HAPTIC VIRTUAL ENVIRONMENT SIMULATOR FOR BILATERAL TASKS

A. Bardorfer*, T. Bajd*

* University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia

{alesb,bajd}@robo.fe.uni-lj.si

Abstract: A multi-modal haptic virtual environment simulator for bilateral tasks has been developed. It is an extension to the unilateral simulator, and is meant to be used for quantitative, objective and repeatable assessment of upper limb (UL) functional state. The experimental measurement setup and the methodology for the assessment of upper limb functional state utilizing two Phantom 1.5 haptic interfaces has been developed. The measurement setup consists of a powerful virtual reality simulator, capable of providing quality haptic, visual and audio feedback and capable of network distributed real-time execution as well. The patient's task in the virtual environment is goal oriented and includes a manipulation of a cylinder using both hands and tracking pre-defined positions and orientations with the cylinder. The Phantom 1.5 haptic interfaces serve as kinematic measuring devices and as force feedback generators. By moving the haptic interface control sticks the patient is able to manipulate the object (cylinder) and track the predefined positions/orientations as accurate as possible. This paper describes the overall system architecture description and technical issues of the virtual reality haptic simulator, as well as methods of possible data analysis for obtaining the objective measures of Uls functional state.

Introduction

Upper limb (UL) assessment is a qualitative and quantitative procedure, by which the patient's UL motion and motor abilities -- UL functional state -- is evaluated. The necessity of UL assessment arises mostly in patients with neuro-muscular and neurological disorders (NMD & ND).

Neuro muscular disorders (NMD) are hereditary chronic degenerative and progressive disorders of the motor unit. The motor unit is a set of alpha-motoric neuron and all the muscle fibers connected to the particular neuron. The common prevalent clinical signs of NMDs are the muscle weakness, gradual deterioration of muscle fibers (muscular atrophy), which eventually leads to completely or incompletely paralyzed muscle groups, consequently to movement problems and to gradually becoming bound to a wheelchair. Along with the primary muscle weakness, secondary signs can occur. These are muscle contractures, scoliosis, respiratory complications and cardiac deficiency in the last stage of the disease [1].

Functional impairment differs significantly among various NMD & ND individuals, as well as between patients with the same diagnoses. Therefore patients should be treated and followed up on an individual basis. Concise insight into UL functional state is a prerequisite for planning an optimal treatment and complex care for each individual case. A precise, objective and sensitive quantification of dysfunction of UL may also facilitate better understanding of the natural course of the disease and enable therapists to judge the effectiveness of various treatment therapies. Furthermore, accurate measurement of the functional state of UL is crucial in choosing the optimal assistive technology control interfaces for a particular patient with disability.

Even though the quantification of disability has recently become more interesting to investigators, the techniques for measuring the motion and motor dysfunction remain rather primitive, and the methods of evaluation (assessment protocol) insensitive and subjective to a large extent.

Current approaches for the assessment of functional and motor abilities of ULs are limited to subjective evaluations performed by clinicians. Functional ability tests of the UL, as described in the literature, usually employ the following 4 criteria [2,3]: dexterity and speed of unilateral tasks (picking up and moving a jar, combing hair); dexterity and speed of bilateral tasks (moving hands, picking up objects, unbuttoning and buttoning etc.); ability to write; squeezing a dynamometer for measuring muscle strength. Some authors added joint range of motion measurements [4]. These tests, however, are not specific enough to be efficiently applied in patients with different NMDs & NDs that are affected by various physical impairments such as muscle weakness in Muscular Dystrophy, tremor and bradikinesia (slowness of movement) in Parkinson's disease, ataxia (disturbances in balance and in coordination of the muscle movements), in Friedreich Ataxia and Multiple Sclerosis, etc. Many subjective tests (e.g. Fugl-Meyer [5], Barthel [6]) are widely used in neuro-rehabilitation and have an important role in NMD & ND assessment, but lack objectivity as they produce subjective or semiquantitative results; e.g. ``Parkinson's disease: Impairment Index" may vary by as much as 40 % between various observers [7]. In these tests, the physical therapist assigns the score which is in most cases in a discrete form (yes/no or mild/moderate/severe) and as such grading lacks the resolution.

