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Control of a Stair Climbing Wheelchair

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ABSTRACT

This paper presents investigations into the control of a stair climbing wheelchair particularly for indoor usage. A virtual wheelchair model is developed using Visual Nastran software and linked with Matlab/Simulink for control purposes. The goals are to have a simple, compact and stable stairs climbing wheelchair in order to complete the ascending and descending tasks. The challenges are to ensure the wheelchair seat always stay at the upright position and to control both the front and rear wheel motors while climbing. PID control is used to provide appropriate torque to both front and rear wheels as well as at to the wheelchair seat during climbing. Results show that the wheelchair movement can be controlled smoothly and the seat maintained at the desired position with the adapted approach.

Keyword: PID control, Stair clombing, wheelchair

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1. INTRODUCTION

The use of wheelchair has become crucial for people with spinal cord injury and lower disability in their lower extremities. The widespread use of various types of electric wheelchair is currently known including holding eye-level discussions with colleagues and shopping by balancing on two wheels, going up and down steep ramps, traversing outdoor surfaces (e.g., grass, dirt trails), climbing curbs and stairs [1]. However, there are still limitations for indoor purposes due to small and confined spaces.

There are many studies conducted in areas related to climbing robot and hence, a number of stair-climbing mechanisms have been developed for wheelchair. These include crawler type, leg type, hybrid type and wheeled type; as described below.

A. Crawler type

The crawler type presents a high terrain adaptivity and this is most useful on sand and mud. The first commercial wheelchair models capable of climbing and descending staircases were based on a single-section track mechanism, called Nagasaki Stair Climber, and became available in the mid 1990s [2] and [3].

Lawn et al.[4] continued the development of the "Nagasaki Stair Climber", to a duel section tracked wheelchair capable of negotiating large number of twisting and irregular stairs typically encountered by residents living on the slopes that surround Nagasaki, Japan.

Recent developments include an auto guidance system, auto leveling of the chair angle and active control of the front and rear track angle. This provision of "hardware" has been balanced with the provision of the administrative side of making mobility assistance available to those who need it and thus overall raising the quality of life of elderly and disabled persons living on the Nagasaki Hillsides. Future work yet to be done includes the continued development of the control system with regard to improved automation, safety and general robustness. Further refinement is also required on reducing the weight of the overall stair climber.

Yun et al. [5] have developed a transmuting track wheelchair which has a dynamic track tension characteristic. They have used fuzzy logic control as an optimal estimation algorithm to estimate the proportion of various factors that affect the track tension. Frame of the wheelchair consists of fixed shelf, seat and track transmutation mechanism in which the main factors affecting tension are determined by fuzzy decision. However, vibration occurs when the wheelchair gesture is adjusted, thus another controller needs to be designed to make the main factors steadily follow appropriate value in order to avoid oscillation.
Some disadvantages of these crawler systems are that the entire track is forced to rotate on the edge of the first step when initiating a descent and low locomotion efficiency in barrier free environments [6].

B. Leg type

Sugahara et al. [7] described the means of tuning-up method of walking parameters for a biped robot with leg mechanisms using Stewart Platforms with the rise of 250 mm and certain walking experiments for ascending and descending stairs carrying a human. The stroke range used could be reduced by tuning up the waist yaw and preset zero moment point (ZMP) trajectories for motion pattern generation. Through certain simulations, it was also confirmed that the maximum rise of the stair that WL-16RII could traverse was 250mm.

Solution based on the leg type have the highest adaptivity to rough terrain and can move on stairs or a slope with stability, since the contact points with the ground where the feet support the body can be selected safely, but these mechanisms experience certain problems due to load weight, energy efficiency and speed of movement, and thus are not suitable as means of providing mobility for the elderly or the disabled.[6].

C. Hybrid type

Lawn et al.[8] utilized a hybrid of four robotic legs actuated hydraulically and equipped with independently operated steering and drive motors during stair climbing.

