetic noise caused by metals in the motion platforms. Thus, we developed a new sensor using three sets of tensioned strings. These strings are connected to sandals of the walker. Figure 9 illustrates setup of the sensor. Length of the string is measured by a potentiometer connected to an axis of the pulley. Position of the toe is calculated by length of three strings.

5. Implementation 2: Omni-directional Prototype

We have developed another prototype of the GaitMaster. The system employs a turntable in order to provide omni-directional walking. The prototype 1 has long linear actuators that exceed 2m, which makes large momentum. It is difficult to mount it on a turntable. We therefore developed a new motion platforms composed of three linear actuators top of which a yaw joint is mounted. Figure 10 illustrates mechanical configuration of the prototype. Figure 11 shows overall view of the prototype GaitMaster.

The compact mechanism of the motion platform enables 3 DOF motion. We disassembled a 6 DOF Stewart platform and made two XYZ stages. Three linear guides are applied to support the orientation of the top

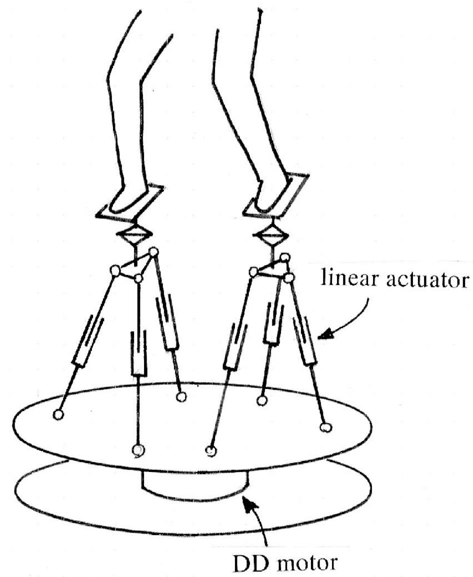


Figure 10. Mechanical configuration of the omni-directional prototype

Figure 11. Overall view of the omni-directional prototype

plate of the motion platform. The payload of each motion platform is approximately 150Kg. The maximum speed of the top plate at loaded state is 50cm/s. A rotational joint around yaw axis is mounted on each motion platform. The joint is equipped with a DC motor that traces orientation of the feet. Full specification of the GaitMaster is composed of 6 DOF motion platforms. However, we assumed that the surface of the virtual space consists of sets of plainer surfaces. Most of buildings or urbane spaces can be simulated without inclination of the floor. Thus, we can neglect the roll and pitch axis of the motion platforms.

A turntable is developed using a large DD motor. The maximum angular velocity is 500 deg/sec. A three DOF goniometer is connected to each foot. The goniometer measures back-and-forth and up-and-down motion as well as yaw angle.

Working area of the foot pad is 32cm (back-and-forth), 28cm (left-and-right), and 20cm (up-and-down). The working area is limited due to the stroke of the linear actuators. Back-and-forth motion is much smaller than normal walking stride. However the walker can change walking direction up to 90 degrees in a single step. Thus, the system has an ability to trace normal turn around motion.

6. Evaluation and Discussion

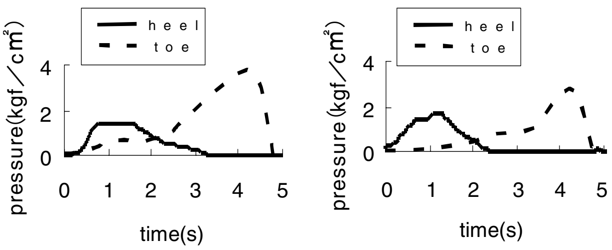
6.1 Measurement of applied force at the sole

There are many methods for evaluation of walking. Since major objective of the GaitMaster is presentation of uneven terrain, applied force at the sole is the most important aspect for evaluation. We therefore measured pressure of the sole of the walker for evaluation of naturalness of walking. Two force sensors are put underneath the sole of the walker: one is at the toe and the other is at the heel. Each sensor is composed of straingauge and diaphragm. Sensing range of the sensor is 0 ~ 20 Kg/cm2 and linearity is 1%.

We measured pressure of the sole while climbing up 12cm-hight stair and going down 8cm-hight stair. The prototype 2 is used for this experiment. We set the same size sitars in the real world for comparison.

