Control of Sit to Stand Mechanism of Assistive Device for Paraplegics

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Abstract: This paper focuses on position control of sit to stand mechanism of a device developed at Air University for paraplegic patients. A dynamics model of the mechanism is presented. A nonlinear robust sliding mode controller is designed to position the end effector of the mechanism correctly. Stability of switching surface is ensured and control law is devised. The position control is successfully verified through simulation results.

1. Introduction

Paraplegia refers to the paralysis of the lower half of the human body. It is the impairment affecting either motor or sensory function of lower extremities. Rehabilitation is a process that aims to restore independence and self-determination in disabled individuals. Rehabilitation process involves various kinds of therapies and assistive mechanisms that are used for training of and exercises by disabled persons.

Extensive studies have been conducted on assistive mechanisms of rehabilitation robots. These are aimed to assist the disabled person and to aid in restoring mobility of affected limbs. Such robots facilitate the patient during the training sessions[1, 2]. Various types of robotic systems designed for lower-limb rehabilitation include treadmill gait trainers[3], foot-plate-based gait trainers[4], over-ground gait trainers[5], stationary gait and ankle trainers [6] and active foot orthotics[7].

A great concern for such rehabilitation devices is the presence of a reliable control system onboard. Some previous studies insight the recent developments, challenges observed and the control strategies designed for the lower extremity exoskeletons [8].The Assistive Device for Paraplegics (ADP) under study in this work is was developed at Department of Mechatronics, Air University[9]. In this paper, we propose a control scheme for Sit to Stand (STS) mechanism of ADP. STS mechanism is responsible for assisting the patient in changing posture from sitting position to standing position and vice versa. A device for rehabilitation of the paraplegic patients has been discussed in [10]. The device aims to restore movement of the patient by applying enough amount of electrical stimulus based upon the angle of the knee joint. To improve the performance of the device, PID parameters have been optimized which improve the performance of the device. The study presented in [11, 12] focus on the development of PID controller to improve performance of the rehabilitation devices discussed in these studies.

The developed assistive device in [9]has non-linearity in dynamics behavior due to structural complexity or coupling in the system. For this purpose, an advanced control technique is proposed for STS mechanism of the device in this study which is sliding mode control (SMC). Study of sliding mode
control and its variants for robotic gait rehabilitation is discussed in [13],[14]and [15]. The position control of PUMA 560 is improved using sliding mode controller and yields better positioning for the manipulator. Some of many variations of sliding mode control are given in the studies [16-19]. The contribution of this paper is to design SMS control scheme for the STS mechanism and verify the applicability of the control scheme through simulation results of the system after implementation of the control system in MATLAB® Simulink.

2. Dynamics Model of the STS Mechanism
Dynamics modeling is the first step towards the control implementation. It involves mathematical modeling of the STS mechanism to describe its motion between sitting and standing position. The STS mechanism is considered as RPR (Revolute–Prismatic–Revolute) mechanism having a revolute joint followed by a prismatic and then again a revolute joint. A free body diagram of the STS mechanism is shown in Figure 1 (b) whereas a CAD model is shown in figure 1(a).

![Figure 1. (a) The CAD model of Assistive Device for Paraplegics, (b) Free body Diagram of STS mechanism[9]](image)

The equations of motion are derived using Lagrange approach. The Lagrange method refers to the total energy of the system. The equations of motion of the STS system derived are given in (1) to (3).

**Link-1:**
\[ \tau_1 = \left( m_1 l_1^2 + lzz_1 + m_2 d_2^2 + lyy_2 + m_3 l_3^2 + lxx_3 S_3^2 + lyy_3 C_3^2 \right) \dot{\theta}_1 + 2 m_2 d_2 \dot{d}_2 \dot{\theta}_1 - m_2 d_2 \dot{\theta}_1^2 + \left( m_1 l_1 + m_2 d_2 \right) g C_1 + m_3 g l c_3 (S_1 S_3 - C_1 C_3) \]  

**Link-2:**
\[ \tau_2 = (m_2 + m_3) \ddot{d}_2 - m_2 d_2 \ddot{\theta}_1^2 + m_2 g S_1 \]  

**Link-3:**
\[ \tau_3 = \left( m_3 l_3^2 + lzz_3 \right) \ddot{\theta}_3 - \left( lxx_3 S_3 C_3 - lyy_3 C_3 S_3 \right) \dot{\theta}_1^2 + m_3 g l c_3 (C_1 C_3 - S_1 S_3) \]  

Where \( \tau_i \) is the torque produced at \( i \)th joint, \( d_2 \) is displacement of linear actuator, \( C_i S_i \) is \( \cos (\theta_i) \sin (\theta_i) \), \( m_i \) is mass of the \( i \)th link, \( l \) moment of inertia of the \( i \)th link along respective axis and \( l \) is the length of \( i \)th link. Link-1 is actuated by first revolute joint, link-2 is actuated by the prismatic joint and link-3 by the second revolute joint. The parameters like mass and moment of inertia are computed from the 3D CAD model by assigning a material to the model. The link lengths are taken from the actual system.