Morales et al.[6] designed a hybrid two decoupled wheelchair mechanisms in each axle; one to negotiate steps and the other to position the axle with regard to the chair in order to accommodate the overall slope. Kinematic model and trajectory planner were utilized to improve the trajectory planning on complex notation. This has promised high percentage of time reduction in the climbing /descent process by using optimized trajectory planner algorithm (Sliding mode control). However, this method requires more complicated stabilization process and increased power consumption because high computation resources are used in the control algorithms.

Young et al.[9] presented a 7 degree of freedom two-legs stair climbing wheelchair with laser distance sensors to measure the heights and widths of the stairs and wheelchair direction error. The proposed wheelchair can climb steep stairs (more than 30 degrees slope), while maintaining the seat trajectory statically stable at all times. However, there is no stability control incorporated to ensure the stability of the wheelchair.

D. Wheeled type

Lawn et al.[10] developed front and rear wheel clusters connected to the base of the wheelchair via powered linkages for high single step capability. This mechanism allows the wheelchair to climb up and down the stairs as well as enter directly into and from a van. A minimum control system based on two single chip computers and RC servo MUX and RC servo controllers have been embedded to operate the model. However this method required too complex structure with eight wheels mounted at the base of the wheelchair and may be perceived as a little too robotic, thus not suitable for indoor purposes.

Quaglia et al.[11] introduced mechanical concept for a stair climbing mechanism which incorporated a four-bar linkage with twelve wheels on both right and left sides that can generate a relative motion between the frame and the seat. Two functioning modes of operation were used for each locomotion unit from rolling on wheels to stepping on legs without any command, but only based on surface and dynamic conditions. However, this configuration gives unstable condition at the middle of the stairs and requires a lot of energy during steering operation because of the local skidding between wheels and ground.

Sugahara et al.[12] proposed transformable wheeled four-bar linkages, which can transform from parallelogram mode to straight and dogleg mode, for to TBW-1 Matsushima to complete the ascending and descending stair climbing task. This method ensures a lower ground contact pressure and wide support polygon than iBOT because all the four wheels are in contact with the treads at all times. However, the stability control and sensing method for motion planning have not been studied and these are just based on the inverse kinematic derivation and manually setting of joint angle transition to traverse stairs.

Teruaki I [13] designed a solid model for self-propelled stair climbing wheelchair using Computer Aided Design software tool to validate the feasibility of the approach. The work has focus on the process-oriented approach only to help the user to achieve goal using intensive simulation-based study. However, no physical modeling has been used to validate the simulation as well as the safety measures and no control algorithm implemented.

Chun-Ta et al.[14] reported on the usage of rotational multi-limbed structures, which were mounted pivotally on the opposite sides of the base. The author made use of short arm, long arm and support triangle actuated with rotational multi-limbed structure in order to rotate through epicyclic gear trains to ensure the stability of the wheelchair. However the project has not progressed to proper control method for stability purposes and has used more motors and complex mechanism, hence is not suitable to use in domestic environments.

2. STAIR CLIMBING WHEELCHAIR ON TWO WHEELS

There are many studies conducted in areas related to wheel chair on two wheels. For example they have focused on step climbing while the wheelchair is in inverted pendulum condition. Takahashi et al.[15] have proposed a rear wheel shaft position movement control scheme in order to raise the front wheels by using small force when climbing about 75mm step at an inverted pendulum position. The optimal design of rear wheel shaft position has been conducted to cater for instability of the wheelchair when the wheel shaft is just under the centre of gravity. Proportional integral controller has been successfully implemented in order to maintain the inverted pendulum condition in the presence of an impact and to recover small inclination from backward and forward body position movement. Moreover, Takahashi et al.[[16] have provided detailed wheelchair modelling during inverse pendulum control of the front wheel raising while Takahashi et al.[[17] have shown the experimental result of step climbing using power assist wheelchair. A new scheme for front wheel raising called back and forward moving scheme in which the wheelchair goes back first and goes forward was introduced in [18]. A further scheme has been reported by Takahashi and co-workers [19][20] in which to move the seat instead of moving the rear wheel shaft. The seat is moved slowly and the desired chair body inclination is increased depending on the seat movement. All the methods discussed have been realized with PI control until Takahashi et al.[[21] decided to improve the performance with an observer based optimal control (LQG or H2) with an added separate integral action. The control approach has been tested and has shown better performance than PI control.

