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Dual Stewart Platform Mobility Simulator

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Abstract - **A robotic mobility simulator is being developed to allow training on various hapticly simulated surfaces while still being in the safe clinical environment. The simulator is integrated with a rich virtual environment displayed in front of the patient. The system uses two Stewart platform robots to render the walking surface geometry and condition. The hardware components of the platforms and the considerations behind their design are presented here. In addition, the nine state algorithm used for simulating the treadmill functioning is described along with the procedure used to transform the motion of the robots into walking in the virtual environment.**

Keywords - **haptics, virtual rehabilitation, virtual reality, robotics, Stewart platform**

I. INTRODUCTION

Rehabilitation of gait for individuals post-stroke is performed using task specific training and body weight supported treadmill training [8][2]. In both approaches the ability to manipulate the environment to reproduce varied walking conditions is limited. A mobility simulator is being developed to allow training on various surfaces while still being in the safe clinical environment.

A variety of walking simulators have been developed by other groups. Hollerbach developed the Sarcos Biport and the Sarcos Treadport [1][5]. The former robot simulates walking using two 3DOF platforms, each attached to one foot. The latter is a tilt-able treadmill that can simulate walking up-hill. A tether attached to the user's back can simulate inertial forces.

Miyasato developed a treadmill instrumented with height-adjustable plates under the conveyor belt. By changing the elevation of the plates the ATR-GSS treadmill can simulate stair climbing or walking on uneven terrain [6].

More recently, Comeau et al. developed a virtual reality gait simulator using the CAREN system (E-Motek Co., Amsterdam, Netherlands). CAREN is a large Stewart platform that supports the weight of a normal person. The walking surface angle is simulated by changing the orientation of the platform in real-time, while the user explores a virtual environment.

The system presented in this paper models the walking surface using two Rutgers Mega-Ankle (RMA) robots. The RMAs are larger versions of the original Rutgers Ankle platforms developed for ankle training in sitting [3][4].

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II. THE RUTGERS MEGA-ANKLE ROBOT

The main design objective for the Rutgers Mega-Ankle robot (shown in Figure 1) was the creation of a device suitable for clinical use and flexible enough to render realistic walking surface shapes and properties. The original Rutgers Ankle (RA) robot developed by our group satisfied most of the requirements set by the design objective.

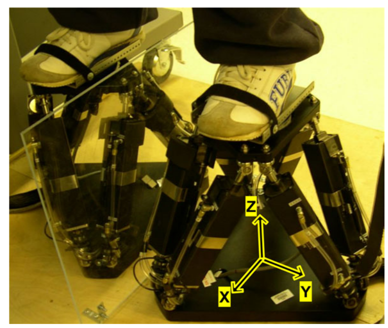

Figure 1. The Rutgers Mega-Ankle robot. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

The Stewart platform architecture [7] provides 6DOF and good size/power ratio, a compact size device being more appropriate for clinical use. The pneumatic actuators of the RMA can sustain forces for long periods of time without overheating. In comparison with hydraulic actuators, the pneumatic ones are cleaner and require smaller sized equipment. The drawback the original RA robot was its reduced force and torque capability. The Rutgers Mega-Ankle upgrade uses larger actuators to provide four times the force of the original device, which allows individuals to train in standing

A. Hardware components

The RMA robot consists of two triangular plates interconnected by six double-acting pneumatic actuators. The large plate is bolted to the floor, while the smaller one is mobile and attached to the user's foot. The ends of the actuators are connected to the bases with 2DOF spherical joints positioned on a 10.16 cm radius circle on the mobile base. The joints are grouped in three pairs placed 120 degrees apart. The distance between two neighboring joints on the fixed base is 5.08 cm.

Due to their increased length, the position of the actuators is closer to vertical than in the RA design. This caused singular configurations when one of the actuators reached the vertical orientation hence losing one degree of freedom. Such configurations could also damage the robot if forced to move in the direction parallel to the horizontal axel. To prevent such situations, the ranges of motion of the joints on the fixed base were reduced to 165 degrees. The joints connected to the mobile base were also limited to a range of 170 degrees, to prevent the actuators from reaching unrecoverable orientations.

The workspace of the platform (Figure 2) allows 30 cm displacement in the horizontal plane and 12 cm displacement vertically. The pitch and roll angles range is ±25 degrees, while the yaw angle range is ±40 degrees.

