ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

DEVELOPMENT OF A ROBOTIC SYSTEM FOR BILATERAL TELEREHABILITATION

Adriano A. G. Siqueira
Robotic Rehabilitation Laboratory, Mechatronics Group, University of São Paulo at São Carlos, São Carlos, SP, Brazil.
Center for Robotics of São Carlos and Center for Advanced Studies in Rehabilitation, University of São Paulo, SP, Brazil.
http://www.crob.usp.br/, http://www.fm.usp.br/nap_near/
siqueira@sc.usp.br

Konstantinos P. Michmizos
Department of Mechanical Engineering, Massachusetts Institute of Technology, Boston, MA, USA.
konmic@mit.edu

Hermano I. Krebs
Department of Mechanical Engineering, Massachusetts Institute of Technology, Boston, MA, USA.
Department of Neurology, University of Maryland School of Medicine, Baltimore, MD, USA.
hikrebs@mit.edu

Abstract. *The This paper presents the development of a robotic telerehabilitation system and a set of computer games for robot-aided therapy in a bilateral configuration. The aim here is to create a suitable framework where two or more patients, each one working with a robot, can interact not only visually, through the game screen, in an interactive configuration, but also physically, through direct reflection of the forces applied by the patients, in a cooperative configuration. To ensure system stability in the cooperative configuration, robotic teleoperation techniques are implemented and evaluated. Experimental results obtained from the robotic telerehabilitation system adapted to work with the lower extremity robot Anklebot are presented.*

Keywords: *telerehabilitation; rehabilitation robotics; teleoperatio; serious games*

1. INTRODUCTION

In the last decades, robotic rehabilitation has been developed as a complementary therapy for recovery of both upper and lower limbs movements of stroke and spinal cord injured patients (Krebs, *et al.*, 2008). However, while upper-extremity robot-aided therapy is already recommended by the American Heart Association (Miller, *et al.*, 2010), lower-extremity robotic therapy has not proven to be effective (Hidler, *et al.*, 2009, Hornby, *et al.*, 2008). Hence, alternative approaches for gait rehabilitation should be studied to improve the efficacy of the already proposed solutions. In Forrester, *et al.* (2011), preliminary studies with stroke patients training dorsiflexionplantarflexion by playing video games with the Anklebot robot (Roy, *et al.*, 2009) are shown. Although the patients have performed the movements while seated, the improvements in paretic ankle motor control during floor walking and the increase of walking speeds suggest that approaches based on ankle motor control recovery may result in effective locomotor therapies.

Robotic telerehabilitation can be one of these alternative approaches. Telerehabilitation, considered here as a remote rehabilitation, can be carried out unilaterally, ie, only the patient performs movements interacting with a robotic interface, while the therapist monitors the patient performance through information transmitted via the Internet. In this configuration, the therapist can remotely change the settings of the robot controller or the computer game that the patient is currently working on. When both the patient and the therapist (or another patient) interact with robots and exchange their information, we have a bilateral system.

This paper presents a robotic system and a set of computer games that perform bilateral telerehabilitation for lower extremity recovery using two Anklebots. In Carignan and Krebs (2006), two variations of bilateral telerehabilitation according to the level of interaction between the robots users are defined: the interactive and cooperative approaches. In an interactive telerehabilitation, the two or more players interact with each other through the graphical environment of the game, with no direct transmission of force between the robots. Each player independently move his/her robot, whose position is associated with an object of the graphical environment of the game, for example, the paddle in the game Pong. On the other hand, in the cooperative telerehabilitation, patient and therapist (or two patients) interact both visually, through the game screen, and physically, by feeling the motion performed by the other player through the force transmission between the robots. In this case, the therapist change the behavior of the patient, through direct movements applied to the local robot. A set of cooperative bilateral games for upper limbs rehabilitation was developed in Carignan and Olsson (2004), using virtual reality techniques and two MIT-Manus robots. The proposed telerehabilitation system uses a virtual model of the object being transported by the patients (Olsson, *et al.*, 2004).

To implement cooperative bilateral therapy, concepts of robotic teleoperation must be considered. This is a wider field of research, with applications that include remote transportation of objects in hostile environments, such as in space exploration or nuclear plants, and remote-controlled endoscopic surgeries (see, for instance, the da Vinci Surgical System, www.davincisurgery. com). In traditional teleoperation, a human operator conducts a task by applying force to a master robot. The resulting position of the master robot is transferred and replicated in the slave. When the slave robot contacts the remote environment, the contact forces should be directly reflected to the operator, improving the performance of the task. However, if the teleoperation is performed in a communication network subject to excessive delays, the teleoperated system may become unstable.