A noteworthy feature of the iBOT 3000 Transporter is that it operates on an articulated wheel clusters design [22]. Stair climbing is achieved by controlling the cluster rotation on the basis of the position of the centre of gravity (CG), whether operated by the user or an assistant. The device strives to keep the CG of the system above the ground-contacting and between the front and rear wheels at all times, regardless of disturbances and forces operating on the system. The control system requires the device to dwell on each step for a few seconds before allowing another cluster operation. This hiatus helps keep the device from running away on stairs [22]. Each cluster may rotate about its central axis while the wheels may rotate about their hubs.

However, this mechanism needs user to face down the staircase and always hold the handrail or require an assistant to generate the control signal by causing a center of gravity shift as these may limit the wheelchair to broken arms user. The seat height is too high to transfer to and from the iBOT, and in driving the device in standard function within close quarters, thus not suitable for indoor purposes [1].

Stability for the iBOT wheelchair seat has not been taken into consideration during stair climbing process as the user must grip the handrails all the times to make sure that the seat is in the upright position.

The wheelchair prototype presented in this paper maintains the same behavior as the commercial iBOT, with the addition of important property such as a capability to stabilize the wheelchair seat during ascending and descending staircases. A wheelchair using cluster wheels is developed in MSC Visual Nastran 4D software which mimics real system and can be characterized as a highly nonlinear, complex and unstable system. This mechanism is quite simple and thus can be used for indoor purposes without the user needing to hold the guardrails all the times or assistants. In addition, the wheelchair seat is kept stable during the stairs ascending process and the user needs not to face down the stairs.

3. SYSTEM MODEL

A new modified and simplified version of wheelchair model using cluster mechanism is designed using MSC Visual Nastran 4D (VN) design software [23] as shown in Fig. 1. The VN software environment can provide a visualization showing the stair ascending and descending process, stabilizing and other functional features. It allows performing design and simulation of rigid body dynamics, determining part interference and collision responses, identifying stresses induced by motion, producing physics-based animation as well as control testing [24]. It provides a wide range of modeling and analysis capabilities, including linear static, displacement, stress, strain, vibration and heat transfer. In addition, it can easily be integrated with Matlab/Simulink for developing and testing controllers. The gravitational force is taken into account by Visual Nastran, thus approximating the real system. Furthermore, it saves time and money because if any changes are required, they can easily be tested in the software first before the actual system is developed.

The wheelchair was modeled in a basic form comprise in a two pairs of cluster wheels, frames and axes connected to the seat as shown in Fig 1.. Three pairs of motor are required in order to control the climbing and stabilizing tasks; τ_F and τ_R represent torques applied at the front and rear wheels respectively while τ_S represents the torque for the tilt angle. Link 1 is used to cater for the whole weight of the human body while Link 2, which is located at the centre of the axle, is to cater for the seat and battery weights. The sensors are attached at the respective reference bodies for control and measurement.

The humanoid model is designed and approximated using the anthropometric data based on Winter's work [25]. In this research, the humanoid model is developed as a rigid body with 1.5 m in height and the weight of 71 kg. The dimensions and specifications of the wheelchair model are shown in Table 1.

