Balance NAVE; A Virtual Reality Facility for Research and Rehabilitation of Balance Disorders

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ABSTRACT

We are currently developing an immersive virtual environment display for research into the rehabilitation of balance disorders, called the Balance NAVE (BNAVE). Using this system, the therapist can create varying degrees of sensory conflict and congruence in persons with balance disorders. With the capability of changing visual scenes based on the needs of the therapist, the BNAVE is a promising tool for rehabilitation. The system uses four PC's, three stereoscopic projectors, and three rear-projected screens, which surround the patient's entire horizontal field of view. The BNAVE can accommodate many types of sensors and actuators for a wide range of experiments.

1. INTRODUCTION

Maintaining balance during everyday tasks requires the integration of sensory information from the vestibular system of the inner ear; vision; and somatosensation. The latter is the feeling of where the joints are in space and the sensation of pressure on the skin. The brain interprets these signals to define the position of the body. If this process is disrupted by illness or injury, then postural instability, dizziness and severe nausea result. Such disruption can result from aberrant sensory signals, conflicting sensory information, or a disruption of the areas in the brain that integrate these signals.

Almost 7% of persons seen in emergency rooms [4] and 2.6% of persons seen by their primary care physician [21] complain of dizziness. Symptoms can be debilitating, with complaints of severe dizziness, nausea, blurred vision, and dysequilibrium. Depending on the specific cause and symptoms, treatments can include medication, vestibular physical therapy, surgery or any combination of these three. Vestibular physical therapy is a relatively recent intervention that has been shown to be effective with certain balance disorders. [19] The Balance NAVE (BNAVE) at the University of Pittsburgh (Fig. 1) was developed for use in vestibular physical therapy for balance disorders.

Figure 1: The BNAVE with a viewer.

In this paper, we will present the background and rationale for building the BNAVE, requirements to which it was built and the critical design aspects that allow it to meet those requirements. The BNAVE is a stereoscopic, projection-based environment, based on the original NAVE display at Georgia Tech. [29]

2. VR IN BALANCE THERAPY

Unilateral peripheral vestibular dysfunction (physical damage to the inner ear) is the most common disorder seen in vestibular physical therapy. The signal coming from the vestibular system is altered by disease or injury, causing a sensory mismatch in the brain, resulting in dysequilibrium, dizziness and nausea. Usually, the brain will adapt to this change in the vestibular signal by "re-weighting" this signal in relation to the other senses. However, this adaptation does not occur in some, and the problem becomes a chronic illness with significant disability. Physical therapists treat this illness by prescribing certain exercises that promote adaptation. Exercises are based upon the patient's diagnosis, symptoms, age, health and physical ability.

Treatment relies on challenging the patient's postural control system with varied experiences in visual environments. These challenges require varying levels of sensory integration of the vestibular, visual and somatosensory signals, where the patient is exposed to both congruent and conflicting signals. The central nervous system adapts to the varied combinations of balance signals, which in turn will improve the patient's balance and reduce symptoms. The advantage of virtual reality (VR) technology, over conventional methods, is to allow the therapist to provide a variety of stimuli to each patient with great specificity. The therapist can place a patient in situations with graded levels of sensory congruence or conflict, then change the conditions in response to the progression of the patient. In addition, the therapy can be done in a controlled, safe environment, which is particularly important for frail individuals at high risk for falling.

A visually appropriate virtual environment (VE) may be an effective tool for the rehabilitation of impaired human balance. The VE should produce a postural adjustment response in the viewer. [14][17] Adaptation to the VE can affect the viewer's post-exposure postural stability [7] [12] and his or her vestibulo-ocular reflex. [23][24][2] Kramer et al. recast several important experiments in vestibular and oculomotor research using certain VEs and got much the same results as with conventional methods. [13] In one study, [23] patients with significantly damaged vestibular systems were not able to adapt their oculomotor reflexes to the natural environment, because it required too great a change from their oculomotor systems' current states. The therapists were able to improve the patients' stability, using a series of VEs to gradually adapt them to the natural environment. Persons with traumatic brain injury who received a form of VE-based balance training showed varying degrees of improved balance. [25][6][20][11] Finally, there is a strong connection between balance disorders, anxiety and panic disorder. [31][33] The BNAVE is well equipped to expand on already successful research in this area. [32]

3. TECHNICAL CHALLENGE

Initially, we intend to use the BNAVE for assessment and treatment of balance disorders, and to research certain basic science questions. Requirements for this work give rise to specifications for the BNAVE, which in turn drive its design.

