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A New Intelligent Approach to Patient-cooperative Control of Rehabilitation Robots

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ABSTRACT

This paper presents a new method to control rehabilitation robots. An intelligent algorithm called Brain Emotional Learning Based Intelligent Controller (BELBIC) is participating to develop an admittance control scheme. This control system modifies the reference trajectory based on reactions of patient during therapy. Three main reactions has been identified and included in reference trajectory: small variations, force shocks in a single moment and variable level of participation. This reference trajectory can facilitate all patient-cooperative rehabilitation systems with an evaluation factor. Tracking performance of BELBIC on a 2-DOF exoskeleton was compared to PID with simulations and better results were observed especially when controller encountered a force shock.

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1. INTRODUCTION

Stroke is a highly prevalent condition, especially among the elderly, that results in high costs to the individual and society. It is a leading cause of disability, commonly involving deficits of motor function. However, some degree of motor recovery generally occurs spontaneously in patients who survive. In recent years, new techniques of physiotherapy have been developed to encourage active training of the disable limb, which have demonstrated promising results. The idea of physiotherapy has followed using different robots in rehabilitation which has enhanced its performance and accuracy in comparison to traditional methods of rehabilitation which were treated by human [1, 2].

The focus of prior researches in rehabilitation robots was mainly on mechanical design and rehabilitation techniques and their development issues. Mechanical design is strongly depended on application category of rehabilitation robot. They are categorized as an exoskeleton or an end effector, a lower limb rehabilitation robot or an upper limb one, an assistive robot or a therapeutic.

Rehabilitation techniques, on the other hand, include the way robot interacts with patient, like the way robot and patient cooperates to complete the motion. Development of each technique consists of the force interaction between robot and patient issues during the motion (control scheme) which is known as admittance /impedance method and also design of low level controller to track a desired reference trajectory (control method).

There are two different rehabilitation techniques for these robots. In the primary and most common strategy, robot moves along a predefined trajectory and carries disable limb. This method is used in most rehabilitation robots. Since robot does not consider force of limb and moves independent to motion of limb, this property is called Continues Passive Motion (CPM) [3, 4].

For rehabilitation robots with CPM property, mechanical design and control is very simple and low cost, however some principles of rehabilitation will be missed. In passive control method, robot might be a source of danger for patient because it just repeats the motion without considering unwanted reaction of patient. Besides, it is not such an effective method for stroke patients because their disability has caused by neurological problems and not physiological ones, then a passive repetitive motion won't help retraining of related parts in neural system. Furthermore, a passive

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motion does not encourage the patient to do exercises during therapy and consequently reduces the efficiency of cure [5, 6].

Patient-cooperative strategy needs to cope with force and position of robot simultaneously. Therefore it needs a low level controller which is able to control both at each moment. To do this, impedance or admittance control [4-9] is usually implemented because these methods control the relationship between force and displacement instead of force or displacement itself individually. Introduced by Hogan [7] in 1950, impedance and admittance method are most popular control methods in applications which requires force and position control simultaneously. Impedance control has been used for modification of ARMin II rehabilitation robot [4]. That work is the expansion of a new control idea which was introduced for prior rehabilitation robot before. Erol applied impedance control with an intelligent method to control PUMA 560 robot [6]. Hogan applied impedance control for MANUS and some other rehabilitation robots [7]. Olinger used impedance control to implement active control of a 1-DOF lower limb robot [8].

Admittance/impedance control is the description of how controller deals with physical parameters of environment like position and force. It requires a low level controller to track relevant reference trajectory like a simple PID or an intelligent controller [6, 7, 10]. Krebs et al. used a simple PID to implement impedance control of a rehabilitation robot [9]. Akdogan et al. applied a fuzzy method to have an impedance control on a simple lower limb rehabilitation robot [10].

Evaluation of all control methods could be done with simulation in software. To accomplish this, simulators use mathematical models for robot and controller and input trajectories to provide estimation on how effective controller is. In rehabilitation applications, a practical mathematical model of patient behavior during therapy is also required which is not currently available. This estimation has to consist of all different types of patient motions and reactions. It is ultimately essential to have a realistic model of patient behavior to evaluate the controller in an effective way. In this research, a graphical demonstration of patient reaction has been introduced, and then a new control method has been applied to implement admittance control.

