Robotics and Virtual Reality: The Development of a Life-Sized 3-D System for the Rehabilitation of Motor Function

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Abstract— **We have been developing and combining state-of-art devices that allow humans to visualize and feel synthetic objects superimposed on the real world. This effort stems from the need of platform for extending experiments on motor control and learning to realistic human motor tasks and environments, not currently represented in the practice of research. This paper's goal is to outline our motivations, progress, and objectives. Because the system is a general tool, we also hope to motivate researchers in related fields to join in. The platform under development, an augmented reality system combined with a haptic-interface robot, will be a new tool for contributing to the scientific knowledge base in the area of human movement control and rehabilitation robotics. Because this is a prototype, the system will also guide new methods by probing the levels of quality necessary for future design cycles and related technology. Inevitably, it should also lead the way to commercialization of such systems. [1]**

Keywords— **Human, Motor learning, Adaptation, Human-machine interface, Teaching, Neurorehabilitation**

I. INTRODUCTION

This effort stems from the need for a device that extends the current capabilities for exploring how the brain controls movements, learns new movements, and recovers movement skills after an injury. What is needed is a device that allows large, three-dimensional, realistic human motor tasks and environments, not currently represented in the practice of research. The platform under development, an augmented reality system combined with a haptic-interface robot, will become a general tool for scientific exploration and eventually stroke rehabilitation. Because this is a prototype, the system will also shape new methods by probing the levels of quality necessary for future design cycles and related technology. Inevitably, it should also lead the way to commercialization of such systems.

A. Motivations for developing a new technology

There is a clear need for a capable testbed for scientific study on upper-extremity motion. Robotic devices, designed to interface with humans, have already led to great strides in both fundamental and clinical research on the sensory motor system. The programming flexibility of these devices allows for a variety of scientific questions to be answered in psychology, neurophysiology, rehabilitation, haptics, and automatic control. Recently, we have begun developing and combining state-of-the-art devices that allow humans to visualize and feel synthetic objects superimposed on the real world for the purposes of rehabilitation. This paper's goal is to outline our motivations, progress, and future objectives, as well as to invite other researchers in related fields to join in the development.

However, much of this research has been constrained by the limitations of available technologies. In order to achieve significant advances in these diverse fields, the next generation of human-interface robots must be stronger, operate in three dimensions, be safe, backdrivable (i.e., allow the user to easily push back), move within a large workspace and have an accompanying three-dimensional visual interface. Meeting all these requirements is the goal of the proposed instrumentation development.

The current economic landscape makes rehabilitation a likely target. The US spends $30,000,000,000/year on physical rehabilitation. The largest subgroup of this population - 30% - is stroke victims. Labor costs comprise 60 to 70% of rehabilitation costs. About 3.5 million stroke survivors will be discharged from inpatient rehabilitation in the US this year. Beyond age 55, the likelihood of stroke doubles every ten years, and people over the age of 60 years will increase by 10 million (22%) over the next 10 years. Survival rates from stroke continue to increase due to the improvement acute medical care. Based on these numbers, if new technology could remove just 5% of the labor costs on 10% of stroke survivors, the savings would be $300 million. It would seem that it is only a matter of time before the economics of labor-intensive expenses give way to technological breakthroughs.

However, all these cost considerations are two-edged swords. Currently there is too little money spent on labor for rehabilitation. It is a difficult task to establish "waste" in an economy, but a reduction of the patient's time with the therapist is certainly not optimal for brain injured individuals. Instead, the technology should focus on patient benefit by enabling the therapist to be more productive and to allow for extended rehabilitation. Meanwhile, the money for therapy is being cut. Medicare's 2001 incentives encouraged a reduced length of stay.