Physical Safety: In order to prevent the subjects from falling, they will wear a parachute-grade harness that is supported from a rigid structure in the ceiling. We also made the front opening of the BNAVE wide enough so the viewer is unlikely to grab it or fall on it.

Subject Inputs and Outputs: The BNAVE design must allow for many types of sensors and actuators for our experiments. These include, but are not limited to, a various floor surfaces, treadmill, head-tracker, human motion analysis sensors, eye trackers, autonomic function monitors, video cameras, and force plate.

Wide Field of View: The field of view (**FOV**) of a camera or an eye refers to the entire angular area it can see. Including peripheral vision, the human eye can see everything in an approximately 130-degree horizontal arc and a 95-degree vertical arc. Using both eyes, the average person can see approximately 180 degrees horizontal by 95 degrees vertical. This is the viewer's FOV.

Whatever scene the BNAVE produces must cover the viewer's entire horizontal FOV, when he or she is looking forward at the center of the display. (Fig 2) Visual motion cues in the peripheral visual field are processed differently than those seen in central vision, and the therapist should be able to control the mix of central and peripheral stimuli. [16][18][1][22] When the viewer is standing at the average expected viewing position (Fig 2 & 9) the BNAVE display fills all of the

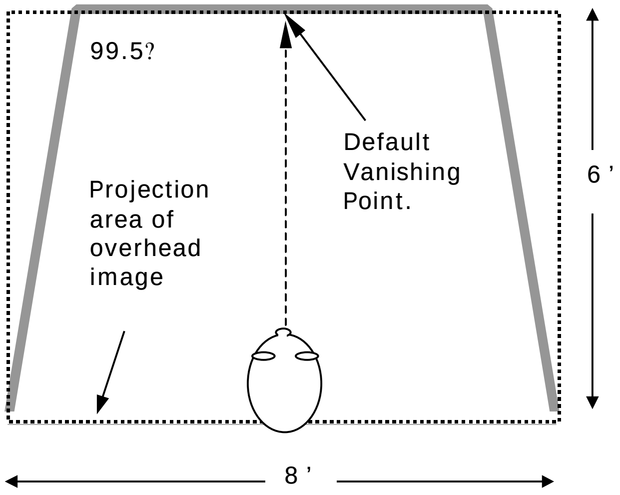

Figure 2: Schematic of the BNAVE projection screens and viewer.

180-degree horizontal field of view, and 80-degrees of the vertical field of view.

Perspective Correction: In the natural world, objects in the visual scene all appear to converge to a single point in the distance. A classic artistic technique is to make everything in a painting appear to converge to a single fixed point on the canvas, called the vanishing point. This creates a strong illusion of depth in the flat image. [19] The BNAVE display will do the same thing with every image it displays, converging the scene to a point directly in front of the viewer, at eye level.

In “fixed point” mode, the BNAVE will always use the same vanishing point, a location at eye level on the centerline of the front screen. (Fig 2) In “head-tracked mode”, the BNAVE will re-compute the vanishing point every time the viewer moves his or her head, using information from the head-tracking sensor. The effect will be that the perspective correction will be correct in approximately the direction of the viewer’s gaze. In the future, we hope to add software that can use information from the eye-tracker, so the BNAVE can use the true direction of gaze.

The head-tracking sensor is a Polhemus Fastrak [28] system. The sensor is affixed to the apex of the headgear with its primary axis aligned with an axis in the antero-posterior direction, midway between the eyes.

Light Headgear: Many persons with balance disorders are older, and many of these patients tend to look down at their feet often by tilting the head**.** By contrast, healthy test subjects tend to hold the head vertical. [19] Light headgear is more comfortable and less likely to confound test results, particularly where head tilting occurs. For head tracking, the viewer wears a small sensor attached to an adjustable plastic headband, weighing approximately 4 ounces. When a stereoscopic image is needed, the viewer wears a pair of large, passive polarizing glasses (fig 5), weighing approximately 5 ounces.

Stereopsis: Each person has a fixed distance between his or her eyes, which guarantees that each eye will always see the world from a slightly different angle. While the brain integrates both views into a single image, it exploits the differences to see depth. [5] For example, each eye of a person looking at a box will actually see a slightly different image of that box. However, the viewer will only be aware of a single box and will have a good intuition of where it is in the room.