ISSN: 1727-1983 © 2005 IFMBE

Some objective tests for the assessment of UL exist, such as the Nine-Hole-Peg-Test [8], Jebsen-Taylor Hand Function Test [9] and TEMPA [10], but the only measurable physical property remains the time taken to complete the test. The trend in rehabilitation diagnosis is to provide objective and repeatable test methods to decrease subjective judgments and increase the therapist's ability to obtain reproducible findings and meaningful/accurate results.

Some work has been reported on using visual-only virtual environment (VE) technology (non-immersive synthetic environments) in rehabilitation. Wilson et al. [11] presented the evidence that knowledge and skills acquired by disabled individuals in simulated environments can transfer to the real world. Despite many questions of ethics and safety, researchers have agreed that VE technology could bring benefits to the rehabilitation world, if used with caution [12-15]. According to Jones [13], it is anticipated that with VE techniques, retraining could provide accurate measures of difficulties, according to the patients' progress in a rehabilitation program. Significant potential therefore exists for mechatronic devices to improve quantitative assessment, monitoring and treatment of individuals with movement disabilities. For example Reinkensmeyer et al. [16] used a simple robotic measurement device to identify the contribution of different motor impairments to decreased active range of motion of reaching in brain-injured subjects. Bardorfer [17] already built a unilateral haptic UL assessment system, which proved to be an objective measure of the functional capacity of the UL in patients with various forms of NMD & ND. The emphasis of the haptic tests was on the accuracy of movement, speed, and force exertion capacity, which are the three elements of the Elementary Resource Model by Kondraske [18]. However, these haptic tests were all unilateral, employing only one hand at a time.

Real life tasks, however, are usually bilateral, employing both upper limbs. Some previous work was reported using two robots in rehabilitation, however not for the UL assessment purposes, but rather for therapy. For example MIME with the potential of being advantageous when employing a bilateral exercise as a training paradigm, particularly when the central nervous system (CNS) is undergoing plastic changes early after stroke [3].

In this paper, we describe a new approach in UL assessment techniques, using two commercially available 3D (3 degree-of-freedom) haptic interfaces, that enable bilateral manipaltion of simulated virtual objects, either by using both upper limbs or two fingers (grasping).

Materials and Methods

Haptic technology combined with 3D visualization techniques was introduced and a VR based system that uses two Phantom 1.5 haptic interfaces and solely open-source code was designed. It runs under Real-Time Linux and is capable of network distributed execution.

The virtual environment is realistically rendered both graphically at high frame rate, and haptically by simulating as much of the physical phenomena, such a static and dynamic friction, as possible. The objects in the virtual environment have their respective dynamic models, taking care of proper dynamic behavior of the scene.

The core of the simulator is a haptic rendering loop, which consist of three parts/modules:

- Collision detection;
- Force model calculation;
- Dynamic model(s) calculation;
- Force exertion.

The collision detection module checks whether one of the haptic interfaces probes collide with any of the objects in scene and checks the collisions between the objects themselves.

The force model calculation takes care of the following force sub-models:

- Penetration stiffness sub-model;
- Friction sub-model;

The haptic scene was composed of a cylinder in a constrained environment, as represented in Figure 1.

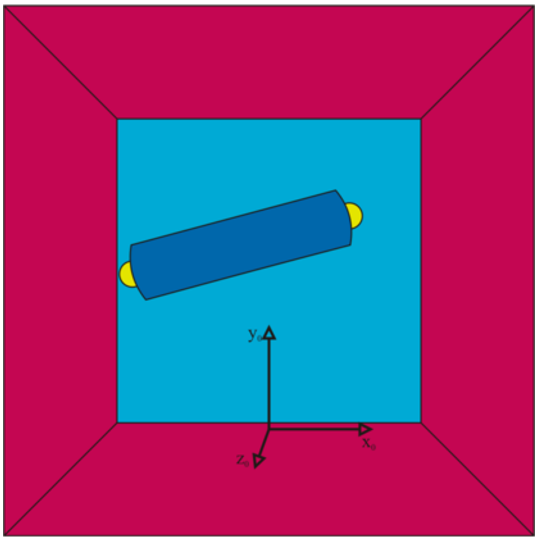

Figure 1: The simple virtual environment.