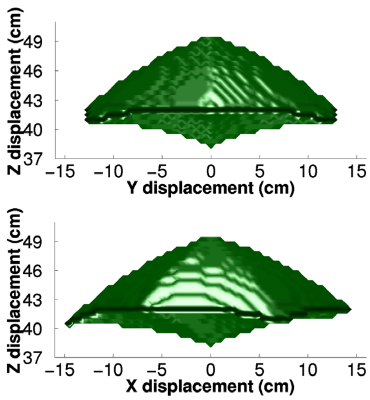

Figure 2. Rutgers Mega-Ankle workspace seen along the X and Y axes. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

The force and torque output of the RMA platform at an elevation of 45 cm and horizontal orientation is illustrated in Figure 3. The minimum upward Z force across the entire workspace is 3,150 N, enough to lift about 300 kg. The torque output however is limited and depends on the leverage the patient has on the end-effector.

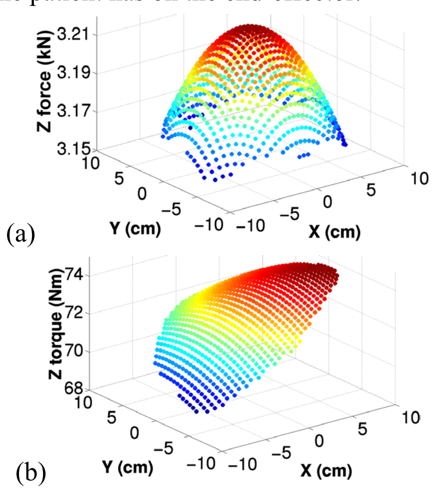

Figure 3. RMA robot force and torque output at an elevation of 0.45m and horizontal orientation. (a) Force; (b) Maximum pitch-up torque with 100kg load. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

The minimum torque output about the X-axis is 68 Nm when the weight of the patient is 100 kg. This means the platform is able to balance the torque created by a 100kg patient only if the weight is applied within 7 cm from the center of the foot binding. To overcome this limitation the patient is suspended in an unweighing system that can reduce the patient's effective weight by up to 60%. The use of the unweighing frame also gives the patient a sense of stability while standing on top of the mobility simulator 50 cm above the floor.

B. Dual platform configurations

The relative position of the two platforms affects the distance between the user's feet. During walking, while the swinging foot passes the supporting foot, the ankles get very close to touching each other. Hence, the distance between the two platforms must be as small as possible in order to simulate realistic gait. Figure 4 shows four possible configurations of the dual-platform system. The system kinematics are defined by five reference frames: the user's reference frame, the fixed base reference frames and the mobile base home reference frames.

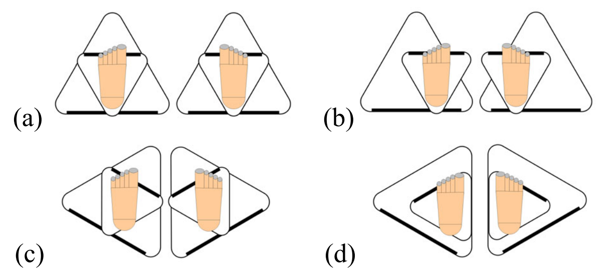

Figure 4. Dual platform configuration possibilities. (a) Aligned; (b) Aligned-displaced; (c) Close; (d) Close-rotated. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

In an aligned configuration, (Figure 4a) all five reference frames are parallel to each other. Because this situation does not take advantage of the triangular cut of the bases, the minimum distance between the user's ankles is 55.8 cm. This configuration is suitable for sitting exercises or special lateral step training. A simple way to make this configuration work for walking is to move the mobile base home positions inward (Figure 4b). The distance between the ankles is reduced to 355mm, but the workspace of mobile platform is almost zero.

A configuration suitable for walking is shown in Figure 4c. The distance between the user's ankles is reduced to 25.4 cm. This configuration requires software transformations of the readings since the platforms are not aligned with the reference frame. The controller handles these transformations transparently based on the given foot binding orientation. An ideal situation would be the one shown in Figure 4d where the mobile bases are rotated and displaced inward reducing the ankle distance to 12.7 cm. Unfortunately, this configuration cannot be reached by the current design of the platform, and the workspace would be practically zero.