To simulate this effect, the BNAVE’s display is able to present each eye with an image of the virtual environment that is appropriately offset from what the other eye sees. This capability is implemented using projectors that generate linearly polarized light, and passive polarizing light filter glasses.

Floor Projection: Given the width of the BNAVE display, the viewer can turn the head from side to side a few degrees and still have most of his or her FOV engaged by the projected visual scene. However, patients with vestibular disorders tend look down at the floor. Eventually, the BNAVE will also project more of the virtual environment onto the floor where the viewer is standing.

3. APPROACH AND SOLUTIONS

A variety of projective, immersive displays now exist. The original such display is the CAVE developed at the University of Illinois at Chicago. [3][26] It is essentially a small room, where each wall is a rear-projected screen. “CAVE” is a trademark, which stands for "CAVE Automatic Virtual Environment." Functionally similar displays are the 3D cube at Chalmer's Medialab [30], TAN's "CUBE"[31] and Trimension's ReaCTor [32]. Some displays simply use a very large screen or "wall" to create a sense of immersion, such as Fakespace's Immersive Workwall [26] or MechDyne's MD-Wall. [27] Of interest are dome displays, like Trimension's V-Dome. [32] Finally, there are re-configurable displays like Fakespace's RAVE [26] or MD MegaPlex, [27] either of which can be a wall or a cave or anything in between. So-called immersive workstations are not considered here, because they require the user to be seated too close to the display. The virtual displays listed above are impressive in many ways, but require shutter glasses, which do not allow for maximum FOV.

After discussion with members of the Virtual Environment Group at Georgia Tech we decided to base our virtual display on their NAVE (**N**AVE **A**utomatic **V**irtual **E**nvironment). [29] It is a stereoscopic, projection-based environment similar to the CAVE but completely PC-based and built at a low cost of roughly $60,000. The current NAVE at Georgia Tech design is a three-screen environment. Each screen is eight feet wide by six feet in height. The two side screens are positioned at 120-degree angles to the main central screen to give a three-sided display area that is sixteen feet wide and approximately seven feet deep. Imagery for each screen is generated on a 500 MHz PIII, and back-projected in stereo. A fourth PC is used to coordinate the three screens, and to provide audio output. The user experiences the NAVE while seated in a Thunderseat wearing passive stereo glasses. Software support for the NAVE is based on the Simple Virtual Environments (SVE) Toolkit. [29]

Interestingly, almost all the literature to date on the use of VR in the study of balance disorders refers to experiments where HMDs were used. Two experiments used a wide-FOV HMD display, which has low resolution. [13][33] Only one study used a fully operational CAVE. [10][26] The relative uniqueness of the BNAVE should permit some valuable experimental insights.

3.1 Primary Display

The primary display for the BNAVE is an enclosure surrounding the viewer made of three rear-projected screens. (Fig 1,2 & 3) They are held in place by a moveable wooden frame built by the Carnegie Mellon University's Drama department. Each screen's display is produced by a VREX 2210 LCD-based stereoscopic digital projector, which in turn is controlled by an Intel PIII computer. These computers are connected by a standard ethernet to another computer, which controls sensors, actuators and other peripherals. The display application, written by the Virtual Environments Group at Georgia Tech, synchronizes the display for each projector to produce a continuous scene or landscape across all three screens.

Mirrors are used to reflect the projection beams of two of the projectors. (Fig 3) The mirrors are adjustable in vertical and horizontal dimensions, and each projector rests on an adjustable mount. Unlike the NAVE at GA Tech, the viewer in the BNAVE may be standing. So,