This paper first explains the general patient cooperative rehabilitation system (section II). Then it explains simulation issues of patient reaction during therapy (Section III). Then it presents dynamic of a rehabilitation robot and introduces control methods (Section IV, V). Simulations and discussions will be discussed in next part (Section VI) and finally conclusions will be drawn.

2. GENERAL VIEW OF PATIENT COOPERATIVE REHABILITATION SYSTEM

Figure 1 shows the diagram of the patient cooperative control system with admittance control. It consists of a two DoF electrically actuated robot, a low level intelligent controller and some blocks which are responsible in providing required trajectory for patient cooperative work.

Patient-cooperative control strategies are mainly based on compensating patient weakness to complete a desired motion. They always need to measure contribution of patient to determine how much help is required to complete the motion. In the other words, force/displacement of patient should be measured and subtracted from a desired trajectory to achieve reference trajectory for a closed loop controller. Thus, we always need a measurement tool in control system [6].

This strategy is apparently more sophisticated to be implemented but some obvious profits have made it popular among rehabilitation engineers [5]. Using this strategy, disable limb has the higher priority to do the motion than robot, so it helps neurological defeats to cure gradually. It should be noted that patient cooperative strategy can be converted to CPM by simply neglecting the contribution of patient in control loop. Therefore, it can be used as a multipurpose system either in physiological disabilities or neurological ones.

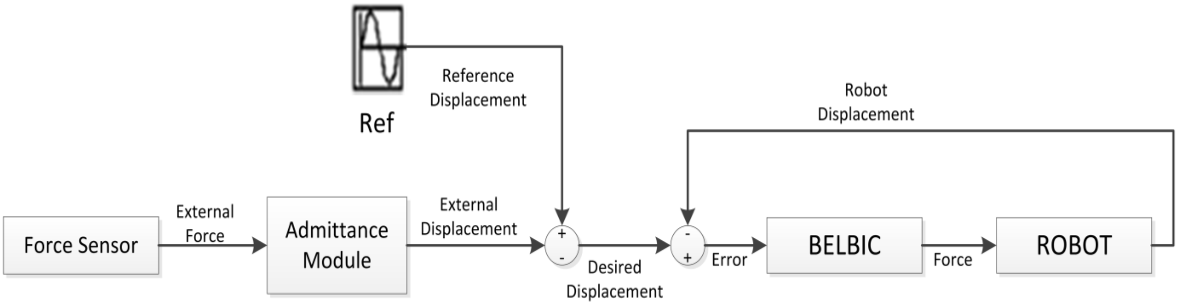


Figure 1. General diagram of control system

The proposed patient cooperative control system consists of a part dedicated to dynamic modeling of robot which comes in formulas (1-4). Another part consists of a lower level intelligent controller named BELBIC which is applied to implement admittance control with the mathematical description coming in formulas (6-14). A force sensor is installed on patient's disable limb in parallel to admittance control block which simply relates every measured force to its relevant position using formula (5). Ref block is producer of desired trajectory, in this case, a sinusoidal function. External displacement will be subtracted from Ref and the result will be conducted to closed loop control scheme of BELBIC. With such an active system of input generation working along with a robust controller, the system is supposed to handle patient's unwanted movement and irregular contribution.

3. PATIENT REACTION SIMULATION

Disable people cannot move regularly and smoothly. While they try their best to accomplish a specific motion, they might be able to do it independently in some intervals or move completely by robot motion. They also might exert very strong pulses of force to robot which is not predictable. Therefore, regarding the modeling of patient behavior, it's obvious that the magnitude and direction of patient force is unpredictable and vary from patient to patient and either varies in different phases of therapy of one patient. Thus, patient behavior cannot be simply modeled. A distractive consequence of this poor modeling is that patient-cooperative control methods can be hardly evaluated by simulators.

In this section different kinds of motions in patient reaction are explained and relevant mathematical models will be assigned to them. The final purpose is to prepare a reference trajectory for patient-cooperative controller which consists of all different possible motions of patient during therapy. It will be used to evaluate every controller following patient-cooperative control strategy of rehabilitation robots.

The rehabilitation robot used here is a planar 2-DOF robot. Practically, it is an exoskeleton which is used for repetitive motions of lower limb. It moves the patient's leg frequently to recover his/her motor functionality. Considering these repetitive motions, a suitable primary force trajectory for this robot might be a sinusoidal wave. It is supposed to simulate a periodic adduction/abduction of leg or elbow over their natural motion range. The sinusoidal wave has amplitude of 0.7 *N* and frequency of 0.08 *Hz*. It represents a typical force reaction of patients under physiotherapy programs. The magnitude and frequency of force can be different for each patient. For sake of simplicity, this experiment just considers a common force signal. Therapy time is 50 seconds here and all different force interactions of patient and robot will be emerged in this period.