The graphics of the scene was intentionally left as simple as possible to isolate the operator’s/patient’s activities to the main goal, which is precise and accurate manipulation of the cylinder using both hands. The dynamic model of the testbed environment was obtained using Lagrangian dynamics. The mechanics were modeled as a second order system. The contacs between the haptic probe (operator’s fingertip) and the surfaces were modeled as a point-surface contact with friction. The anomaly because of neglecting the soft skinny fingertips nature is minimal.

Two friction models were implemented:

ISSN: 1727-1983 © 2005 IFMBE

- Karnopp's friction model, and
- Hollerbach's model.

The Karnopp's friction model is characterized in Figure 2.

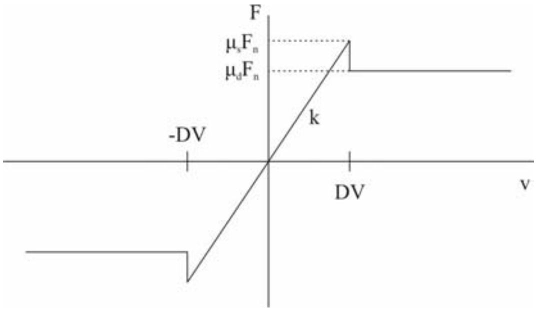

Figure2: The Karnopp's friction model.

The $-DV < v < DV$ interval is the interval of the velocities of the "sticky" contact. Outside this interval, the friction is a classic Coulomb friction:

$$F_{fr} = \begin{cases} \frac{\mu_s F_n}{DV} v \frac{v}{|v|} & |v| < DV \\ \mu_d F_n \frac{v}{|v|} & |v| > DV \end{cases}$$

where μ_s is the static friction coefficient, μ_d is the dynamic friction coefficient, v is the current probe speed, relative to the surface, and F_n is the normal force, the user is applying perpendicular to the surface.

The Hollerbach's model on the other hand, relies on two states: the "sticky" contact and sliding state. The "sticky" contact is modeled as a virtual spring, connected to the reference point. This mode is active whenever the speed v is below the minimal threshold $v < v_{\min}$. The transition to the sliding state happens whenever the force of the virtual spring exceeds the threshold $F_{fr} > F_{\max}$. Otherwise the friction itself is the Coulomb Friction:

$$F_{fr} = \begin{cases} K(c - SCP)F_n & sticky \\ \mu_d F_n \frac{v}{|v|} & sliding \end{cases}$$

where c is the virtual spring reference position, SCP is the Surface Contact Point, and F_n the normal force.

Figure 3 shows the Hollerbach's friction model graphical representation.

Figure 3: Hollerbach's friction model.

Both models are non-linear as is the real world friction itself. Both models therefore inject highly non-linear properties into the system, causing overall stability problems.

Results

The measuring system and the methodology as described above were used for some preliminary assessments of the UL functional state. Figure 4 shows the measurement setup.

Figure 4: The measurement setup.

The haptic interfaces had to be rotated to allow for optimal inter-coverage of the individual workspaces of the Phantoms. The geometric relations of both Phantoms are shown in Figure 5.

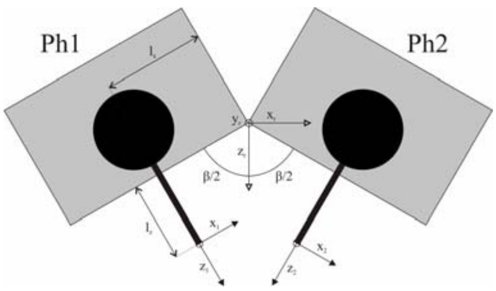

Figure 5: Geometric relation of both Phantom 1.5 haptic interfaces.

Figure 6 shows a sample tracking session; a cylinder central position as well as it's orientation, along with the reference points T_n.

ISSN: 1727-1983 © 2005 IFMBE

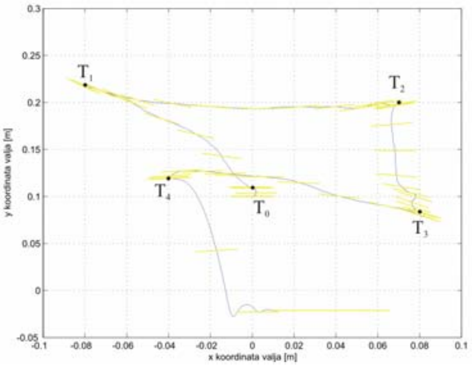

Figure 6: Sample tracking session.