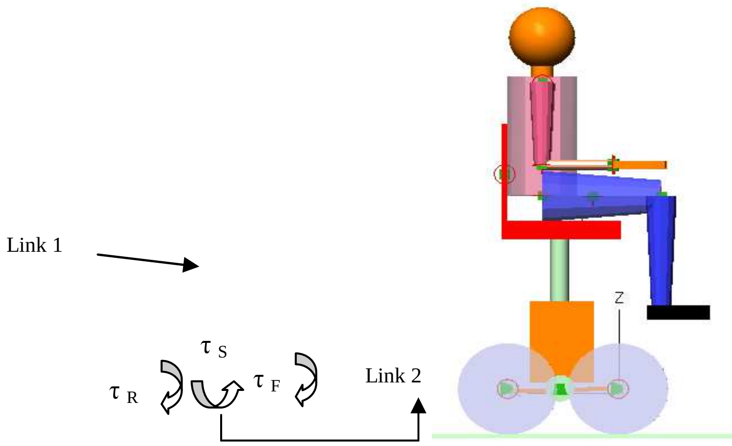


Figure 1. Complete wheelchair model

Table 1. Dimensions and specifications of the wheelchair model

Body segment	Dimension (m)	Mass (kg)
Wheel	0.18 x 0.07	3
Seat	0.45 x 0.43 x 0.08	2
Back rest	0.02 x 0.4 x 0.45	1.35
Front horizontal axis	0.04 x 0.55	1
Back horizontal axis	0.04 x 0.55	1
Base link	0.38 x 0.06 x 0.04	2
Left connecting rod	0.34 x 0.02 x 0.01	1.5
Right connecting rod	0.34 x 0.02 x 0.01	1.5
Left base joint	0.05 x 0.02	1.58
Right base joint	0.05 x 0.02	1.58
Vertical rod	0.03 x 0.59	3.03
Battery	0.38 x 0.23 x 0.32	2

The VN environment can easily be integrated with Matlab for control design purposes by installing the VN model as a plant into the Simulink library, where the VN icon can then be used in the Simulink environment. Simulink in Matlab is used as a platform for control purposes thus each time the simulation is active, the wheelchair system designed in VN is also receiving control signals and giving the system outputs. Matlab is a well known software package for modeling, simulation, dynamics system analysis, continuous and discrete time analyses, and it supports linear and nonlinear system types. In the VN icon, the user has to specify the input and output parameters to be controlled or measured as shown in Fig. 2. PID control is adopted in this work for controlling the movement of the wheel and tilt angle of the wheelchair during both ascending and descending staircases, and the tuning parameters were selected by using heuristically method.

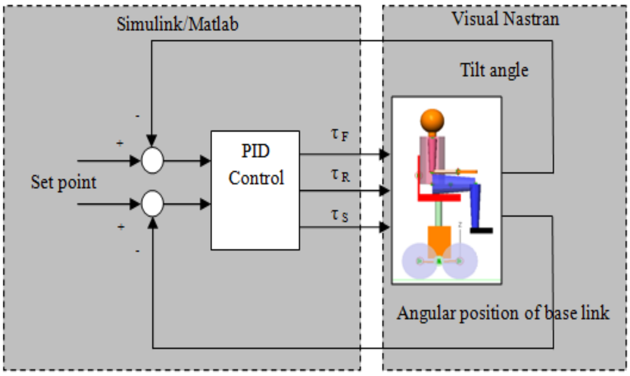
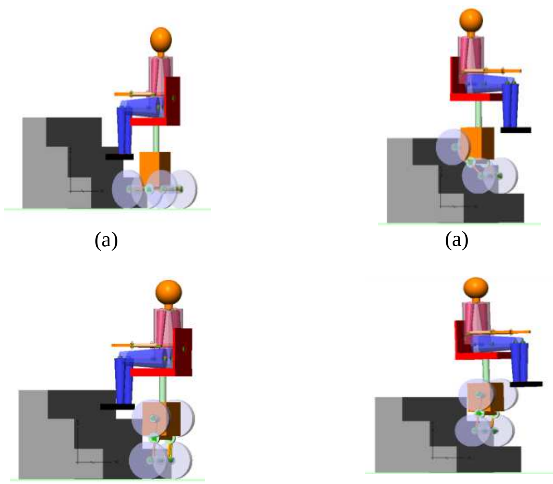