Ironically, recent research supports the opposite pratice—i.e. early, intensive therapy or massed practice for stroke survivors [1], where the impaired limb is forced to be using constraints on the less effected limb [2, 3]. Recent research supports "task-specific activity for rehabilitation," in which motions relevant to activities of daily living should be part of recovery [3-5]. Training on a variety of different tasks provides a better overall improvement in function than

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repetitions of the same task [6, 7]. It would appear that the tireless, precise, and swift capabilities of a robot certainly allow for such massed practice to take place while logging data for assessing progress. However, many more exciting benefits are possible when a haptic device is coupled with a three dimensional graphics display.

B. Distortions and altered reality

Virtual Reality (VR) is a head tracked, stereovision, computer generated environment that usually displays objects at arms length. VR makes it possible to rapidly present various rehabilitation tasks with no setup and breakdown time, but haptic-VR also provides many more important possibilities that are not possible with real-world applications – *distortions of reality*. Properties of objects can be changed in an instant, and this element of surprise is critical for studying how the sensorimotor system reacts and adapts to new situations. A glass of water might have a transition from full to empty, or be replaced with a solid mass, or violate natural physical laws. For rehabilitation, friction can be suppressed, or mass can reduced during the early stages of recovery.

Moreover, distortions can be programmed to go far beyond the simple idea of making the physical system easier to manage. Recent work in our lab suggests that distortions that amplify the errors made by stroke survivors leads to beneficial results in a short amount of time [8]. Moreover, the human brain and spinal cord remain modifiable, even in the adult, and even following many brain injuries. Consequently, one can exploit the adaptive properties of the nervous system for rehabilitation to trigger the recovery process [9-11]. Such devices can also be used to objectively test different therapeutic theories. The system described below would be the first of its kind allowing the full range of possibilities described above.

II. METHODOLOGY

A. Design overview

In order to achieve significant practical application, human-interface robots must safely operate in three dimensions with a large workspace and an appropriately designed visual interface. To implement this requirement it is necessary to develop instrumentation allowing movement targets, feedback of force or errors in movement. Most importantly, however, will be that the instrumentation superimposes images on the real-world, so that this display allows a view reality if desired. The sections below describe the three main components of the system we have developed: display, robotics, and software.

B. Display Choices

Currently, there are 4 forms of VR: head mounted display, augmented, Fish Tank, and projection-based [see ref. 1 and 2 for a review]. A totally immersive VR system is the head mounted display (HMD) where the subject sees only the computer-generated image [field of view of 120°H X 90°V] and the rest of the physical world is blocked from view. Augmented VR systems often use HMD technology, with these systems both the computer generated images and the physical world is visible to the subject. Computer images can be overlaid on the physical world, preserving the ability for the subject to see their own limb while encountering artificial objects.

The system (Fig. 1) is called a Personal Augmented Reality Immersive System (PARIS). It was designed, modeled and presented as a full sized simulation in a *CAVE* environment (Johnson et al., 2000). It employs a Christie Mirage "field sequential stereo enabled" DLP projector and a double mirror-folded light path to illuminate the overhead high contrast black screen. Their 2000 ANSI Lumen model can generate the needed brightness in ambient conditions.