The first teleoperation studies that take into account the effects of delay on the stability of the system date from the 80s. In Anderson and Spong (1989), the authors use concepts of telecommunication networks to ensure system stability even in the presence of delays. An analysis of power transmission between the robots is done and passivity-based criteria are used to ensure stability. Extending the results of Anderson and Spong (1989), Niemeyer and Slotine introduce the concept of wave variables (Niemeyer and Slotine, 1997a), which provides a natural framework for analysis and implementation of teleoperated systems with delays. The use of wave variables (or the wave transform) ensures that the communication between the robots is passive, so that the system is stable. More details can be found in Niemeyer (1996), Niemeyer and Slotine (1997b), and Niemeyer and Slotine (1998). A recent overview on teleoperation systems can be found in Hirche and Buss (2012).

In this paper, two control strategies for teleoperated systems described in Niemeyer (1996) were implemented in the robotic telerehabilitation system developed for two Anklebots. The first strategy is the classical symmetrical PD control, where the positions and velocities of one robot are defined as desired positions and velocities for the other robot, and vice-versa. Although this approach provides good results with small delays, it proves unstable in the presence of high delays. The second strategy uses wave variables to transmit the information between the robots, such that the teleoperated system is stable even with excessive delays.

To evaluate the robotic telerehabilitation system, four computer games for rehabilitation of ankle movements were developed. Two of them are characterized as interactive games: The Shipwreck and Soccer 2014, since they promote interactive telerehabilitation without direct force transmission between players. The remaining two games, Beam and Target, were designed using the concepts of teleoperation, and thus are characterized as cooperative ones.

The paper is organized as follows: Section 2 presents the robotic telerehabilitation system developed for the Anklebot robots; Sections 3 and 4 present respectively the interactive and cooperative games including experimental results obtained from the implementation of the teleoperation techniques; and Section 5 presents the conclusions.

2. ROBOTIC TELEREHABILITATION SYSTEM

In this section we present the robotic telerehabilitation system used to evaluate the bilateral games developed in this work. The robotic system consists of two Anklebots exchanging information through an internet connection. The Anklebot is a low-friction, backdrivable three-degrees-of-freedom robot which allows independent and active assistance in the dorsi-plantar flexion and inversion-eversion degrees of freedom of the foot relative to the shank. The third degree-of freedom, the internal-external rotation, is passive (Roy, et al., 2009). The active movements are provided by two linear mounted in parallel such that a dorsi-plantar flexion torque is produced at the ankle if both push or pull in the same direction. An inversion-eversion movement is produced if the two links push or pull in opposite directions.

The bilateral games were developed in Tcl/Tk. The communication between the games and the real-time robot controller is done using shared memory. The same structure is used to transfer information from the games (or the real-time robot controller) to the internet communication process, and vice-versa. Figure 1 presents a scheme of the robotic telerehabilitation system.

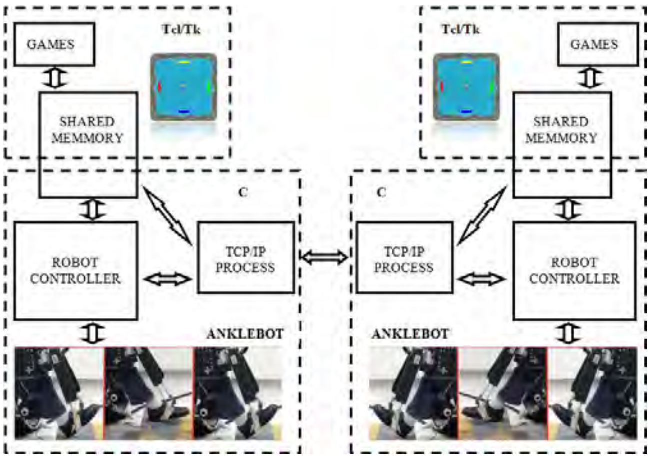


Figure 1: Robotic telerehabilitation system.

ISSN 2176-5480

The internet communication between the robots was performed through sockets using the TCP/IP protocol. The two most common transport protocols over IP are the TCP (Transmission Control Protocol) and the UDP (User Datagram Protocol). Although the UDP is faster, it does not guarantee that the transmitted data will be received properly. On the other hand, the TCP is reliable, since it has flow and congestion control, data checking, among other features.

A socket refers to a channel of communication between internet protocols (TCP or UDP) and applications, being identified by the protocol and the local or remote address (Donaho and Calvert, 2009). A given application can access different sockets. And a given socket can also be accessed by multiple applications. The communication by sockets considers the Client/Server structure. In this case, both client and server create their respective sockets. On the server computer, the socket is configured to continually check if a client is requesting a connection. If so, the server accepts the connection and begins to communicate with the client. The communication is interrupted only when the connection is terminated in one of two ends.