Figure 2. Control System Structure

4. SIMULATION AND RESULTS

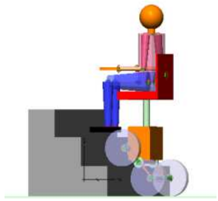
A. Ascending stairs

The proposed control approach was implemented in Simulink with VN for evaluating the effectiveness of the control method for ascending step 1 and step2. The control objective is to produce sufficient torque for lifting the rear wheels over the front wheels using cluster mechanism while maintaining the human body on seat at the upright position. For this particular dimensions and specifications of wheelchair model, the simulation in Visual Nastran was conducted on the specific stairs. Each stair had a depth of 0.28 m, height of 0.285 m and width of 1.81 m. Fig. 3 shows the movement of the wheelchair in VN environment while ascending the stairs. As noted does not need to hold the handrails and face backwards while climbing up the stairs. The controller provides sufficient torque at the front wheels in order to lift the rear wheels over the other wheels. When the motor at the front wheels work, it will automatically lock the front wheels and unlock the rear wheels to prevent the wheelchair from slipping away. The mechanism repeats the same process with climbing up the second step. Fig. 4 shows the simulation results for climbing up the first step. The PID controller maintains the tilt angle to zero degree position in less than 2.5 s as can be seen in Fig. 4 (a). Fig. 4 (b) shows the orientation of the wheelchair base link which is set to the desired angle depending on the stairs specifications. It can be clearly seen that the climbing process was completed in 1s and the performances of the wheels and seat torques are shown in Fig. 4. In order to climb up the second step, the motors require higher torques to support the human and wheelchair weights as well as to maintain the tilt angle at zero degree position as shown in Fig. 5. As noted the PID control was able to control the movement of the rear wheels so that they can perform smoothly in 1 s.



(a) (a)

(b) (b)



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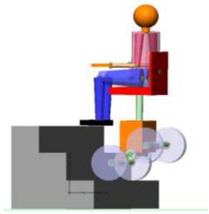

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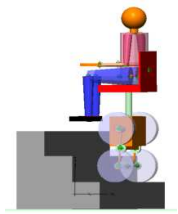

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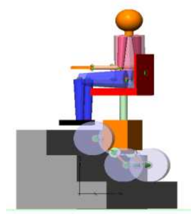
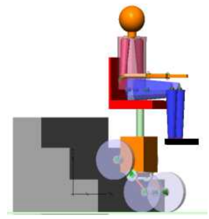


(f)

Figure 3. Ascending stairs



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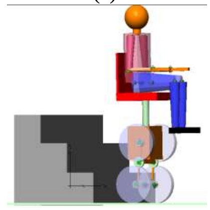

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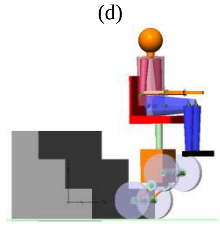