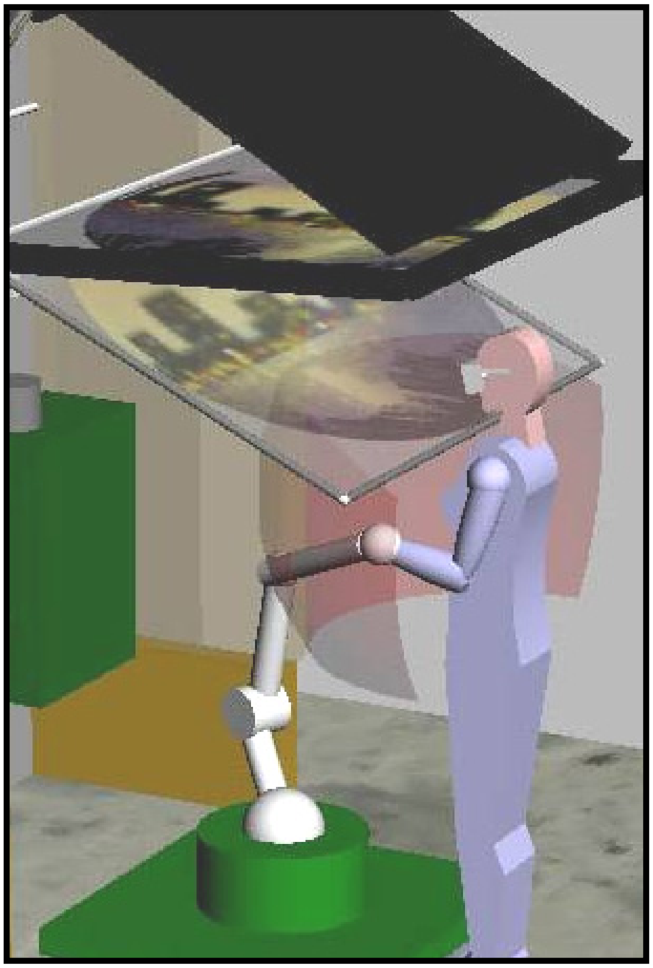

Fig. 1. Design concept of the PARIS and robotic system. The subject should be able to either stand or sit.

PARIS's graphics are displayed on the overhead screen is viewed as reflected in the sloping half-silvered mirror presented at the user's shoulder height. The robotic arm is manipulated within the volume below this mirror, the so called augmented space. With this volume illuminated, the user sees his hand(s) with the graphics superimposed. Without illumination, only the graphics are visible. The slope of the mirror can be adjusted to configure a variety of field of views and the unit contains a motorized height adjuster to cover the range from seated to standing.

PARIS were first put into place for research at the University of Illinois at Chicago, where one of us (Scharver) developed a haptic-VR interface that uses medical radiographic data for sculpting cranial implants for skull fractures [12]. We have since turned our attention to rehabilitation, requiring the tracking and storing movement patterns on a larger workspace robot.

C. Robot Choices

While industrial robotic devices typically have a transmission that provides a mechanical advantage and rejects disturbances, haptic robotic actuators often have extremely small mechanical advantage, allowing the user to easily push and move (*back-drive*) the robot at the expense of strength. However, servo control (moving the robot precisely thorough a series of positions) becomes and so admittance control is an alternative, where motions are entirely governed by a force sensor at the handle. Admittance control systems have to have very fast and accurate to be realistic.

Given these issues, we are currently using three commercially available robotic devices, each of which are specifically designed for haptic interaction with humans: The PHANTOM 3.0 (SensAble Technologies), the whole arm manipulator (WAM) (Barrett Technologies), and the Haptic Master (FCS Inc.). In short, their strengths and weaknesses make each of them suitable for different applications. The PHANTOM 3.0, our current tool for development, is a large-workspace, light-touch device with an extensive library for control and rendering of haptic objects. The safety of such a device is ideal for development. The WAM is still evolving, but offers more strength while remaining backdrivable. The Haptic Master possesses the mechanical advantages of an industrial robot and uses admittance control to deliver a haptic display. It provides an excellent tool for accurate servo-control of limb trajectories in space.

C. Software Choices

<u>Multithread vs. separate computers</u>. There are separate software components for haptic, graphic, and display control. First, the General Haptic Open Software Toolkit (GHOST) provides an interface for controlling the PHANToM robot. It initializes the robot, performs force calculations, and operates the servo loop. Second, the Coin3D [Systems In Motion] library implements the Open Inventor [TGS, Inc] scene graph, and it provides a comprehensive range of graphics and interactive objects. Finally, the CAVE Library [VRCO Inc] manages display parameters to establish the sense of depth and scale. While one might consider separate machines dedicated to each of these components, they must interact with each other very closely, and must therefore be present on a single machine. Multiple threads split these components into separate sub-processes running asynchronously on a single dual processor PC without the latency associated with communication.