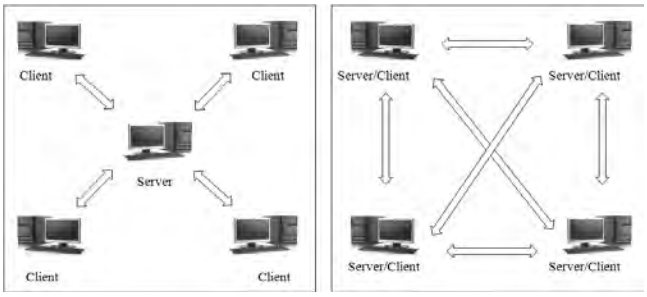
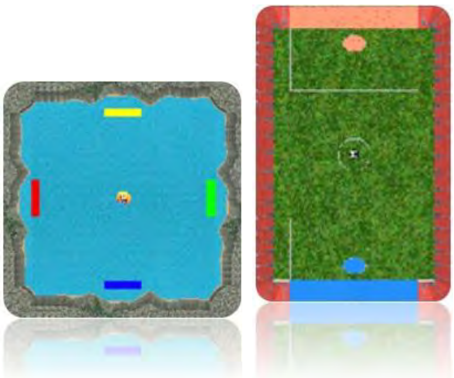


Figure 2: Network configurations, centralized (left) and peer-to-peer (right).

There are different network configurations for communication between servers and clients, such as the centralized configuration where only one computer is the server and the other are clients, or the peer-to-peer configuration where all computers can take both the role of the server as the client, Fig. 2. For the specific application of only two Anklebots, the simplest case applies where a computer is the server and the other is the client. However, if a larger number of robots is used in the robotic telerehabilitation system, the selection of the network configuration must take into account the location of the robots (remotes or local), the internet delays and the characteristics of the games being played.

3. INTERACTIVE GAMES

Firstly, we reprogrammed two games initially developed to be used with the Pediatric Anklebot, (Michmizos and Krebs, 2012b), to work as interactive games: The Shipwreck and Soccer 2014, Fig. 3. In the original versions of these serious games (SG), algorithms based on the kinematic data and on the user performance were implemented to perform an online adaptation of the game parameters (Michmizos and Krebs, 2012a). The SGs were designed to address motor impairments including poor coordination, impaired motor speed or accuracy, and diminished strength, as well as to address cognitive or perceptual impairments. For each of the games, the user moves a paddle using his/her ankle. Dorsi-plantar flexion and inversion-eversion control screen movements of the paddle in vertical and horizontal directions, respectively.



(a) Pong (b) Soccer

Figure 3: Interactive games for telerehabilitation - The Shipwreck and Soccer 2014.

ISSN 2176-5480

1) The Shipwreck: In this game, the user has to prevent a ship from crashing into the rocks, by using a set of paddles (ship barriers) (see Fig. 3). Dorsi-plantar flexion (inversion-eversion) control the vertically (horizontally) moving barriers. If the ship is saved by a barrier or falls on the rocks, 20 points are added or subtracted on the scoreboard, respectively. After deflected by a paddle or hitting a rock, the boat bounces with random coordinates. To reduce cognitive load and facilitate motor planning, the game allows play with less than four barriers. In that case, the rocks on an unprotected side are replaced by a sandy beach (not shown) that deflects the boat towards the opposite direction.

For the telerehabilitation implementation, each Anklebot moves only one degree-of freedom, dorsi-plantar (DP) flexion or inversion-eversion (IE). The extension to simultaneous control of both degrees-of freedom can be performed in a straightforward way. However, all configurations regarding the degree-of freedom being used by the two robots can be set. The two players can move the same degree-of-freedom or each player can move a different one. In the case where both players use the same degree-of freedom (DP, for example), the barriers of the opponent player are placed in the degree-of-freedom not moved by the players (IE). For the case where only two barrires are used, the opponent barrier is placed in the opposite side, wherever the degree-of-freedom being used. Figure 4 shows the *set-up* used to evaluate the interactive and cooperative games with the two Anklebots.

Figure 4: *Set-up* dos experimentos de telereabilitação com dois Anklebots.

Regarding the data to be transmitted through the internet communication, for the *The Shipwreck* game we considered the game control strategy centered on the figure of the server, that is, all the computations related to the ship position and to the prediction of the next bounce on the rocks are performed on it. We are continuously sending the barriers' positions from one robot to the other, and the position of the ship from the server to the client. Also, the original *The Shipwreck*, described in (Michmizos and Krebs, 2012b), computes the position where the ship will bounce the rocks at the next ship movement. This information is sent to the robot controller and if the player does not move within some predetermined period of time, the robot starts the movement with a compliant behavior. This prediction, computed always in the server, is sent to the client after each bounce.