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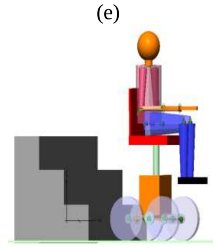
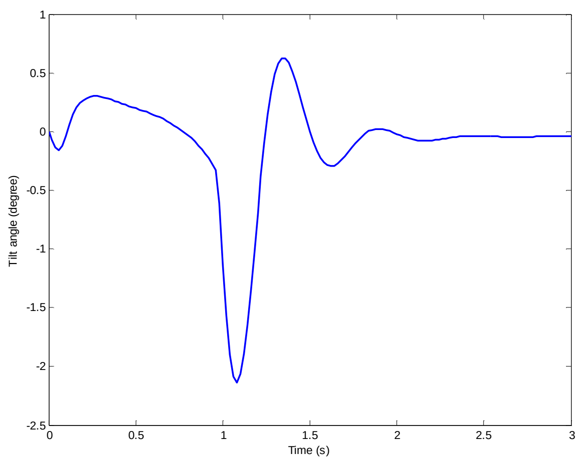
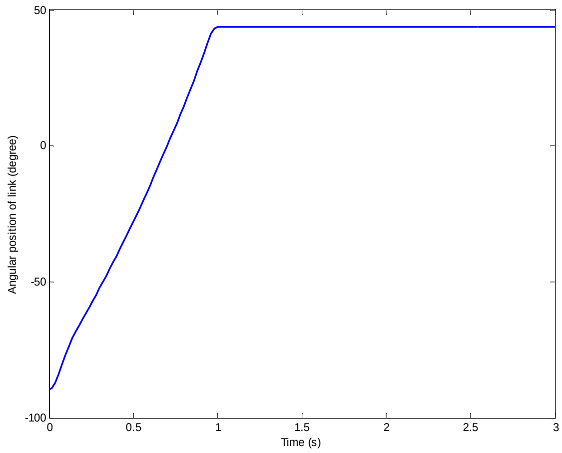


(f)

