A FULL MOTION MANUAL WHEELCHAIR SIMULATOR FOR REHABILITATION RESEARCH

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INTRODUCTION

Wheelchairs are the most common assistive devices for enhancing mobility with dignity [1], and are used by over 10 million users in developed countries alone [2]. Yet several major problems are still faced by manual wheelchair users today, including upper-body injuries induced by wheelchair propulsion [3], and difficulty navigating complex environments [4]. This paper describes a comprehensive manual wheelchair simulator being developed at Toronto Rehabilitation Institute's new Challenging Environment Assessment Laboratory (CEAL) - see Figure 1. The simulator is intended to enable and encourage research that can meaningfully address the challenges faced by wheelchair users, thus potentially improving the lives of millions.

Recent advancements in virtual reality (VR) technologies have resulted in a more widespread use of VR as both a training and assessment tool in the rehabilitation field [5]. In the context of wheelchairs, VR makes it possible to evaluate the accessibility of public buildings, reliably test novel wheelchair devices, assess patient capability, and train users to perform complicated, but necessary, maneuvers. Indeed, VR has already been found to be safe, cost-effective and highly motivating in a variety of vehicular training applications [6]. However, despite the large wheelchair user population world-wide, wheelchair simulation remains highly under-utilized. A recent review of wheelchair simulators around the world [6] lists only 14 such simulators, seven of which are intended to simulate manual wheelchairs and the remainder of which simulate powered wheelchairs. Of the manual wheelchair simulators, only one [7] has a mobile platform and force feedback, and is limited to simulating simple, planar motions.

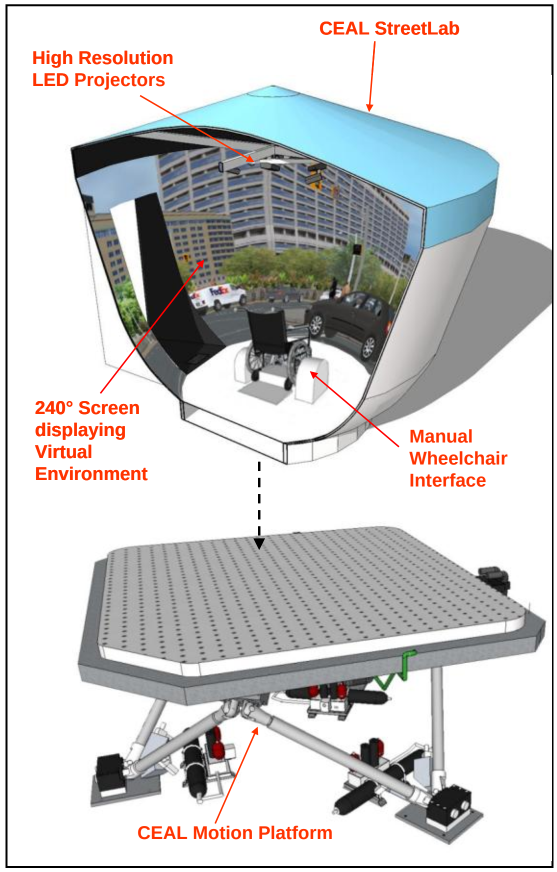

Figure 1: Full Motion Manual Wheelchair Simulator

By using CEAL's 6 degree-of-freedom, hydraulic motion platform, Toronto Rehab's manual wheelchair simulator will be uniquely capable of simulating non-planar motions such as tip-overs and wheelies. The wheelchair simulator will also benefit from state-of-the-art surround sound and projection systems within CEAL's StreetLab (images will be presented on both a 240° screen and the floor beneath the wheelchair). With the extensive range of measurement technologies available within StreetLab (e.g. motion tracking, eye tracking, EMG and EEG monitoring, etc [8]), it is anticipated that this project will play a vital role in learning how different sensory information (e.g. from vision, hearing and touch) is used by manual wheelchair users, and how the use and integration of these sensory signals may be influenced by age, injuries, or illnesses.

Specifically, participants will be studied while navigating a virtual environment with appropriate stimuli (i.e. visual and auditory feedback from projected scenery, and tactile feedback from the effects of slopes, bumps, and icy surfaces, etc). In order to achieve manual wheelchair simulation within CEAL, two major components are currently under development: 1) a physical wheelchair interface, and 2) a mathematical model of a manual wheelchair. The manual wheelchair simulator is anticipated to be fully functional by August, 2011.