2) Soccer 2014: In this game, the user plays a soccer game with his/her opponent (Fig. 3). The child must play both defense and attack. During the defense phase, the player controls the goalkeeper which has the shape of an elliptical paddle (see Fig. 3). The opponent advances towards the center of the field and selects randomly to send the ball to the left or right corner of the goalpost. The goalkeeper now has to move left or right (by inversion/eversion of the ankle) to defend the ball. After the ball is defended, the child has to move his/her ankle near the neutral position so that the goalkeeper will be approximately at the center of the goal. When positioned near the center, the goalie becomes an attacker and takes a circular shape (not shown). The attacker has to kick the ball (dorsiflexion of the ankle) towards the opponent's goalpost. The kick is visualized as the circular attacker moves upwards until it crosses the middle-line. The ball is released with a speed analogous to the speed of the actual kick. Since the opponent goalkeeper is moving at a constant speed, the probability of scoring increases with the speed of the kick. If the computer goalie is able to defend the shot, the child needs to plantarflex the ankle and move the attacker to the neutral position to defend again his/her goalpost. As in the *The Shipwreck* game, the game computes where the ball will hit the goal and send it to the robot controller, allowing the movement assistance if needed (Michmizos and Krebs, 2012a).

In the Soccer game, the control strategy is performed in a decentralized way. When the ball is in the field of the player, the local computer (server or client) moves the ball and send its position to the remote computer. It also computes and sends the prediction where the goal will hit the opponent goal when the player kicks the ball. When this prediction arrives at the remote computer, it starts to take care of the game control until the next kick.

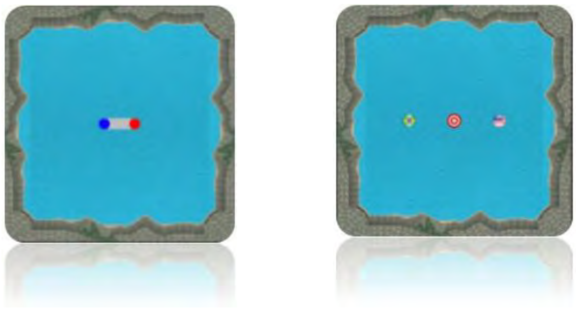
4. COOPERATIVE GAMES

In this section, it is presented two new games, named *Beam* and *Target*, specially designed to evaluate cooperative behavior of two or more players. In these games, unlike the previous games, the motion of one player is directly connected with the motion of the other one, with force reflection from one player to another. To implement these

ISSN 2176-5480

games, two robotic teleoperation techniques were studied: the symmetrical PD controller and the teleoperator based on the wave variables approach.

The cooperative game Beam consists in moving a beam in the game environment , where each extremity of the beam is virtually connected to the end-effector of the Anklebot robots, Fig. 5. The DP and IE degrees-of-freedom are respectively related to the horizontal and vertical movements of the beam extremities. If a player makes a movement in a given degree-of-freedom, a corresponding torque is applied in the other robot, moving it to the same direction, if no resistance is applied by the opponent player. Otherwise, the player who start the motion will feel this opposite resistance.



(a) Beam (b) Target

Figure 5: Cooperative games for telerehabilitation - Beam and Target.

We also developed the *Target* game, where the same teleoperation techniques were applied to ensure the direct force transmission between the players, Fig. 5. In this game, the players initially can move freely their balls in the game environment. Once both players reach the target, the teleoperation controller starts and one player can apply force to the opponent player. New targets are also be created during the game, inducing the players to move cooperatively to reach them.

4.1 Robotic Teleoperation

In this section, we briefly present the two robotic teleoperation approaches used to implement the force reflection between players in the cooperative games described above. More details on the symmetrical PD controller and the teleoperator based on the wave variables approaches can be found in Niemeyer (1996).

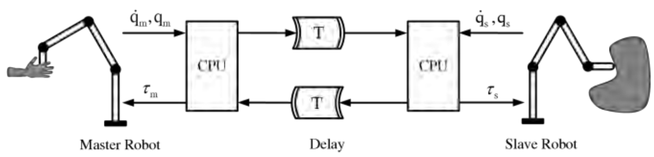


Figure 6: Robotic teleoperation system.

The basic concept of a robotic teleoperator can be described by Fig. 6, which considers the teleoperation as a sequence of elements transmitting motion and force from the human operator to the remote environment, or in our case to other human operator. In the local environment, the human operator interacts with a master robot manipulator. In a similar way, in the remote environment the slave robot manipulator interacts with a given object or other human being. The robot controllers are connect over internet, transmitting information in both directions and subject to communication delay T.