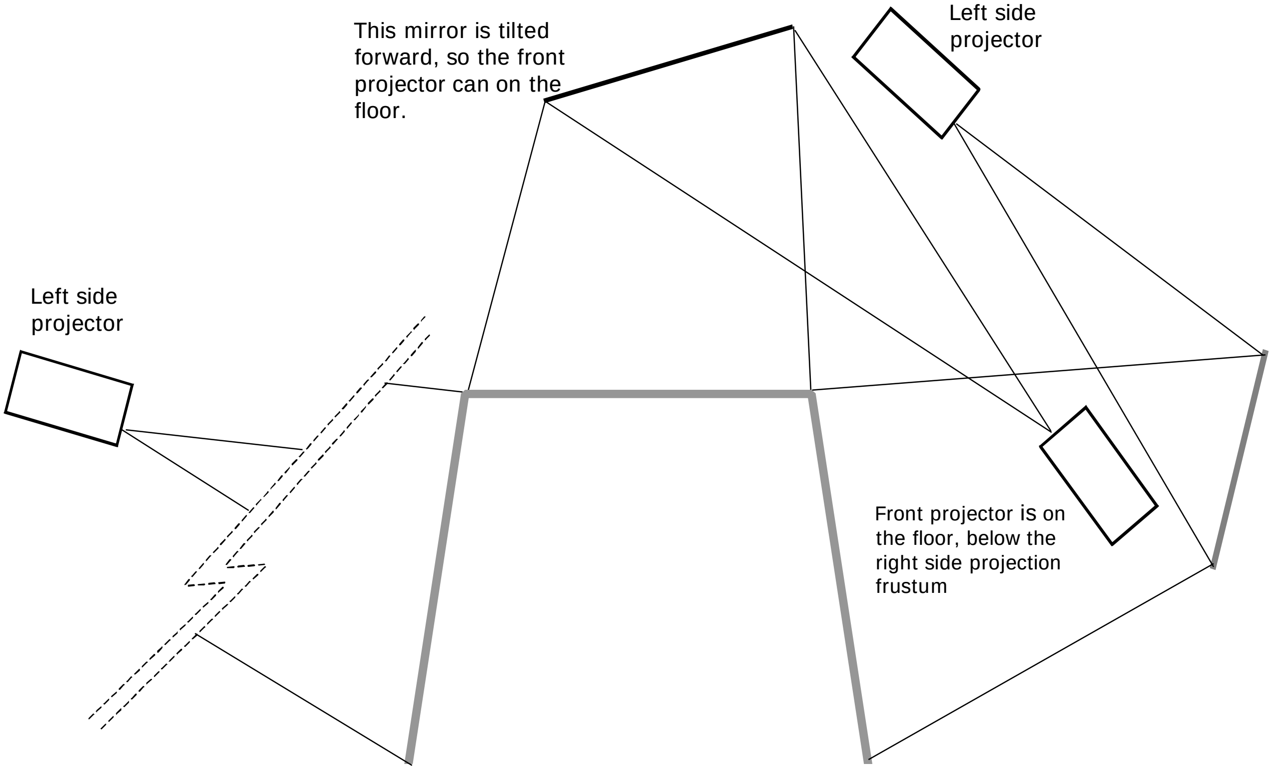

Figure 3: Layout of the BNAVE, showing projectors, mirrors and screens.

we turned the projectors and the screens on their sides, making the BNAVE taller and narrower.

For a wide FOV and light headgear, we decided to use a projective, immersive display rather than an HMD. Available HMD's simply cannot provide the same high-resolution, wide-angle display available in most projective designs. Furthermore, most HMD's have significant weight, while projective displays require no headgear for monoscopic images. For stereopsis, the viewer wears light shutter glasses or even lighter polarizing film glasses, as with the NAVE.

3.2 Floor-Projected Scene

We plan to add a fourth projector, mounted overhead, so the BNAVE can extend the scene to include the floor. (Fig 4) We will take advantage of the keystone correction in the VR2210's projection frustum, so that the light is slanting downward, onto the viewer, which will put most shadows behind him or her. It will also completely avoid any ropes, cables or wires coming from the ceiling down to the test subject.

To absorb unwanted light and glare, the subject will wear matte black light-absorbing clothes and a short-billed visor cap. Also, the part of the overhead projection image that overlaps the side screen will always be black. (Fig 2) This, in effect, shuts off the beam for those areas, preventing conflict with the side scene. Areas that are not a projection surface are painted a light-absorbing matte black.

3.3 Safety

The test subject is secured in a harness that allows normal movement, but prevents falls. The harness itself is a collection of straps similar to what mountain climbers use, attached to a ceiling-mounted frame by ropes. The tester allows enough slack in the ropes so the subject can move about normally, but can only fall one or two inches.