WHEELCHAIR INTERFACE DESIGN

The wheelchair interface will be mounted within CEAL's StreetLab, and will be used to generate inputs required by the mathematical model, and provide the subject with force-feedback at the wheelchair's hand-rims (for example, increased resistance on uphill slopes).

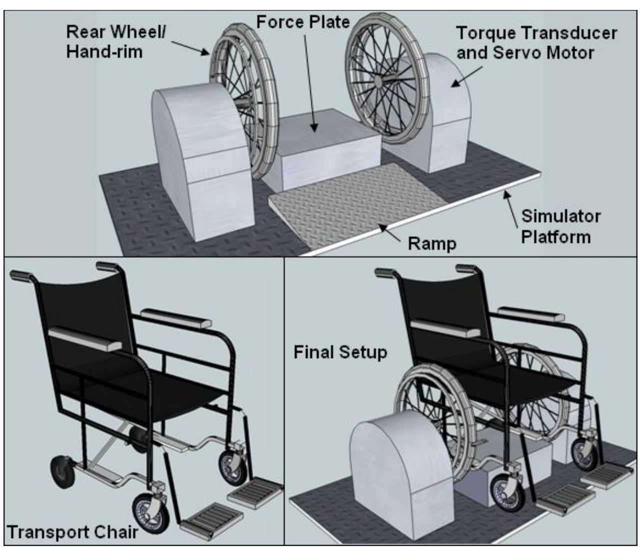

Figure 2: Wheelchair Interface

The wheelchair interface is currently under development, and is being designed such that:

- it allows a non-ambulatory patient to be wheeled into the simulator in a transport chair, and docked to the simulator quickly and safely
- all major wheelchair parameters are adjustable (i.e. seat height, seat width, seat depth, seat tilt angle, rear wheel axle position, and rear wheel camber)
- a force platform will detect the user's shifting centre-of-gravity in real-time
- motion capture equipment will detect the user's hand and torso positions in real-time (for calculating changing moment of inertia values)
- torque transducers are integrated with the interface hand-rims to detect the user's input torques
- torque-mode controlled servo motors will provide force feedback at the interface hand-rims
- redundant safety systems ensure patient safety (software monitoring, mechanical speed switches, torque limiting couplings, and panic buttons that activate emergency braking)

10-DOF MATHEMATICAL MODEL

In order to calculate the force-feedback required to accurately simulate different slopes and surface types, and correctly compute the wheelchair's attitude and position within the virtual environment, wheelchair dynamics must be considered. The mathematical model being developed is unique in its ability to predict non-planar wheelchair motions (e.g. wheelies and tip-overs), in addition to normal planar motions where all four wheels remain on the ground. To accomplish this, we consider the motion of the user relative to the chair, and thus require real-time inputs of the user's hand and torso positions, and centre-of-gravity position, in addition to the user's input torques. All of these inputs are supplied by the wheelchair interface described in the preceding section.

The model has a full 6 Degrees of Freedom (DOF) at the chair centre of gravity, 1-DOF at each rear wheel (about the wheel axle), and 1-

DOF at each caster wheel (about the swivel axis), giving it a total of 10-DOF. Each of the four wheels is modeled as a spring/damper combination, which allows computation of dynamic vertical loads (including wheel lift-off). In order to compute the rear wheel forces, a single contact point transient tire model [9] has been implemented. Caster orientation and forces are also included using a model presented in [10].