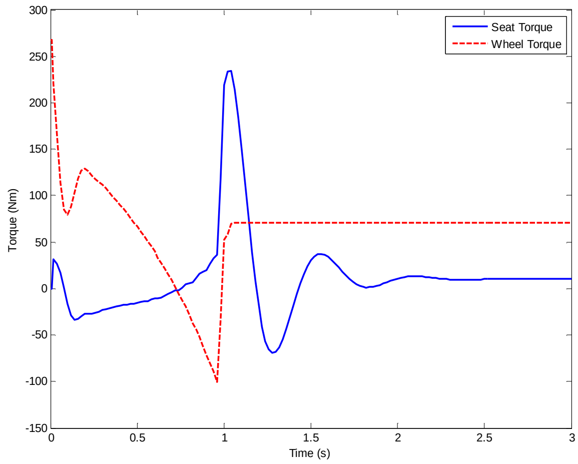
Figure 6. Descending stairs



(a) Tilt angle

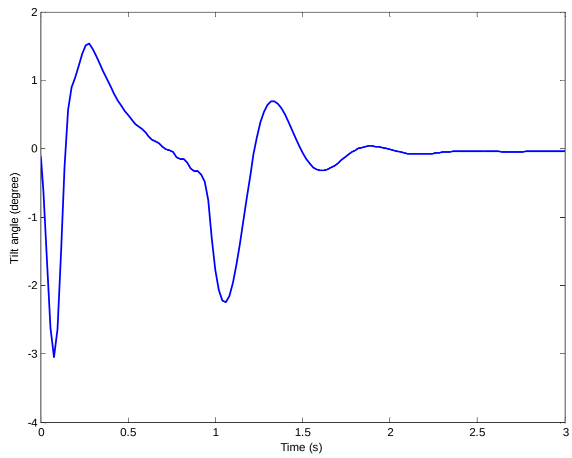


(b) Angular position of link

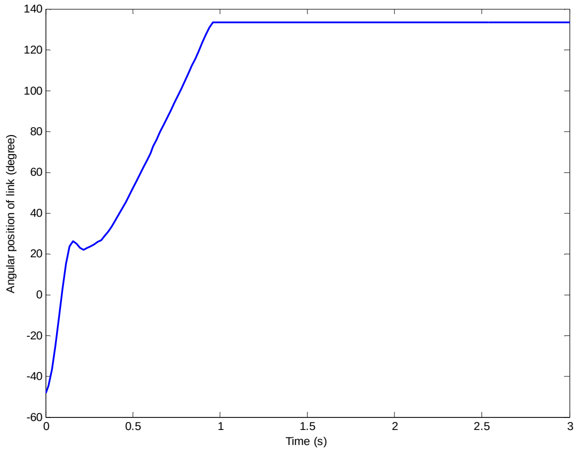


(c) Control torques

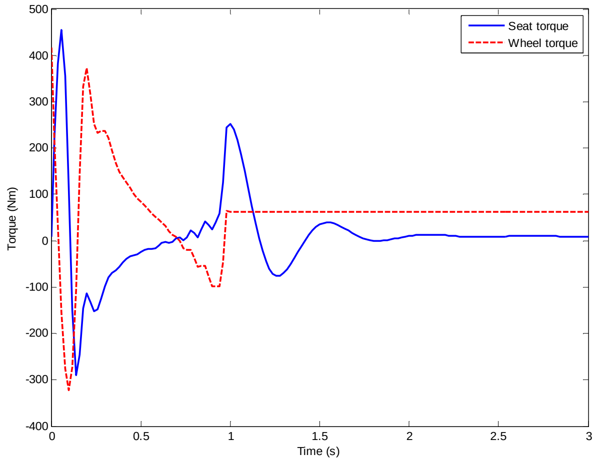
Figure 4. Wheelchair performance during ascending step 1



A. Tilt angle

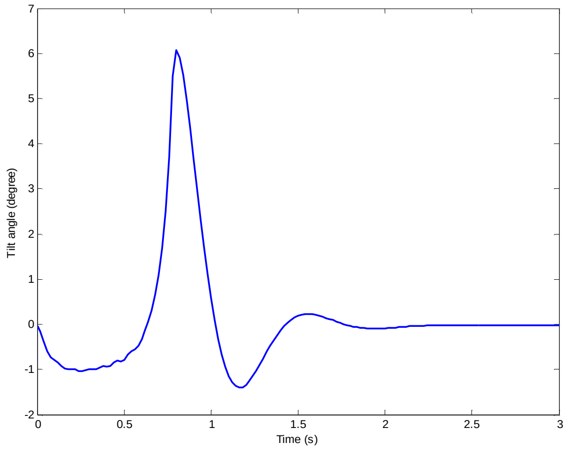


B. Angular position of link

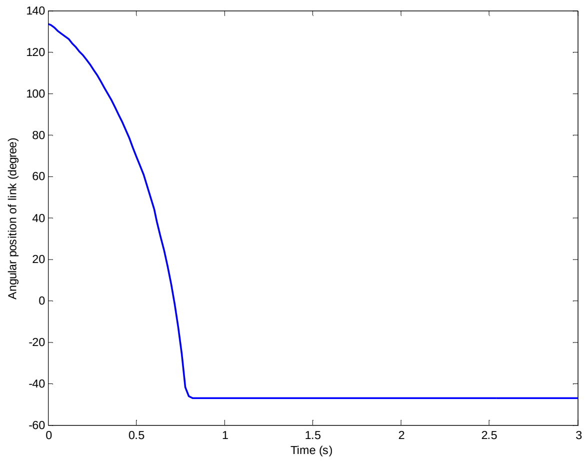


C. Control torques

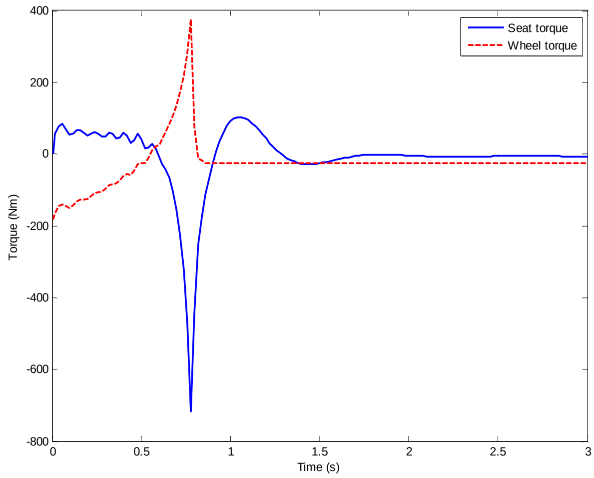
Figure 5. Wheelchair performance during ascending step 2