We also had to keep the screens and frame of the BNAVE itself out of reach of the viewer. The ceiling height in our lab space limits the screens to eight feet in height. We also had to maintain a 3/4 aspect ratio in the projected image, because the projectors and the projector computer's video display both use a 3/4 ratio. Anything different would waste projector and/or graphics card capacity. As a result, the screens could not be wider than six feet. In our design, we angled the side screens from the front screen at an angle of 99.5 degrees. (Fig 2) This makes the open side of the BNAVE eight feet, which is adequate for safety. Significantly, this still allows the floor projection to be six feet by eight feet and completely fill the floor space in the BNAVE frame. The overhead projection has the same aspect ratio and resolution as the side screens.

3.4 Data Gathering and Software

The experimenter uses a fourth networked computer to control the visual scene, all actuators and all sensors. These include eye trackers, video cameras, joystick, force platform and treadmill. For example, the subject might navigate a visual scene by using a joystick attached to this computer. More often, the user's motion in the VE will be controlled by a program or directly by the therapist.

To drive the visual display properly, the BNAVE uses software that integrates the different scenes projected on the screens, maintains the illusion of the three dimensional space, provides head-tracked perspective correction, and interacts with peripherals such as the joystick. The software was written by the GA Tech group and is based on their SVE toolkit. Software on

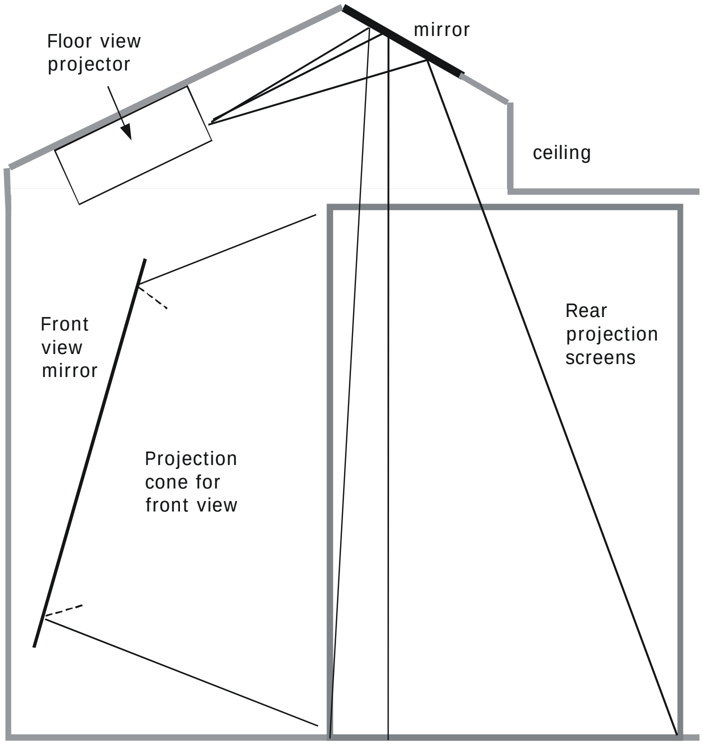

Figure 4: Side view schematic of planned overhead projection.

the console machine, written in LabView, controls the sensors, actuators, navigation through the visual scene, and the recording of data.

3.5 Stereopsis

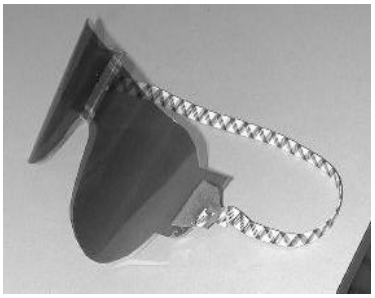
Figure 5: Polarizing film glasses

To produce a stereoscopic image, the BNAVE software simultaneously generates two different views into the current virtual world, one for the left eye and one for the right eye. Each VREX 2210 projector, [33] projects both left and right eye images at the same time, using linearly polarized light (LPL). To an observer wearing a pair of passive linear polarizing film glasses, (fig 5) the image looks three-dimensional. This works because the left lens only admits the left-eye image (it blocks out the right-eye image) and the right lens only admits the right-eye image.

With linear polarization, the separation of the left and right eye images is dependent on the orientation of the glasses with respect to the projected image. In the BNAVE display, the digital projectors' scan lines are vertical on the three vertical screens. (Fig 6) As long as the top edge of the glasses are perpendicular to those scan lines, the viewer will see the stereoscopic image correctly. So, the viewer can turn the head from side to side, holding the head level, with no problem. (Fig 8) Unfortunately, this arrangement gives rise to two problems when we add a floor projection.