Firstly, we implemented the symmetrical PD controller. In this method, joint positions and velocities of the master robot are transmitted to the slave robot and used as desired positions and velocities for the slave PD controller. Analogously, the positions and velocities of the slave robot are defined as desired positions and velocities for the master controller. It is well known that this approach is unstable if large delays are present in the communication network, due to the lake of passivity introduced by the delay.

The second implemented method is the teleoperator based on the wave variables. The use of wave variables (or wave transform) guarantees the system stability, even in the presence of high delays. For a robotic teleoperator system, the wave variables are defined as:

$$u = \frac{b\dot{q} + \tau}{\sqrt{2b}}, \tag{1}$$

ISSN 2176-5480

$$v = \frac{b\dot{q} - \tau}{\sqrt{2b}}, \tag{2}$$

where b is the wave impedance, $\dot{q}$ are the joint velocities of the robots, and τ are the applied torques. The above equations consider as input the velocities and torques of the robots, resulting in the the wave variables u and v. However, any combination of two input variables and two output variables can be defined. For example, if we define as input variables $\dot{q}$ and v, the output variables u and τ are define as:

$$u = \sqrt{2b}\dot{q} - v, \tag{3}$$

$$\tau = \sqrt{2b}v + b\dot{q}. \tag{4}$$

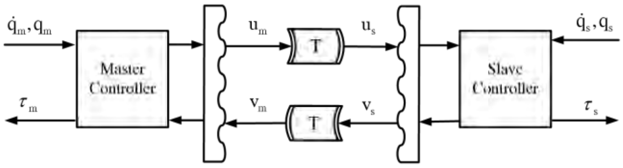


Figure 7: Basic robotic teleoperation system based on wave variables.

The basic robotic teleoperator based on wave variables are shown in Fig. 7. The subindexes m and s refer to the master and slave robots, respectively. In both sides, the robot variables ($\dot{q}$ and τ) are used to generate the wave variables u_m and v_s, which are transmitted through the internet. Considering the delay, the receiving wave variables u_s ans v_m are given by:

$$u_s(t) = u_m(t - T),$$
$$v_s(t) = v_m(t - T),$$

where the output variables are computed as:

$$u_m(t) = \frac{b\dot{q}_m(t) + \tau_m(t)}{\sqrt{2b}}, \tag{5}$$

$$v_s(t) = \frac{b\dot{q}_s(t) - \tau_s(t)}{\sqrt{2b}}. \tag{6}$$

In Niemeyer (1996), it is proposed a impedance matched robotic teleoperator based on wave variables, Fig. 8. This teleoperator, which considers the matched impedance techniques developed for eletronic systems, was proposed to eliminate undesirable effects that occur in the basic teleoperator system, mainly the wave reflections generated by the internal loop of the wave variables approach. In this structure, both robots are controlled by PD controllers and damping elements are introduced in the wave transforms and in the control laws. The resulting equations of this robotic teleoperation system are:

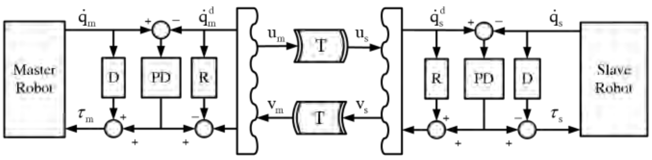


Figure 8: Impedance matched robotic teleoperation system.

ISSN 2176-5480

$$\dot{q}_s^d = \frac{\sqrt{2b}u_s - \tau_s + D_s\dot{q}_s}{b - R_s}, \tag{7}$$

$$\tau_s = K_s\left(q_s^d - q_s\right) + B_s\left(\dot{q}_s^d - \dot{q}_s\right) - D_s\dot{q}_s, \tag{8}$$

$$v_s = \frac{(b + R_s)\dot{q}_s^d - \tau_s + D_s\dot{q}_s}{\sqrt{2b}}, \tag{9}$$

and

$$\dot{q}_m^d = \frac{\sqrt{2b}v_m - \tau_m - D_m\dot{q}_m}{b + R_m}, \tag{10}$$

$$\tau_m = K_m\left(q_m^d - q_m\right) + B_m\left(\dot{q}_m^d - \dot{q}_m\right) + D_m\dot{q}_m, \tag{11}$$

$$u_m = \frac{(b - R_m)\dot{q}_m^d + \tau_m - D_m\dot{q}_m}{\sqrt{2b}}. \tag{12}$$

For a perfect impedance matching, the PD controllers' gains and the damping elements are defined as:

$$K_s = \lambda_s^2 M_s, \qquad B_s = \lambda_s M_s, \tag{13}$$

$$R_s = b - B_s, \qquad D_s = \lambda_s M_s, \tag{14}$$

and

$$K_m = \lambda_m^2 M_m, \qquad B_m = \lambda_m M_m, \tag{15}$$

$$R_m = b - B_m, \qquad D_m = \lambda_m M_m, \tag{16}$$

where λ_s and λ_m are the desired bandwidth for the master and slave robots, respectively. Since R_s and R_m are positive parameters, the wave impedance is lower bounded.