Placing the platforms in such close proximity makes it possible for their cylinders to hit each other causing disturbances and damage. The evaluation of the platforms interference was done using a VR simulation with the 3D models taken from the CAD design. Two such models were put side by side at several distances and orientations and the mobile bases were moved through the entire workspace while collision detection was performed between the subparts of each model. The results of the analysis showed that the optimal inter-foot distance was provided by the configuration shown in Figure 4c. The minimum distance between the platforms in this situation was calculated to be 18 cm. This distance added to this configuration's minimum inter-ankle distance of 25.4 cm was still too large for simulating gait. To be able to reduce this distance and avoid interactions between the platforms, a Plexiglas board was installed vertically between the platforms.. With the shield separating them, the platforms were installed 10 cm apart.

III. MOBILITY SIMULATION

The robots are mounted on the floor side by side, and the patient's feet are secured on top of them. The RMA control box is connected over the serial port to a PC rendering a virtual environment. The graphics are then projected on a large monoscopic display in front of the patient (see Figure 5).

Figure 5. General view of the mobility simulator. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

The system simulates walking by moving the platforms back and forth similar to the stepping on a treadmill. Each robot either follows the user's swinging foot or slides the supporting foot backward. The user starts from a position with both feet touching the virtual ground, where both RMA robots support the weight of the user. Upon lifting one foot, the corresponding platform switches the control mode from position to force and follows the user's foot compensating for it's own weight. When the swinging foot touches the simulated ground (in front of the supporting foot), the corresponding platform switches back to position control. When the back foot is lifted to take the next step, the front foot robot slides backwards toward the starting position. The simulation tasks are split between the servo control interface and the PC. The control interface handles the changing of the control mode, sliding the front foot backwards, and coordinating the simultaneous motions of both platforms. The PC performs collision detection and notifies the RMA control interface when the foot touches the ground.

A. *Controller Algorithm*

The algorithm controlling the platforms is defined by a state transition diagram. The nine possible states describe the operation modes of each platform (see Figure 6). The transition between two states is either implicit when the current mode ends, or is triggered by a command from the PC or by the actions of the other platform.

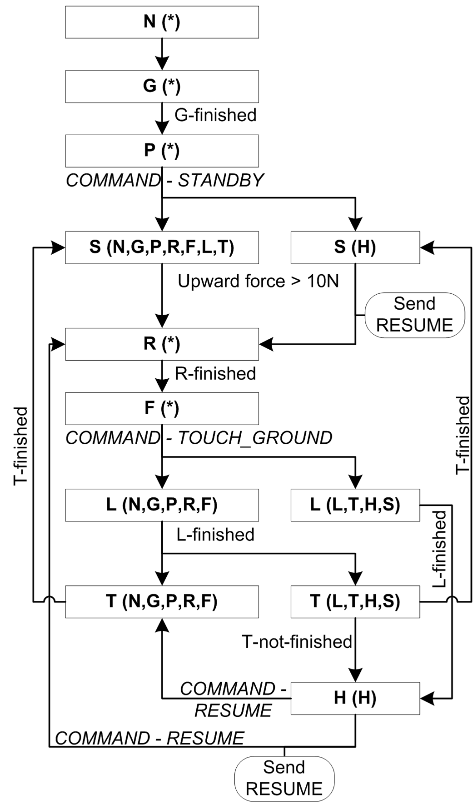

Figure 6. Walking states transition diagram. © 2004 Rutgers University and UMDNJ. Reprinted by permission.

Each cell in the diagram shows the state of the current platform and between parentheses the state of the other. A star means "any state". The comma separating the multiple states on each line should be read as logical OR.

At system startup, both platforms are in state NULL (N). From this state, the platforms switch to PARKING (G) mode, which moves the platforms to the home position located in the middle on the workspace. When the parking position is reached the platforms switch to the PARKED (P) state. This state is used while the VR simulation on the host PC is not running. Any of the remaining states switch to PARKING at the end of the simulation. These transitions are not displayed in Figure 6 to improve its readability.

The transition from PARKED to STANDBY (S) is triggered by the STANDBY command sent by the simulation at startup. This state corresponds to the supporting foot during walking. The controller interface reads the forces applied by the user. If the user pulls up with more than 10 N, it releases the foot by switching to the RELEASE (R) state. The RELEASE state is responsible for gradually changing the control mode over a 200-millisecond interval from holding position to free motion. When the control mode switching is finished, the platform enters the FREE (F) state and follows the patient's foot motion compensating for its own weight. When the simulation sends the TOUCH_GROUND command the platform changes state to LOCK (L).