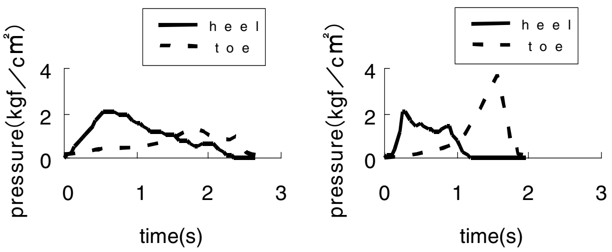
Figure 12 shows result of measurement of climbing-up motion. Peek of each curve indicates the time when the walker lays the weight on the foot. The result shows that transition of the weight at the heel on the GaitMaster is close to that on the real stair. On the other hand, peak weight at the toe on the GaitMaster is larger than that on the real stair. The walker holds a safety bar while walking on the GaitMaster. The result indicates that extra force is applied between the safety bar and the foot pad, so that weight at the toe is increased.

Figure 13 shows result of measurement of going-down motion. The result shows that transition of the weight at the heel on the GaitMaster is close to that on the real stair. On the other hand, peak weight at the toe on the GaitMaster is lower than that on the real stair. The phenomenon is caused by the same reason. The walker holds a safety bar, so that part of the weight is laid on the bar while going down. This reduced the pressure at the toe.



Gait Master Real stair

Figure 12. Sole pressure while climbing up



Gait Master Real sitar

Figure 13. Sole pressure while going down

The results shown in Figure 12 and 13 indicates that transition of the weight on the GiatMaster is close to that on the real stairs. However the walkers could not go through virtual stairs without the safety bar. The result suggests that stability while transition of weight should be increased.

6.2 Observation of user behavior at SIGGRAPH 2000

As a usability test of the prototype GaitMaster, we examined behavior of novice users. We are interested in behavior of novice users. In order to collect subjects for this purpose, we brought straight forward type prototype to the Emerging Technologies venue at the SIGGRAPH 2000 (July 23-28, 2000, New Orleans). Figure 14 shows a scene of our booth. Participant of our demonstration experienced virtual flat terrain as well as staircases.

The major interest of this experiment is tracking performance of the motion platforms. We put safety straps at the foot pad in case the motion platform fails in tracing. The safety straps are put at toe and heel of a sandal (Figure 15). Length of each strap is 10cm. Participants put off their shoes and put on the sandals with safety straps.

Through the observation of the experiment, we found that tracking performance is not sufficient. The position sensor using strings has 0.3s time delay. The delay caused offset between the foot and pad. Walkers often steeped out from the pad. However, the safety straps worked well so that their feet didn't fall down from the pad. We found that the toe strap played main roll in safety, on the other hand the heel strap did not. We therefore removed the heel strap on the 3rd day of the conference. None of the participants suffered from dangerous situation through the 6-day conference.

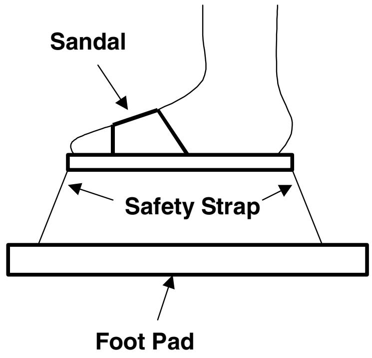


Figure 15. Safety straps

7. Conclusions and Future Work

This paper has shown our research activities on an interface device for locomotion on uneven virtual terrain. Design principal and its preliminary implementations are introduced. Although the current hardware needs improvement, the prototypes showed potential effectiveness of the design.

We evaluated fundamental performance of the prototype implementations. Further evaluation should be needed. For example, subjects' perception when climbing up/down in various situations should be tested. Also, the interface should be combined with high-quality image display, which enables study of relationship between visual and haptic sensation while climbing. Experiments under such condition that the step height of the visually displayed staircase is higher than the step size displayed by the device would be interesting. Design guidelines for the GaitMaster will be derived from these experiments.

Locomotion by walking motion is intuitive and is inevitable in study on human behavior in virtual environments. One of the major application areas of the GaitMaster is rehabilitation. We are working with medical doctors to apply it tele-rehabilitation of walking.

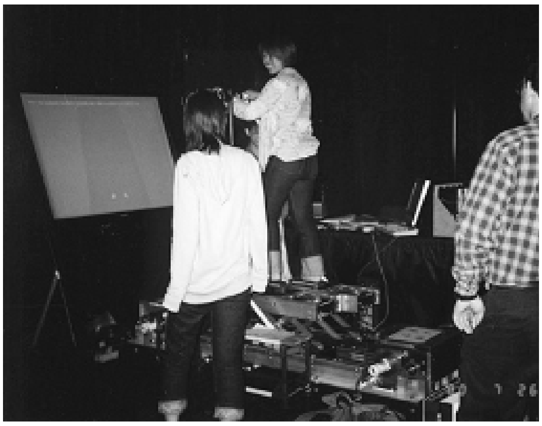


Figure 14. Scene of SIGGRAPH 2000 demo

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