As mentioned before, rehabilitation motions always have some interference. They can be categorized in three kinds of motion: first interference is caused by small continual vibrations of patient. These vibrations have no significant amplitude but high frequency and they are spread out all over the motion range. Figure 2 depicts primary sinusoidal trajectory and another noisy curve indicating small vibrations. These vibrations will be added to desired trajectory to build up a noisy input as shown in Figure 3. As it is observable, the result will be a noisy sinusoidal function.

Second source of interference in patient cooperative rehabilitation works is that patients don't always move in a similar manner. It means that disable patient may move perfectly in an interval but won't be able to move just immediately after it. In the other words, these patients track the reference trajectory with different "levels of participation".

The concept of "level of participation" can be modeled with a multi-step function as depicted in Figure 4. In spite of small vibrations, step function would be multiplied with noisy sinusoidal function to demonstrate different levels of participation. Figure 5 shows the sinusoidal function after these two changes. In Figure 5, patient has not participated between 15 to 30 seconds since level of participation is equal to zero in this interval. Between 40 to 50 seconds he has tracked the reference sinusoidal function almost perfectly, so level of participation equals its maximum value.

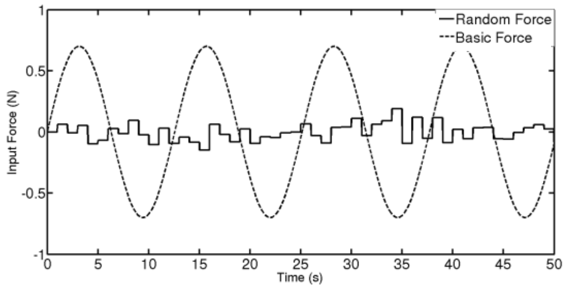


Figure 2. Main sinusoidal wave and noisy force of patient

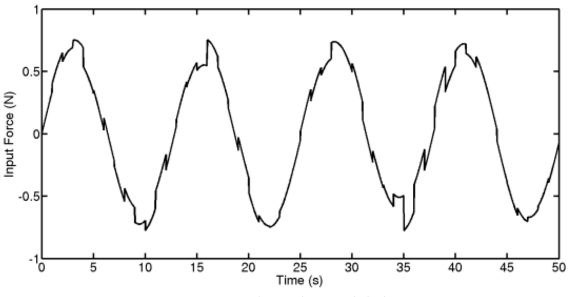


Figure 3. Noisy sinusoidal wave

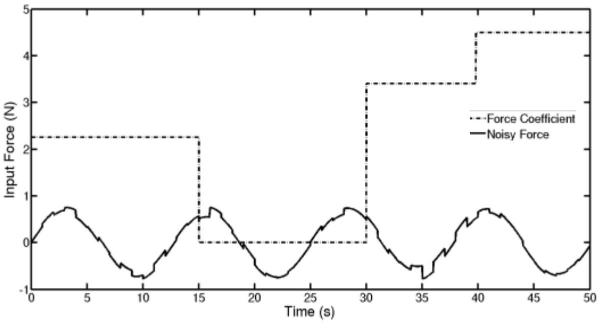


Figure 4. Noisy sinusoidal wave and level of patient participation

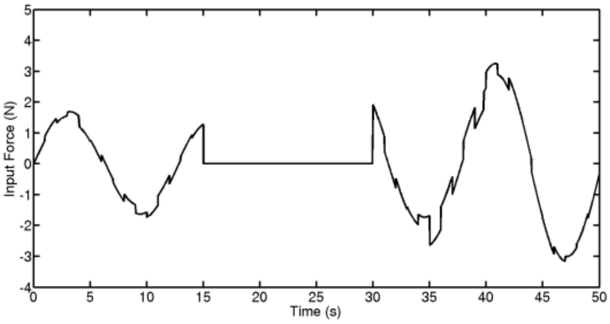


Figure 5. Initial sinusoidal wave affected by random noise and different levels of participation