Tilt Problem: If the viewer tilts the head from the horizontal (9) by about five degrees, a faint double or ghost image will appear. The greater the tilt is, the stronger this effect will be, until the tilt is 45-degress and the viewer sees a double image.

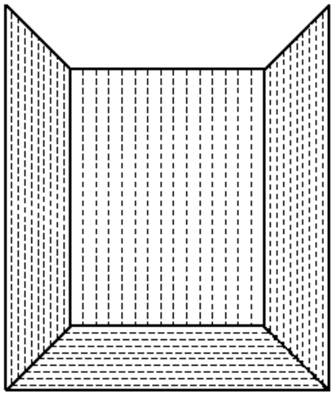
Figure 6: The four BNAVE projection surfaces shown with scan lines.

Floor Mismatch Problem: Digital projectors produce an image with scan lines, just as with a standard monitor. The scan lines in the floor projection are parallel with the lines in the two side screens. (Fig 6) This means that the viewer could look down at the floor, turn his head from side to side and see a continuous scene across the floor and the two side screens. However, the scan lines on the floor are *perpendicular* to the lines on the front screen, which means that the front screen and the floor screen images will be reversed with respect to each other. If the viewer slowly looks down at his feet, (Fig 7) the overall image he sees will be greatly degraded. The floor projection could be rotated by ninety degrees, but then it would not match the side screens. *The floor image cannot be aligned with both the side screens and the front screens at the same time.*

A potential solution to both problems is to convert the LPL for both left and right eye images into circularly

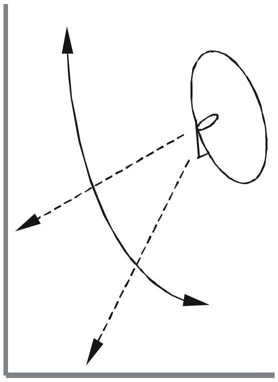
Figure 7: Viewer looks up or or down not tilting the head.

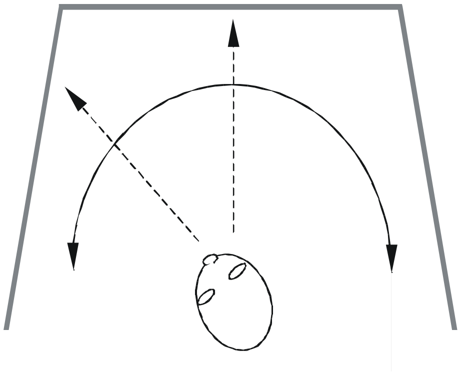
Figure 8: Viewer looks from side to side Keeping head level

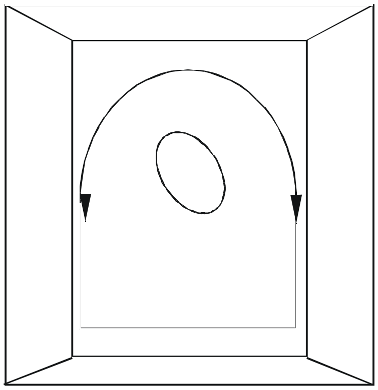
Figure 9: Viewer tilts head while Looking straight ahead.

polarized light (CPL). When the BNAVE is using CPL, the viewer can tilt the head (fig 9) to **any** degree without any degradation of the image. However, turning the head more than (roughly) forty degrees from the perpendicular to a projection surface causes noticeable ghosting. For example, the viewer in figure 8 will see ghosting in the front screen. The viewer in figure 7 will see some ghosting in both the floor and the front screens, but at least the images on them will match. For situations, where the viewer has to be able to look down, CPL may be a reasonable compromise.

Finally, we built the passive polarizing film glasses with larger pieces of linear polarizing film and other materials. (Fig 5) We were able to permanently bend the semi-rigid linear polarizing film with a heat gun and not damage its basic properties.

9. CONCLUSIONS

The BNAVE is a promising tool for vestibular physical therapy and balance research. We welcome inquiries and comments on its function and use.

10. ACKNOWLEDGEMENTS

Thanks to: Thomas Pierce for help with most of the design and construction work of the mirrors and mounts. Christopher Graefe for the photographs. The Drama Department of Carnegie Mellon University for building the BNAVE frame, itself.

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