When the impedance matched teleoperator is implemented, the overall system presents apparent mechanical proprieties (total inertia, apparent damping, and steady-state stiffness) as function of the original mechanical parameters of the master and slave robots, the wave impedance, and the delay. The apparent characteristics are given by:

$$M = M_m + bT + M_s, \tag{17}$$

$$B = 2b, \tag{18}$$

$$K^{-1} = K_m^{-1} + \left(\frac{b}{T}\right)^{-1} + K_s^{-1}. \tag{19}$$

Note that with a higher delay, the apparent inertia increases and the stiffness decreases. On the other hand, increasing the wave impedance b all parameters also increase. Hence, this parameter must be appropriately selected in order to allow good tracking (increasing the stiffness of the system), but not increasing the total inertia.

4.2 Results

In this section, we present experimental results obtained from the two Anklebot robots performing teleoperation through the robotic telerehabilitation system. It is considered the two approaches presented in the previous section. For the experiments, it is used the game Beam and the following PD controllers' gains, K = 60 Nm/rad and B = 0.1 Nm.s/rad.

We first implemented the symmetrical PD controller, where the joint positions and velocities of one Anklebot (dorsi/plantar flexion (DP) and inversion/eversion (IE) joints) are used as desired positions and velocities of the other Anklebot, and vice-versa. Figure 9 shows the joint angular positions for a given motion imposed to the Anklebot 1 (shown in the left in Figure 4) with no delay in the internet communication. It was performed four motions. First, only the left motor of the Anklebot 1 is moved, generating same signal DP and IE motions. From 20 s to 28 s, only the right motor of Anklebot 1 is moved, generating again motion in both degrees of freedom, both in opposite direction. Next, it is performed a DP motion. Note that the IE position remains approximately null. Finally, a IE motion is performed with low motion in the DP degree-of-freedom. Note that, with minimum delay, the Anklebot 2 follows the motions performed by Anklebot 1, with small tracking errors. However, when a delay higher then 100 ms is artificially introduced in the communication network, the symmetrical PD controller presents instability.

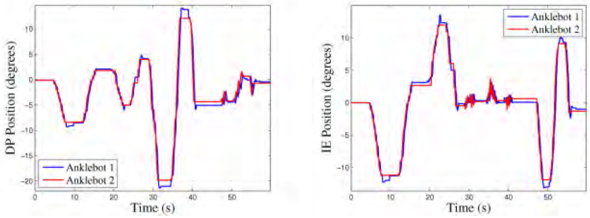


Figure 9: DP and IE positions, symmetrical PD controller, no delay.

After confirming the poor performance (or even instability) of the symmetrical PD controller with high delay, the impedance matched teleoperator based on wave variables was implemented. Figure 10 shows the joint angular positions for a similar motion imposed to the Anklebot 1 in the previous results, again with no delay. The results show a good performance of the controller based on wave variables, with a small drift between the robots mainly at the end of each motion, due to the velocity-based characteristic of the wave variable approach. Figure 11 shows the applied torques in the two Anklebots. The applied torques are of opposite signals for both joints, since the Anklebot 1 is creating opposite torques to avoid the motion imposed the operator, while Anklebot 2 is applying torques to follow the operator movement.

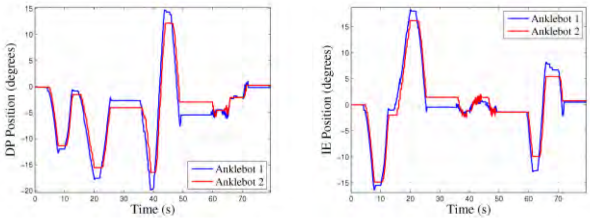


Figure 10: DP and IE positions, teleoperator based on wave variables, no delay.

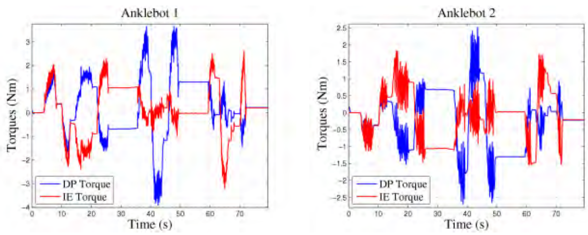


Figure 11: Applied torques, teleoperator based on wave variables, no delay.