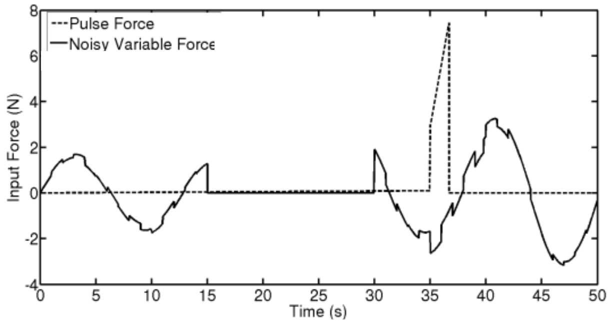


Figure 6. Adding pulse force to noisy sinusoidal wave with different levels of participation

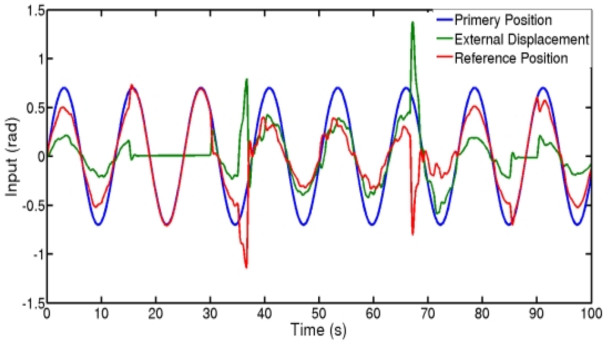


Figure 7. Original sinusoidal wave and proposed patient affects and their difference

Last effect of disabled patient motions on robot is the "force shocks". When patient is asked to track a primary trajectory, he/she might exert a big force completely unintentionally as a result of neurological problems. Sometimes these shocks have even larger intensities than sinusoidal wave. Figure 6 shows a force shock which has occurred at about 35 seconds. It will be added to wave shown in Figure 5.

Figures 2-6 depict force effect of patient during therapy. But most of rehabilitation robots are preferred to have a function of position as their reference trajectory. Here an admittance module has been applied to convert final force wave of patient motion to relevant position wave just like what is shown in Figure 7. Final entry of control system will be a function of displacement like green wave in Figure 7. The range of experiments has increased to 100 seconds to have a more realistic simulation of patient behavior during rehabilitation.

Figure 7 is a comprehensive depiction of matter. Blue colored wave is desired trajectory, the sinusoidal wave. Green wave is generated reference trajectory based on external force to robot. Then result of their subtraction, green colored wave, will be entry of any arbitrary patient-cooperative controller of rehabilitation robots. As shown in Figure 7, the reference trajectory of robot is severely bad behavior. Then patient-cooperative strategies of rehabilitation robots require a robust controller to cope with these kinds of external effects.

4. DYNAMIC OF THE ROBOT

The proposed rehabilitation robot is 2-DOF planar manipulator which is actuated by electrical motors. Figure 8 shows the manipulator. For sake of patient's safety, velocity and acceleration of both bars have been limited [11, 12]. Furthermore, robot movement area has been confined by controller and also mechanical structure makes it move in a special range. First bar just can move from -1.67rad to 1.67rad and second bar can move from *0 rad* to *3 rad*.

The dynamics of a serial n-link rigid robot can be written as:

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) = \tau \qquad (1)$$

where $\boldsymbol{q}$ is the n×1 vector of joint displacements, $\dot{\boldsymbol{q}}$ is the n×1 vector of joint velocities, $\ddot{\boldsymbol{q}}$ is the n×1 vector of joint accelerations, $\boldsymbol{\tau}$ is the n×1 vector of actuators applied torques, $\boldsymbol{M}(\boldsymbol{q})$ is the n×n symmetric positive definite manipulator inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is the n×l vector of centripetal and Coriolis forces and $\boldsymbol{G}(\boldsymbol{q})$ is the n×1 vector of gravitational forces.

We consider mass and length of bars equal to one. Then 2-DOF planar robot matrices will be given by following formulas:

$$M = \begin{bmatrix} \frac{5}{3} + \cos(q_2) & \frac{1}{3} + \frac{1}{2}\cos(q_2) \\ \frac{1}{3} + \frac{1}{2}\cos(q_2) & \frac{1}{3} \end{bmatrix} \quad (2)$$

$$C = \begin{bmatrix} -\frac{1}{2}\dot{q}_2^2 \sin(q_2) - \dot{q}_1\dot{q}_2 \sin(q_2) \\ \frac{1}{2}\dot{q}_1^2\, sin(q_2) \end{bmatrix} \quad (3)$$

$$G = \begin{bmatrix} \frac{3}{2}gcos(q_1) + \frac{1}{2}gcos(q_1 + q_2) \\ \frac{1}{2}gcos(q_1 + q_2) \end{bmatrix} \quad (4)$$

Each degree of freedom has its own control system because they are not dynamically similar and each of them should track its own reference trajectory independently. Second degree of freedom has lower intensity of force because it should carry a lower mass.