The measured data is used to calculate simple tracking accuracy measures such as the linear and angular error (MSE).

Discussion

Currently, the gathered data is analyzed off-line, using Matlab. In the future, a standalone application using Matlab and Latex in the lower layers of software is planned and would enable simple automatic report generation for the observers. A similar analysis sub-system that produces a condensed printable reports of the patient's tests has already been developed for the unilateral haptic virtual environment simulator and the unilateral haptic tests [17].

Conclusions

The bilateral task in haptic virtual environment was demonstrated and a bilateral haptic simulator was developed. It has been shown that bilateral tasks can be advantageous in terms of employing both upper limbs either for assessment or training purposes. It has also been shown that the realistic and complex modelling of the real world can lead to a usable virtual system. However, at this stage, many problems, such as slipping of the object due to sliding mode with friction prevent the large-scale virtual environment content development without further models simplifications.

Acknowledgments

The authors would like to thank all the partners of the I-Match project of the European Commission framework 5, IST-37280 and to all the students, participating in the simulator development.

References

[1] H. B. BROOKE: A clinicians view of neuromuscular diseases, 2nd ed., Williams & Wilkins, 1986

[2] E. BELL , K. JUREK, T. WILSON, Hand skill. A gauge for treatment, Am J Occup Ther, vol. 30, no. 2, pp. 80-86, 1976

[3] H. B. SMITH, Smith hand function evaluation, Am J Occup Ther, vol. 27, pp. 24-51, 1973

[4] J. BEAR-LEHMAN, B. C. ABREU, Evaluating the hand: issues in reliability and validity, Phys Ther, vol. 69, pp. 1025-1033, 1989

[5] A. R. FUGL-MEYR ET AL., The post stroke hemiplegic patient. A method for evaluation of physical performance, Scand J Rehab Med, vol. 7, pp. 13-31, 1970

[6] D. T. WADE, C. COLLIN, The Barthel ADL Index: A Standard Measure of Physical Disability?, International Disability Studies, vol. 10, pp. 64-67, 1988

[7] D. T. WADE, Measurement in Neurological Rehabilitation}, Oxford Medical Publications, 1992

[8] V. MATHIOWETZ ET AL.: Nine hole peg test. IN: D. T. Wade, Measurement in Neurological Rehabilitation, Oxford Medical Publications, pp. 171-171, 1992

[9] R. H. JEBSEN, N. TAYLOR, R. B. TRIESCHMANN ET AL., An objective and standardized test of hand function, Arch Phys Med Rehabil, vol. 50, pp. 311-319, 1969

[10] J. DESROSIERS ET AL., Upper extremity performance test for the elderly (TEMPA): normative data and correlates with sensorimotor parameters. Test d'Evaluation des Membres Superieurs de Personnes Agees, Arch Phys Med Rehabil, vol. 76, pp. 1125-1129, 1995

[11] P. N. WILSON, N. FOREMAN, D. STANTON, Virtual reality, disability and rehabilitation, Disability and Rehabilitation, vol. 19, no. 6, pp. 213-220, 1997

[12] H. RING, Is neurological rehabilitation ready for 'immersion' in the world of virtual reality?, Disability and Rehabilitation, vol. 20, no. 3, pp. 98-101, 1998

[13] L. E. JONES, Does virtual reality have a place in the rehabilitation world?, Disability and Rehabilitation, vol. 20, no. 3, pp. 102-103, 1998

[14] M. L. LATASH, Virtual reality: a fascinating tool for motor rehabilitation (to be used with caution), Disability and Rehabilitation, vol. 20, no. 3, pp. 104-105, 1998

[15] R. KORPELA, Virtual reality: opening the way, Disability and Rehabilitation, vol. 20, no. 3, pp. 106-107, 1998

[16] D. J. REINKENSMEYER ET AL., Mechatronic assessment of arm impairment after chronic brain injury, Technology and Health Care, vol. 7, pp. 431-435, 1999

[17] A. BARDORFER ET AL.: Upper Limb motion Analysis Using Haptic Interface, IEEE/ASME Transactions on Mechatronics, vol. 6, no. 3, pp. 253–260

[18] G. V KONDRASKE: A working model for human system-task interface, J. D Bronzino (ed.): The Biomedical Engineering Handbook, 2nd ed., Vol II, CRC Press, 2000

ISSN: 1727-1983