<u>Communication between robot and display</u>. Although the haptics and graphics threads run within the same process on one machine, they must contain consistent representations of what the user should feel and see. The robot's thread must quickly communicate with the display thread so that graphics are synchronized with the robot's state. All libraries must be set to use consistent units of measurement. Currently, geometry is duplicated between the GHOST and Coin3D scene graphs. A GHOST sphere with a radius of 10mm corresponds to a Coin3D visual sphere with a radius of 10mm. Calibrating the graphics display places these two objects in the same location. A user feels the surface of a sphere when they move the robot's stylus toward that sphere's graphic. The robot updates its position as reported by GHOST, and copying that information to the Coin3D scene graph quickly updates the graphics to correspond with the robot's movements.

C. Preliminary Experiment

We have conducted preliminary experiments to test the hypothesis that (at the very least) the new system can produce results that we find using the planar manipulandum robot that has been used in many previous research studies [8]. Four healthy young adults volunteered and signed informed consents based on university guidelines. Each performed a total of 828 movements on the device, reaching to targets at a fast pace. All targets were 10cm from the previous in a small region in front of the user. All targets were in the horizontal plane at chest height. The experiment was broken into the following phases:

- 90 movements unperturbed to establish a baseline pattern.
- 372 movements with constant exposure to the so-called "curl" force field, which pushes the hand proportional to the hand's speed and counterclockwise to the direction of motion.
- 240 movements with random, intermittent removal of the force field every 1 in 8 of the trials (catch trials) to determine the after-effects.
- 12 movements of a "training refresher," Identical to the learning phase.
- 120 movements without any force, to show "washout" of the effect

Force and motion data was stored at 100 Hz.

III. RESULTS

The resulting trajectories collected on the haptic-AR system (Fig. 2) did not differ significantly from those collected on the manipulandum robot. Subjects made nearly straight movements when undisturbed (Fig 2A). The force field disturbed hand movements in all subjects early in training (Fig 2B), but original movement patterns were recovered later (Fig 2C). After-effects were evident when the forces were removed (Fig. 2D), which slowly "washed out" after returning to the unperturbed condition (Fig 2E).

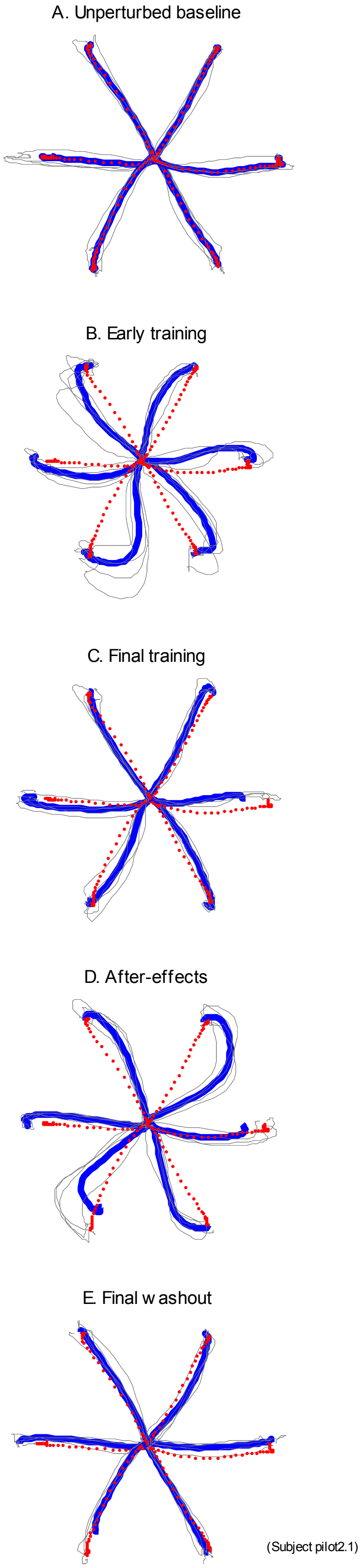

Fig. 2. Resulting hand trajectories in the horizontal plane for a subject on the haptic-AR system. Each plot shows movements from successive phases of the experiment. Bold lines indicate average trajectories. Dotted lines repeat the initially observed baseline pattern (in A) for comparison.