5. APPLYING BELBIC TO ADMITTANCE CONTROL

Rehabilitation robot practically has uncertain and bad behavior inputs. Furthermore, a 2-DOF exoskeleton is not just the same as hand anatomy, therefore its dynamic is more affected by external forces of patient. These specialties make control of rehabilitation robots to have some more requirements in comparison to any other ordinary robot. Then there should be such a controller which can meet these requisites.

One of the most elementary concepts in control of rehabilitation robots is keeping track of force and position together. In the other words, the manipulator control system should be designed not to track a motion trajectory alone, but rather to regulate the mechanical impedance of the manipulator. To handle this problem, admittance and impedance control have been introduced. The concept of admittance is the inverse of impedance. The underlying concept of compliant motion control using admittance control is to take a position-controlled robot as a baseline system and to make the necessary modifications of the admittance to this system in order to enable the execution of force based tasks. Then it's suitable for rehabilitation robots. Admittance control and impedance control are dual. What is difficult for the one is easy for the other, and vice versa. Impedance control needs a large amount of computational operations and an exact model of robot should be available to be used in formulations [13]. Furthermore, it needs an accurate measurement of impact force. Admittance control is the ideal choice in simulated contact with stiff and heavy objects and it totally eliminates the friction. But it just works well with robust devices. Furthermore, main problem with admittance control is requiring a position based, noise resistant, robust controller for its implementation [8].

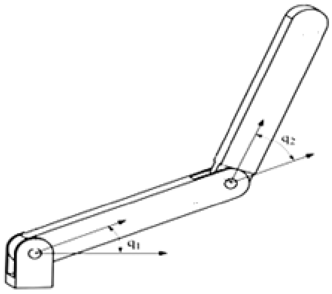


Figure 8. Two-DoF planar robot

Since BELBIC is known to be a robust controller, composition of BELBIC and admittance control seems to be suitable for rehabilitation robots. In next part, a summary of admittance control will be introduced first, and then structure of BELBIC will be explained more.

5. 1. Admittance Control In contrast to pure position control which rejects disturbance forces in order to track a given reference motion trajectory, admittance control attempts to comply with the environmental interaction and react quickly to contact forces by rapidly modifying the reference motion trajectory.

Admittance control block in Figure 1 receives measured force from patient and convert it to relevant displacement using Equation (5):

$$X_{adm} = F_{adm}(M_{adm}s^2 + C_{adm}s + K_{adm})^{-1} \quad (5)$$

X_{adm} is external displacement, F_{adm} is external force, s is Laplacian operator, and K_{adm} is coefficient of admittance control which should be set in such a way to obtain correct value of displacement from relevant external force [7]. All coefficients are selected using trial and error method and are unchanged during therapy. C_{adm}, K_{adm} and M_{adm} are relevant to damping, stiffness and inertia consequently. $M_{adm}$is usually neglected in rehabilitation applications because it is used to simulate an object. Then inertia just will be applied if robot is planned to work in a virtual reality environment [7].

If patient is unable to keep moving over reference trajectory, K_{adm} should be increased to make admittance force more and vice versa. Likewise, higher amount of C_{adm} , causes less vibration of patient during therapy. It should be noted that, some values of C_{adm} and K_{adm} might cause the control system to work out of order. Then they should be set in such a way that control system performs stable.

5. 2. BELBIC BELBIC is an intelligent controller which works based on subtraction of a reward signal and a punishment signal which are determined according to relative success and failure of control work at each moment. The main idea of BELBIC has come from what really happens in nature. Amygdala produces the reward signal and Orbitofrontal calculates a punishment signal as shown in Figure 9. Definition of concepts of BELBIC is quite flexible and based on application. Emotional learning formulations in Amygdala can be defined in following equations [14].

