Modelling and Control of a Wheelchair on Two Wheels

Salmiah Ahmad* and M. O. Tokhi
Department of Automatic Control & Systems Engineering, University of Sheffield, UK
**s.ahmad@sheffield.ac.uk*

Abstract

Wheelchairs on two wheels are needed for disabled persons to perform some of the essential tasks in their living and work environments. In fact it offers great advantages and efficiency for the user. Besides allowing a disabled to lead independent life, it is expected not to take much space during mobility as compared to when it is on four wheels and thus a wheelchair on two wheels has associated design and development challenges. These include modelling and controller design for the system to perform comparably similar to normal four-wheeled wheelchair. In this paper physical model of a wheelchair on two wheels that mimics double inverted pendulum is designed and a novel fuzzy logic control mechanism is developed and tested with control of the two-wheeled wheelchair.

1. Introduction

The use of wheelchair has become very important for mobility among the disabled with spinal cord injury and the elderly people that experience with difficulty in mobility. The wheelchair is considered not only a means of transportation but also as a way to allow users to express their individuality. In fact it has been tremendously enhanced to address the needs of the user. It has further been subject of a great deal of evolution in terms of wheelchair features and functions including its design, control, styles, range of travel distance, suspension system, manoeuvrability, seating and other significant functions. Much progress has been made in the area of wheelchairs since they were first invented. Many have special features that make life easier for the user. Although everything is not wheelchair accessible yet, wheelchair users have many more opportunities than they previously did.

There are various versions of wheelchair to fulfil users' needs, but the basic features of the wheelchairs are generally similar. The standard manual wheelchair is characterized by a cross-brace frame (allows folding), built-in or removable arm rests, swing-away footrests, a mid to high-level back, two large wheels (usually 20-26") with push rims, two small wheels in the front (castors) and push handles to allow non-occupants to propel the chair. The recent trend is towards customization, which is requested for many reasons including fitting special physical needs, improving or providing special performance.

The needs of wheelchair users have encouraged many researcher in doing detailed research and study on wheelchair design, functions and performance. Both manual and electric wheelchairs have become interesting subjects for researchers in related fields to advance the systems regardless of the type of wheelchair. In order to provide independence among the disabled to function as normal people, significant research has been done world-wide [1-4].

The current research is focusing on development of wheelchair model and further on developing novel control strategies in order to lift the front wheel (casters) and maintain system stability in the upright position. Furthermore, with proper control strategy, the two-wheeled wheelchair is to move forward and backward and even steer while in an inverted pendulum state. This research is aimed to help disabled people who are using the wheelchair as the main means of transport for mobility and cannot stand on their own due to permanent injuries in their lower extremities. Therefore, this will then help them to reach certain level of height to, for example, to pick and place objects on shelves at home or library. Furthermore, they will be able to participate in conversations at eye-to-eye level comfortably with others as normal people do.

2. Modelling of the wheelchair

The MSC Visual Nastran 4D (V.N) environment is used in this work to model the wheelchair. VN is for design and professional development of engineering products involving assemblies of 3D parts. It is a unique virtual environment to perform design and simulation of rigid body dynamics, determine part

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interferences and response to collisions, identify stresses induced by motion, produce physics-based animation as well as platform for control testing. It provides a wide range of modelling and analysis capabilities, including linear static, displacement, strain, stress, vibration, heat transfer. Furthermore, it can easily be integrated with Matlab/Simulink for developing and testing controllers. Complex models drawn in other specified CAD programs can be transferred to V.N to be simulated. The gravitational force is taken into account by VN, thus approximating a real system. Modeling using VN saves time and money on buying the parts and building the model, and if any future changes are required, they can be easily tested in the software before the actual system is developed with more confidence.

The wheelchair model, shown in Figure 1, was developed using the VN environment. The dimensions of the model are approximated to closely imitate an actual system. Only basic elements of wheelchair are considered in the initial stage of the modelling. The humanoid model was designed and approximated with reference to [5].

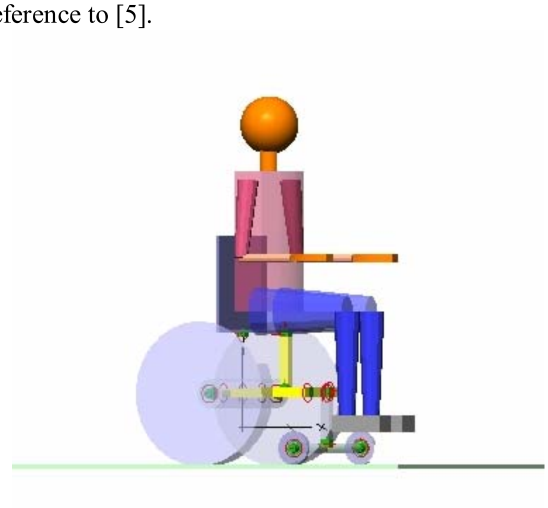

Figure 1. VN humanoid model with wheelchair

The dimensions of various components in the wheelchair model used are shown in Table 1. Since there are only limited shapes in VN, only the basic shapes were initially used in designing the wheelchair. The wheelchair was modelled in a basic form comprising two wheels, two casters, frames and axes connected to the seat. The main focus would be on the motor constraints connecting the two wheels to the horizontal axis, and a further motor connecting the horizontal frames to the vertical axis. Therefore, two independent control torques will need to be developed to control the system. The wheelchair model was built so that to have most of the physical properties of a wheelchair in terms of dimensions and weights. Although it represents the wheelchair in its simplest form, it satisfies the requirements for the design, implementation and testing of the controller.