At the end of the LOCK state, the platform can either start sliding backwards in the TRANSLATION (T) state, or hold position in state HOLD (H). The TRANSLATION state moves the front foot backwards to imitate the functioning of a treadmill. However, if the other foot is touching the virtual ground, the platform must hold the position without generating motion. This is where the HOLD state is necessary. It is used to correlate the motions of the two platforms. In general, when a foot touches the ground while the other foot is still sliding backwards, both platforms switch to HOLD. HOLD is identical to STANDBY, except that it reacts to the actions of the other platform. At the end of the RELEASE state, if the other platform is on HOLD, the current platform sends it a RESUME command to continue with its previous state.

B. PC Simulation Algorithm

The platform controller sends to the PC the position, orientation and state of the two RMA robots. The simulation has to transform this information into walking through the virtual environment.

The position of the RMA robots changes continuously during an exercise. However, the position changes can be considered for generating movement in the virtual world only for a subset of the functioning states presented above. For instance, the inevitable change in position of a platform in STANDBY mode due to the patient shifting his weight from one foot to the other should be ignored by the VR simulation.

At every simulation loop iteration, the PC has to compute (based on the current and previous data) the motion vector of each foot. There are three possible situations: do not move either foot, move both feet independent of each other, or move one foot adding the negative motion of the other to it. The first case applies when both feet are on the ground, which is equivalent with having both feet in one of the G, P, S, L, T or H states. Although the control interface switches the states to HOLD when both feet touch the ground, it is possible for the simulation to receive mismatched pairs of states from the control interface because the communication is not synchronous with the control algorithm.

The independent movement of each foot corresponds to the situation when both feet are in the air. Since it is not possible to jump using the simulator, this case can happen if the patient lifts both feet and remains hanging in the unweighing system's harness. Since both feet are in the air, their motions will be applied to the virtual avatar, but the displacement gain will be reduced to the length of one step.

The last case is the most frequent one and occurs when one foot is in the swing phase (FREE state) and the other is on the surface. In such case, the supporting foot on the surface is sliding back during the TRANSLATE state. Its backward motion is added with changed sign to the forward motion of the swinging foot doubling the length of the virtual step.

To overcome the slow motion allowed by the simulator and increase the realism of the simulation, in the final phase of the algorithm the calculated foot motion vector is scaled by a gain factor that makes the virtual step distance closer to real life values.

IV. Conclusions and Future Work

The system is currently in a development phase. The existing walking algorithm will be extended to support walking surfaces of different elevations such as steps and slopes. In addition, haptic effects will be implemented to simulate the walking surface condition. The development phase will be followed by validation studies with individuals who are healthy and post-stroke..

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References

[1] R.R. Christensen, J.M. Hollerbach, Y.Xu, and S.G. "Meek. Inertial-force feedback for the Treadport locomotion interface". *Presence*, 9(1):1--14, February 2000.

[2] C.M. Dean, C.L. Richards, F. Malouin, "Task-related circuit training improves performance of locomotor tasks in chronic stroke: a randomized, controlled pilot trial". *Archives of Physical Medicine & Rehabilitation. 81(4):409-17, 2000*

[3] J.E. Deutsch, J. Latonio, G.C. Burdea, and R.F.Boian, "Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports," Eurohaptics Conference, Birmingham UK, pp. 11-16, July 1-4, 2001

[4] M. Girone, G.C. Burdea, M. Bouzit, V.G. Popescu, and J. Deutsch, "A Stewart Platform-based System for Ankle Telerehabilitation," invited article, Special Issue on Personal Robotics, *Autonomous Robots*, Vol. 10, pp. 203-212, Kluwer, March 2001

[5] J.M. Hollerbach, Y.Xu, R.Christensen, and S.C. Jacobsen. "Design specifications for the second generation Sarcos Treadport locomotion interface". Haptics Symposium, *Proc. ASME Dynamic Systems and Control Division*, volume 69, pages 1293-1298, November 2000.

[6] T.Miyasato. "Tele-nursing system with realistic sensations using virtual locomotion interface". *Proceedings of the 6th ERCIM Workshop "User Interfaces for All"*, Florence, Italy, October 2000.

[7] D.Stewart. "A platform with 6 degrees of freedom". *Proceedings of the Institution of Mechanical Engineers*, 1965.

[8] K.J. Sullivan, B.J. Knowlton, B.H. Dobkin, "Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery". *Archives of Physical Medicine & Rehabilitation. 83(5):683-91, 2002*