$$Y = Ka.\max(0, Rew - sigmA) \tag{6}$$

$$Y + V_{i-1} = V_i \tag{7}$$

$$SI.V = AM \tag{8}$$

$$AM = 2.sigmA - SI - Rew \tag{9}$$

$$sigmA = \frac{1}{2}(S.V + SI + Rew) \tag{10}$$

where *sigmA* is the Amygdala output, *Ka* is learning rate of Amygdala, *SI* is sensory input, *Rew* is reward value, *AM* is Amygdala output to Orbitofrontal cortex and *V* and *Y* are associative variables. Likewise, the learning law in Orbitofrontal cortex is defined by [14]:

$$X = Ko.(AM - MO - Rew) \tag{11}$$

$$X + \mathrm{W}_{\mathrm{i}-1} = \mathrm{W}_{\mathrm{i}} \tag{12}$$

$$\mathrm{S.W_i} = 0 \tag{13}$$

where *O* is Orbitofrontal cortex output, *MO* is model output, *Ko* is learning rate in Orbitofrontal and *X* and *W* are associative variables. The output of BELBIC is given by [14]:

$$MO = O - sigmA \tag{14}$$

According to above equations, BELBIC is a simple calculation based controller. Figure 1 shows how BELBIC works along with admittance control to control an uncertain and bad behavior plant like rehabilitation robot.

6. SIMULATION AND RESULTS

The proposed control system has been tested on 2-DOF rehabilitation robot and its results have been compared to a PID controller applied to admittance control with patient-cooperative strategy. Simulations are done in MATLAB, using formulas (2-4) for dynamic model of 2-DOF robot which is implemented in software to calculate the position relevant to applied torque. As mentioned before, lengths and masses of the bars are considered equal to unity. Both controllers has tuned as accurate as possible. The formulations of PID and *SI* and *Rew* of BELBIC are as follows:

$$PID = 10e + 0.5\int edt + 0.5\dot{e} \tag{15}$$

$$SI = Rew = 80e + 0.01\, e^2 \int edt + 5\dot{e} \tag{16}$$

Learning coefficients of Amygdala and Orbitofrontal Cortex are 0.1 and 0.03, respectively. Simulations have been depicted in a 100 second period but it has been observed for a longer time interval to be assured of controller stability. As described before, reference trajectory consists of small variations all over its interval, two force shock at 35 and 65 second and different levels of participation. Figure 10 depicts tracking performance and tracking error in first DOF of robot. As it's obvious, error of BELBIC, the green curve, is more regular and even has lower magnitude in comparison to error of PID, the blue curve, all over the interval. Besides, its performance improves when the force shock occurs at 35 second. The error of BELBIC is about 0.7 *rad* while PID has an error of at least 1.4 *rad* at this moment. Then it has decreased to about 50% in comparison to error of PID. Figure 11 shows tracking performance and error of BELBIC and PID in second DOF of robot. Just like first DOF, error of BELBIC is more regular and has lower magnitude in comparison to PID.

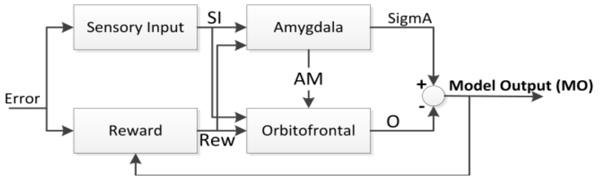
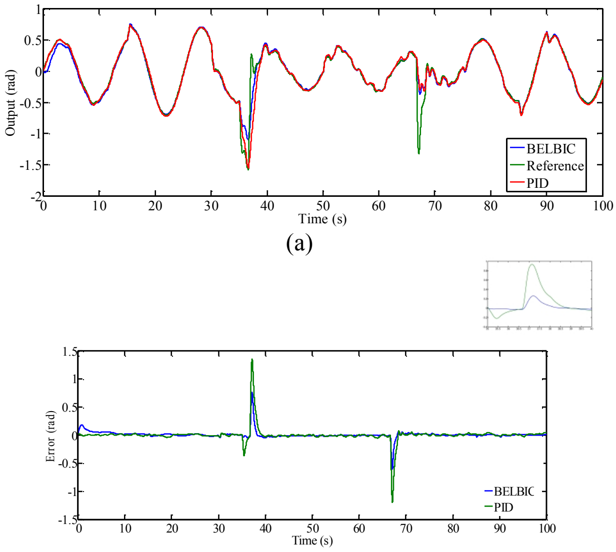