(a) Tilt angle

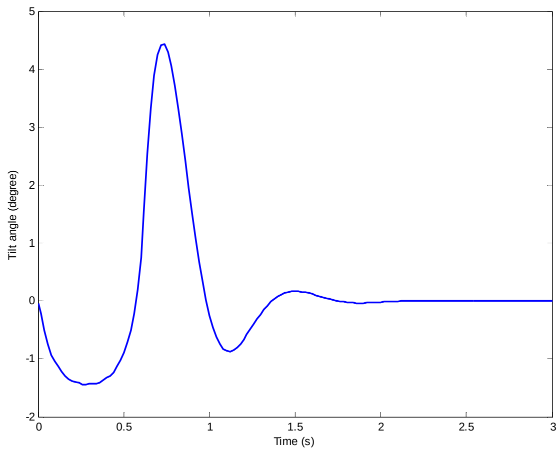


(b) Angular position of link

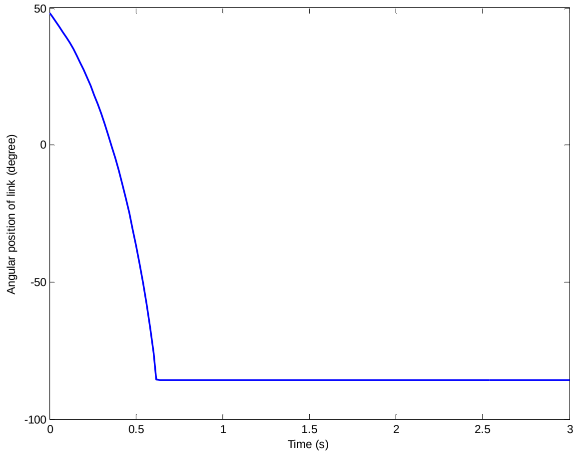


(c) Control torques

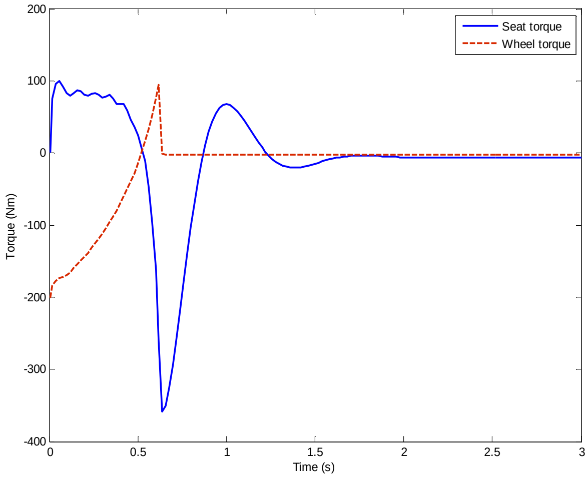
Figure 7. Wheelchair performance during descending step 2



(a) Tilt angle



(b) Angular position of link



(c) Control torques

Figure 8. Wheelchair performance during descending step 1

B. Descending stairs

Fig. 6 shows the descending stairs process for the wheelchair while maintaining the user at the upright position. The same method with ascending stairs was implemented here but at this time, the user faces down the stairs. Fig. 7 shows the performance of the wheelchair during climbing down the second step. As noted, it required less than 1s to perform the descending task as compared to ascending task as shown in Fig. 7 (b) while the seat was maintained at the upright position within approximately 2 s as shown in Fig. 7 (a). The performances for descending step 1 looked similar to step 2, but much lower in terms of the magnitudes of the torques and tilt angle as can be seen in Fig. 8.

5. CONCLUSION

A wheelchair for ascending and descending staircases has been developed in its simplified form. The proposed controller has been successfully implemented and tested within simulation exercises. The results presented has proved the feasibility of the PID control works in controlling highly nonlinear systems such as a wheelchair on stair climbing process while maintaining the stability of the system. It has been demonstrated that the control system is able to perform effectively in order to ensure the comfort and smoothness of the maneuvering tasks.

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