Figures 12 and 13 show the joint angular positions and the applied torques when the slave robot (Anklebot 2) has a contact with the environment. In this example, another operator applies a restrictive force to the robot motion. The contact occurs in the interval between 18 and 23 s, where small movements occur in both robots and the applied torques, regarding the signals, are almost identical. That is, the forces applied by the environment (second operator) on the Anklebot 2 are transmitted almost directly to the first operator, and vice-versa.

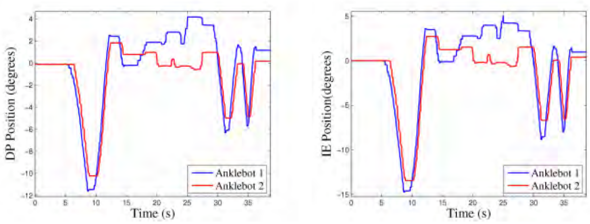


Figure 12: DP and IE positions, teleoperator based on wave variables, no delay, contact with the environment.

ISSN 2176-5480

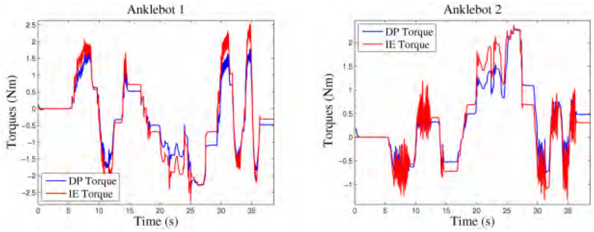


Figure 13: Applied torques, teleoperator based on wave variables, no delay, contact with the environment.

When a delay of approximately 150 ms is artificially created, the teleoperator based on wave variables present stable results, Fig. 14 and 15. However, the drift between the robots is higher, mainly in the DP degree-of-freedom, it is possible to see a great difference between the master and slave positions. In this experiment, the wave impedance is defined as $b = 20$. As shown in Section 4.1, increasing this parameter, the teleoperation system presents better results in free motion due to the increase of stiffness. However, the total inertia is also increased, and the necessary torques to move the master robot increase (compare Fig. 11 and 15).

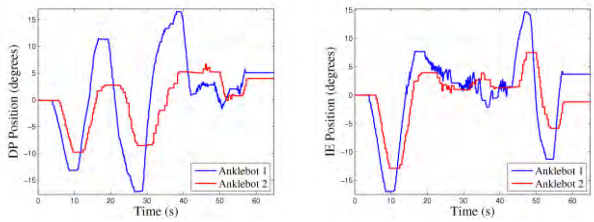


Figure 14: DP and IE positions, teleoperator based on wave variables, delay of 150 *ms*.

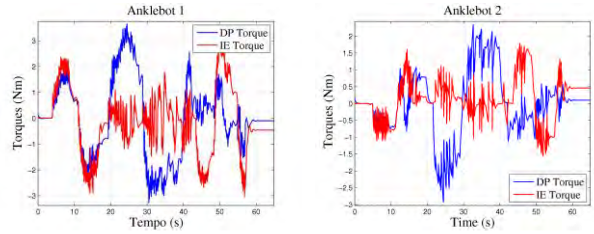


Figure 15: Applied torques, teleoperator based on wave variables, delay of 150 *ms*.

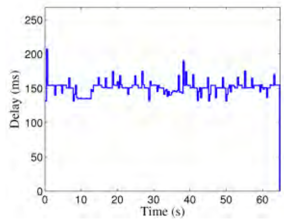


Figure 16: Atual delay measured at the client computer.

Figure 16 shows the atual delay measured at the client, is was artificially created to give an approximately delay of 150 ms. The variation around this value is due to the internet communication, which is also presented when no delay is introduced in the system.

5. CONCLUSIONS

A robotic telerehabilitation system was developed to perform both interactive and cooperative bilateral rehabilitation. The system was evaluated using four computer games, each one with specific characteristics of data transmission and event management. Also, robotic teleoperation techniques were implemented to evaluate the performance and stability of the force reflecting strategy in the cooperative bilateral configuration. The robotic telerehabilitation system was developed for two Anklebot robots, although it can also be adapted to work with any robot which communicates with an external process trough shared memory. The experimental results obtained from the robotic telerehabilitation system show an good performance even with a delay higher than the normally presented in multi-player games available in the internet

ISSN 2176-5480

6. REFERENCES

Anderson, R. J. and Spong, M. W., 1989, "Bilateral control of teleoperators with time delay", *IEEE Transactions on Automatic Control*, Vol. 34, N. 5, p. 494–501.