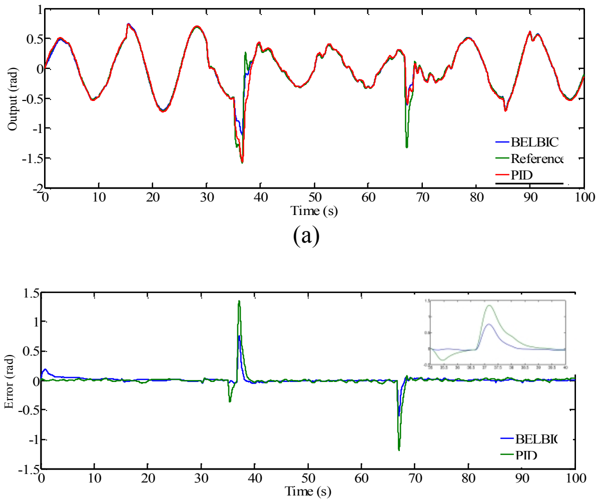
Figure 9. Diagram of BELBIC output generation regarding system error



(a)

(b)

Figure 10. Comparison of BELBIC and PID, first degree of freedom a) position tracking, b) position error



(a)

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Figure 11. Comparison of BELBIC and PID , second degree of freedom a) position tracking, b) position error

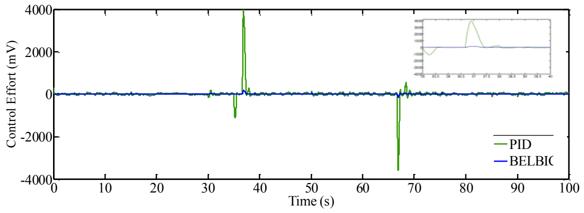

Figure 12. Control effort comparison of BELBIC and PID

Furthermore, focus on error wave in 35 second, when the force shock occurs, shows that BELBIC has an error of 0.2 *rad* while PID has an error of about 0.9 *rad*. Then BELBIC has dealt with force shock with about 20 % of error of PID. The magnitude of error is shown to be less in second DOF than first one.

Since both DOF of robot encounters force shock at the same moment (35 seconds), the effect of shock in second DOF has intensified the effect of error in first one and made its response worse. In practical cases, robot might encounter such a reaction but the magnitude of force shock is not the same.

Another evaluation of BELBIC has been made by comparing the average amount of control effort in BELBIC and PID as shown in Figure 12. When force shock occurs, BELBIC takes a control effort of 500 *Nm* but PID takes about 4000 *Nm* to deal with it. The amount of control effort is a factor of evaluation for controller since it directly affects mechanical design of robot and determines limitations of robot behavior.

Simulations show that BELBIC has worked better with uncertain and bad behavior inputs in comparison to PID. Besides, as its output is an intelligent subtraction of encouragement and a punishment signal, then it won't have a big magnitude in comparison to PID. There is only one limitation with BELBIC which is definition of its inputs intelligently and tuning of internal coefficients. If these presets are done correctly, BELBIC will work better in cases described here.

7. CONCLUSION

This paper has introduced a control approach for rehabilitation robots. First it introduced a general reference trajectory which includes three types of patient effects on robot. Using this input and an intelligent controller, BELBIC, admittance control has been applied to a rehabilitation robot and better performance has been observed specially when desired trajectory has a force shocks. Maximum error in force shock moment has decreased to at least 50% and control effort of BELBIC has decreased to 15% in comparison to PID. Besides, BELBIC has shown more robustness while it encounters a noisy input all over its working interval.

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Rehabilitation Robot

چکیده

دراین مقاله روش جدیدی برای کنترل ربات‌های توانبخش ارائه می شود .در این روش الگوریتم هوشمندی به نام BELBIC برای پیاده سازی کنترل ادمیتانس به کارگرفته شده است .دراین روش کنترلی منحنی مرجع براساس عکس العمل بیمار درهنگام فیزیوتراپی به روز می شود.عکس العمل بیمار به سه گروه تقسیم شده و در منحنی مرجع منظور می شود .این انواع عبارتند از : لرزش های جزیی ،شوک ناگهانی نیرو و همکاری متغیر بیمار .این مدلسازی منحنی مرجع در تمام تحقیقات توانبخشی به عنوان یک فاکتور ارزیابی قابل استفاده است. کارایی کنترلر هوشمند بر روی ربات دو درجه آزادی در نرم افزار شبیه ساز با PID مقایسه شده است و بهبودی نتایج به خصوص در هنگام برخورد با شوکهای ناگهانی نیرو مشاهده شده است.

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