IV. DISCUSSION AND CONCLUSIONS

While these results do not make any great scientific contribution, these results are important departure point for many other more exciting studies in 3 dimensions. Most importantly, it makes it possible to expand the prior neurorehabilitation studies that were conduced in a simple scientific testbed (the planar robot). Procedures can now be extended to activities of daily living in a large, three-dimensional workspace. This device is an initial platform that will hopefully provide a platform for exploring how the nervous system controls movements, teaches new movements, explores novel strategies for training and rehabilitation, assesses and tracks functional recovery, and tests and challenges existing theories of rehabilitation.

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REFERENCES

[1] E. Taub, G. Uswatte, and R. Pidikiti, "Constraint-Induced Movement Therapy: a new family of techniques with broad application to physical rehabilitation--a clinical review. [see comments]," *Journal of Rehabilitation Research & Development*, vol. 36, pp. 237-51, 1999.

[2] E. Taub, N. Miller, T. Novack, E. d. Cook, W. Fleming, C. Nepomuceno, J. Connell, and J. Crago, "Technique to improve chronic motor deficit after stroke," *Archives of physical medicine and rehabilitation*, vol. 74, pp. 347-354, 1993.

[3] R. J. Nudo and K. M. Friel, "Cortical plasticity after stroke: implications for rehabilitation," *Revue Neurologique*, vol. 155, pp. 713-7, 1999.

[4] R. J. Nudo, "Recovery after damage to motor cortical areas," *Current Opinion in Neurobiology*, vol. 9, pp. 740-7, 1999.

[5] C. M. Dean and R. B. Shepherd, "Task Related Training improves performance of seated reaching tasks after stroke: A randomize controlled trial," *Stroke*, vol. 28, pp. 722-728, 1997.

[6] R. E. Hanlon, "Motor learning following unilateral stroke," *Archives of Physical Medicine & Rehabilitation*, vol. 77, pp. 811-5, 1996.

[7] T. Jarus and T. Gutman, "Effects of cognitive processes and task complexity on acquisition, retention, and transfer of motor skills," *Can J Occup Ther*, vol. 68, pp. 280-9, 2001.

[8] J. L. Patton, M. E. Phillips-Stoykov, M. Stojakovich, W. Rymer, and F. A. Mussa-Ivaldi, "Performance Improves With Force-Fields That Enhance Error In Chronic Hemiparetic Stroke Survivors," vol. submitted, 2004.

[9] J. Patton, F. Mussa-Ivaldi, and W. Rymer, "Altering Movement Patterns in Healthy and Brain-Injured Subjects Via Custom Designed Robotic Forces," presented at EMBC2001, the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), Istanbul, Turkey,, 2001.

[10] Y. Rossetti, G. Rode, L. Pisella, A. Farne, L. Li, D. Boisson, and M. T. Perenin, "Prism adaptation to a rightward optical deviation rehabilitates left hemispatial neglect," *Nature*, vol. 395, pp. 166-9, 1998.

[11] M. J. Weiner, M. Hallett, and H. H. Funkenstein, "Adaptation to lateral displacement of vision in patients with lesions of the central nervous system," *Neurology*, vol. 33, pp. 766-72, 1983.

[12] C. Scharver, R. Evenhouse, A. Johnson, and J. Leigh, "Pre-surgical Cranial Implant Design using the PARIS_Prototype," presented at IEEE VR2004, 2004.