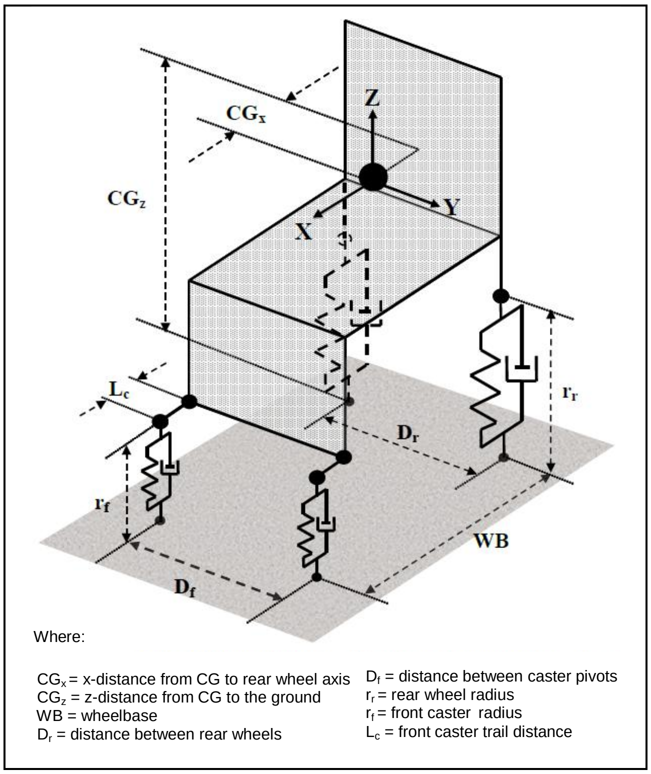

Figure 3: Schematic of Wheelchair Model

To correctly describe the motion of the chair only (which is what the motion platform must simulate), we first separate the wheelchair from its rear wheels. The chair (less its rear wheels) and user are then considered to be a system of two linked rigid bodies, where the motion of the lumped mass chair/user system can be readily determined since all forces external to the system are known (i.e. from the user's input torques and the rear wheel/ caster models). Finally, using the relative accelerations between the user and the chair (determined by motion tracking), the motion of the chair itself is derived.

PRELIMINARY MODEL VALIDATION

Thus far, a preliminary version of the model has been implemented in Simulink, and validated using real-life wheelchair data obtained with commercially available, instrumented hand-rims called SmartWheels^{TM} [11]. During testing, a Quickie GP manual wheelchair (see Figure 4 below) was outfitted with two SmartWheels^{TM}, allowing rear-wheel input torques and velocities to be recorded for the left and right rear wheels. Testing was performed on level ground and an outdoor path of varying slope, and included both straight runs and turns.

Figure 4: Quickie Wheelchair with dual SmartWheels^{TM}

Level Ground

These tests consisted of several straight runs along a level hallway, separated by 180° turns. As shown in Figure 5, the model's predicted left wheel velocity was in good agreement with the velocity measured by the SmartWheel^{TM}. Similar results were obtained for the right wheel.

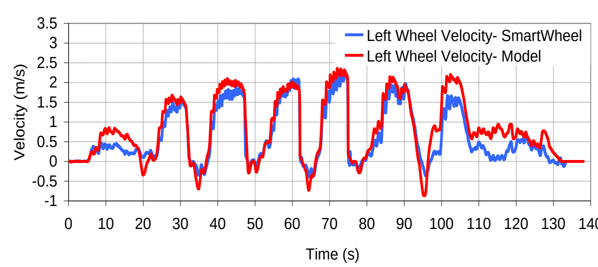

Figure 5: Level Ground: Left Wheel Velocity-SmartWheel^{TM} vs. Model

Slopes

Tests were also conducted on an outdoor path of varying slope (see Figure 6). Again, the velocity of the wheelchair predicted by the model was found to be in good agreement with that recorded by the SmartWheels^{TM}, showing that the model accurately accounts for the effects of different slopes.

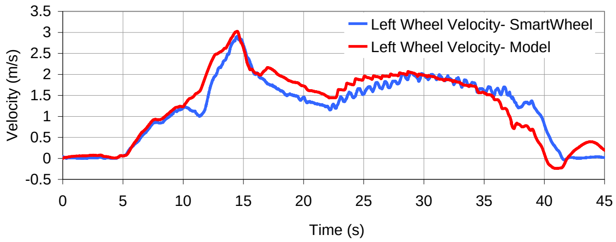

Figure 6: Downhill Slope: Left Wheel Velocity-SmartWheel^{TM} vs. Model

FUTURE WORK

The preliminary results presented show that the mathematical model is almost complete, although validation of the model during wheelies is still to be completed. Detailed design of the physical wheelchair interface has begun, and will be followed by assembly and validation on the CEAL motion platform in April/May, 2011. Completion of the project is anticipated to occur by August, 2011.

As noted above, this simulator is intended to enable research which can meaningfully address the challenges faced by wheelchair users and their caregivers. Researchers wishing to use CEAL facilities (including the manual wheelchair simulator) for their experiments are invited to consult [8] for more information.

ACKNOWLEDGEMENTS

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