3. Sliding Mode Control (SMC)
SMC belongs to the family of Variable Structure Controllers (VSC). Design of VSCs involve two major phases. In the first phase, a switching function is designed which is generally called a sliding surface. The second phase is the design of the control law.

3.1. Sliding Surface design
Ideally, once intercepted, the switched control maintains the plant’s state trajectory on the surface to slide along until it reaches the desired point. This is also known as the sliding phase. This surface acts as guide for plant’s states to fall on to it and slide along until they reach the desired point. If \( x = \) current position, and \( x_d = \) desired position then the error \( \bar{x} \) can be given as (4):

\[
\bar{x} = x - x_d
\]

The sliding surface \( s(x, t) \) can be given as (5):

\[
s(x, t) = \left( \frac{d}{dt} + \lambda \right)^{(n-1)} \bar{x} = 0
\]

Where \( n \) is the order of the system and \( \lambda \) is a constant positive gain. For \( n=2 \), the sliding surface proposed becomes as given by (6):

\[
s(x, t) = \dot{x} + \lambda \bar{x} = 0
\]

3.2. Control Law
The sliding surface ensures that once the system’s states are on the surface, they will tend to take the system to the desired point. But sliding surface only provides the switching information. The phase in which the state start moving towards the surface is known as the reaching phase. In order to ensure that the state reaches the surface, the sliding surface must fulfill the reach-ability condition. Reach-ability condition states that

\[
\dot{s} \leq 0
\]

General form of the control law is stated as (8) where \( U \) is the control input of the system and \( U_0 \) is initial input of the system:

\[
U = -U_0 \text{sgn}(s)
\]

Now for the reachability condition we calculated derivative of the sliding surface as given in (9):

\[
\dot{s} = \dot{x} - \dot{x}_d + \lambda \ddot{x}
\]

The STS mechanism is actuated by a linear actuator at link 2 shown in figure 1(b). The torque input \( T_2 = U \) for link 2. We rearranged (2) and resulting equation is (10).

\[
(m_2 + m_3)\ddot{x}_d = U + m_2 d_2 \dot{\theta}_2^2 - m_2 g \sin \theta_1
\]

After rearrangement of equation (10) we find an equivalent control input \( \ddot{U} \) as given in (11).

\[
\ddot{U} = (m_2 + m_3)\ddot{x}_d - \lambda \ddot{x}(m_2 + m_3) - m_2 d_2 \dot{\theta}_2^2 + m_2 g \sin \theta_1
\]

The overall control law can now be written as (12):

\[
U = \ddot{U} - k \text{sgn}(s)
\]

For the reachability condition we deduced the product \( ss \) which results in equation (13):

\[
\dot{s}.s = \left( \frac{1}{m_2 + m_3} \left[ -k \text{sgn}(s) \right] \right) s
\]

If we choose \( k \) such that the overall sign of the product remains negative then the condition for reach-ability is satisfied.

4. Simulation results
Simulink Model for the dynamics model and the controller formulated was developed. The gains of SMC were tuned after the successful implementation of sliding surface and control law on the plant. The tuning of gains is crucial for acquiring good results. For the simulation purpose the desired position for the STS
mechanism was taken to be 0.2 m from the start point which is maximum length produced by actual linear actuator. We assumed that the STS mechanism was initially at sitting position. We desired the STS mechanism to move the patient from sitting position to the standing position. A young healthy person, to stand up from a sitting position, takes about 2–2.5 seconds. So the desired speed was calculated accordingly. The simulation results of SMC for STS mechanism are shown in figures 2-5. Figure 2&3 shows motion of two revolute joints while figure 4 verifies the tracking of the desired trajectory of the link-2 end-effector. The control input shown in figure 5 is such that it can be implemented in a real system.

![Figure 2. Plot for joint angle $\theta_1$](image2.png)  
![Figure 3. Plot for joint angle $\theta_3$](image3.png)  
![Figure 4. Plot for displacement 'd2' for link 2](image4.png)  
![Figure 5. Control Input Plot](image5.png)

5. Conclusions
In this study, Sliding Mode Controller was proposed for the control of the position of the STS mechanism of the assistive device for paraplegic patients. The dynamics modeling of the STS mechanism show that the system is highly non linear. Thus the simulations were performed using SMC as the non linear controller to control the system. It is shown in simulation results that SMC is able to control the device. The non linear controller performed well in switching the requirements and controlling the motion of the STS mechanism. An oscillation in the position is caused which may be removed and the results may be compared with PID controller as a future work.

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