Carignan, C. R. and Krebs, H. I., 2006, "Telerehabilitation robotics: Bright lights, big future?", *Journal of Rehabilitation Research & Development*, Vol. 43, N. 4, p. 695–710.

Carignan, C. R. and Olsson, P. A., 2004, "Cooperative control of virtual objects over the internet using force-reflecting master arms", In *Proceedings of the 2004 IEEE International Conference on Robotics & Automation*, New Orleans, USA.

Donahoo, M. J. and Calvert, K. L., 2009, *TCP/IP Sockets in C: Practical guide for programmers*, Morgan Kaufmann, 2nd.

Forrester, L;. W., Roy, A., Krebs, H. I., and Macko, R. F., 2011, "Ankle training with a robotic device improves hemiparetic gait after a stroke". *Neurorehabilitation and Neural Repair*, Vol. 25, N. 4, p. 369-377.

Hidler, J. M., Nichols, D., Pelliccio, M., Brady, K., Campbell, D. D., Kahn, J. H. and Hornby, G. T., 2009, "Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke", *Neurorehabilitation and Neural Repair*, Vol. 23, N. 1, p. 5-13.

Hirche, S. and Buss, M., 2012, "Human-oriented control for haptic teleoperation", In *Proceedings of the IEEE*, Vol. 100, N. 3, p. 623–647.

Hornby, T. G., Campbell, D. D., Kahn, J. H., Demott, T., Moore, J. L., and Roth, H. R., 2008, "Enhanced gait-related improvements after therapist versus robotic-assisted locomotor training in subjects with chronic stroke: A randomized controlled study". *Stroke*, Vol. 39, N. 1, p. 1786-1792.

Krebs, H. I., Dipietro, L.,Levy-Tzedek, S., Fasoli, S. E., Rykman-Berland, A., Zipse, J., Fawcett, J. A., Stein, J., H. Poizner, H., Lo, A. C., Volpe, B. T. and Hogan, H., 2008, "A paradigm shift for rehabilitation robotics: therapeutic robots enhance clinician productivity in facilitating patient recovery", *IEEE Engineering in Medicine and Biology Magazine*, Vol. 27, N. 4, p. 61-70.

Michmizos, K. P. and Krebs, H. I., 2012a, "Assist-as-needed in lower extremity robotic therapy for children with cerebral palsy", In *Proceedings of the 2012 IEEE International Conference on Biomedical Robotics and Biomechatronics*, Roma, Italy.

Michmizos, K. P. and Krebs, H. I., 2012b, "Serious games for the pediatric Anklebot", In *Proceedings of the 2012 IEEE International Conference on Biomedical Robotics and Biomechatronics*, Roma, Italy.

Miller, E. L., Murray, L., Richards, L., Zorowitz, R. D., Bakas, T., Clark, P. and Billinger, S. A., 2010, "Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient: a scientific statement from the American Heart Association", *Stroke*, Vol. 41, p. 2402–2448.

Niemeyer, G., 1996, *Using wave variables in time delayed force reflecting teleoperation*, Ph.D Thesis - Massachusetts Institute of Technology, Boston, USA.

Niemeyer, G. and Slotine, J. J., 1997a, "Designing force reflecting teleoperators with large time delays to appear as virtuall tools", In *Proceedings of the 1997 IEEE International Conference on Robotics & Automation*, Albuquerque, USA.

Niemeyer, G. and Slotine, J. J., 1997b, "Using wave variables for system analysis and robot control", In *Proceedings of the 1997 IEEE International Conference on Robotics & Automation*, Albuquerque, USA.

Niemeyer, G. and Slotine, J. J., 1998, "Towards force-reflecting teleoperation over the internet", In *Proceedings of the 1998 IEEE International Conference on Robotics & Automation*, Leuven, Belgium.

Olsson, P. A., Carignan, C. R. and Tang, J., 2004, "Cooperative control of virtual objects using haptic teleoperation over the internet", In *Proceedings of the 5th Intl Conf. Disability, Virtual Reality & Assoc. Tech.*, Oxford, UK.

Roy, A., Krebs, H. I., Williams,D. J., Bever, C. T., Forrester, L. W., Macko, R. M. and Hogan, N., 2009, "Robot-Aided Neurorehabilitation: A novel robot for ankle rehabilitation", *IEEE Transactions on Robotics*, Vol. 25, N. 3, p. 569–581.

Tang, J., Carignan, C. R. and Gattewar, S., 2005, "Virtual environment for robotic tele-rehabilitation", In *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*, Chicago, USA.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.