Table 1. Wheelchair dimensions and specifications

Body Segment	**Type**	**Dimension (m)**	**Mass (kg)**
Wheel	Cylindrical	0.6 x 0.09	5
Castor	Cylindrical	0.14 x 0.02	0.5
Seat	Cuboid	0.4 x 0.01 x 0.4	2
Back Rest	Cuboid	0.4 x 0.01 x 0.4	1
Front Horizontal Axis	Cylindrical	0.04 x 0.55	1.91
Back Horizontal Axis	Cylindrical	0.12 x 0.55	5
Front Vertical Axis	Cuboid	0.04 x 0.04 x 0.23	2.89
Back Vertical Axis	Cuboid	0.04 x 0.04 x 0.23	3.14
Axis connecting Rods	Cuboid	0.04 x 0.04 x 0.4	1.77
Miscellaneous	Cuboid	Varies	2.76

The two-wheeled wheelchair system mimics a double inverted pendulum scenario and accordingly such a situation is the focus of this work. Noticeable research work has been reported on double inverted pendulum [6-7] as well as in the area of inverted pendulum on two wheels [8-10]. The schematic diagram of the system considered in this work is shown in Figure 2, where Torque1 represents the input torque to the wheels. For reasons of simplicity, the torques applied to the two wheels will be the same in magnitude, but different in direction (sign) so as to move the wheelchair only forward or backward. Torque2 represents the torque between Link1 and Link2, and will be used to cater for the whole weight of the human body. The weight here represents the human body weight, for which an average 70kg humanoid is used. The sensors are attached at the respective reference bodies for control and measurement. The control signals applied to VN wheelchair model comprise Torque1 (Nm) and Torque2 (Nm). The measured outputs from the wheelchair system consist of the angular position of Link1 (degree), and angular position of Link2 (degree).

3. The Lock Mechanism

A locking mechanism is introduced in order to secure the wheelchair user not to fall when immobile, especially when the wheelchair is disturbed, or when it is stationary. This is necessary to reduce the number of degrees of freedom (DOF) of the wheelchair system due to limited actuators as compared to the DOF that are active in the system. This stems from the fact that angular rotation of Link2 is not desired after the system has been stabilized, and it is only required at the beginning of lifting stage of the front wheels and when the system is disturbed thus affecting the links' position. The two-wheeled wheelchair system basically comprises four degrees of freedom. These are linear motion, steering motion, rotation of Link1 and rotation of Link2. The locking mechanism is therefore introduced between Link1 and Link2, which corresponds to stopping Torque2 from acting at certain situations. It will be activated as soon as the wheelchair is about stationary condition and will be inactive as soon as it is out of range such that Link2 is moving. A lock mechanism can be realized within VN by incorporating a rigid constraint at the position where the torque is applied. A new input slider meter consisting of logic 0 and 1 is thus applied to indicate whether the locking is eliminated or activated. The rigid constraint (lock) will thus be active only when Link2 is about stationary at the upright position where its angular velocity is very small.

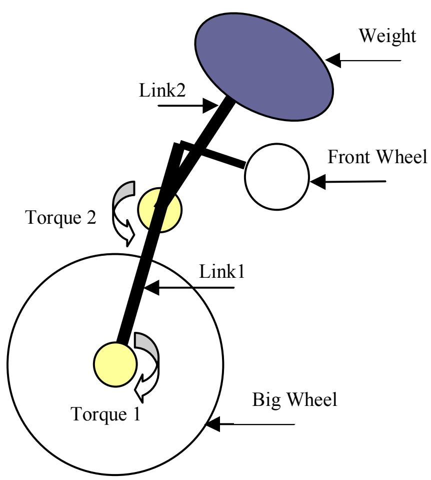

Figure 2. Schematic diagram of wheelchair system

4. Fuzzy Logic Control

Fuzzy Logic control is widely used by researchers for control of complex systems that are difficult to model. It is derived using human expert knowledge and translates human thinking into a set of "If-Then" rules for developing the required control signals. In this paper Mamdani-type fuzzy rules are adopted, and three inputs to the fuzzy logic controller are considered.

Two steps of control are involved in fulfilling the transforming four-wheeled normal wheelchair to two-wheeled wheelchair: lifting and stabilization. Therefore, two sets of controllers have to be designed for both lifting and stabilizing stages according to two different desires; Error1 and Error2.

For the first fuzzy controller (FLC1), the controller inputs are angular position error in Link1 (Error1), change in angular position error in Link1 (Change of Error1) and angular position error of Link2 (Error2). For the second fuzzy controller (FLC2), the three controller inputs are angular position error in Link2 (Error2), change in angular position error in Link2 (Change of Error2) and angular position error of Link1 (Error1). The effect of Error2 is taken into account in FLC1 while Error1 is taken into account in FLC2. In this manner the design considers the effect of dynamics of each link on the whole system dynamics. Gaussian membership function was used to represent the Mamdani type fuzzy algorithm. This function is believed to give smooth and steady response of the system. The five membership levels used are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB). On the other hand, the three levels of membership function used are Negative (N), Zero (Z), and Positive (P), resulting 75 rules. Figure 3 shows the overall FLC1 structure. Table 2 shows the implemented fuzzy rules for FLC1 when Error2 is (N). The same rules are applied when Error2 is Z and P. Details of lifting and stabilizing stages have been discussed in [11]. It has to be stressed here that the same design structure is basically used for all the controllers, thus only one fuzzy logic controller is designed that is compatible to all situations.

Table 2: The fuzzy rules

E1 \ ΔE1	NB	NS	Z	PS	PB
NB	**PB**	**PB**	**PB**	**PS**	**Z**
NS	**PB**	**PB**	**PS**	**Z**	**NS**
Z	**PB**	**PS**	**Z**	**NS**	**NB**
PS	**PS**	**Z**	**NS**	**NB**	**NB**
PB	**Z**	**NS**	**NB**	**NB**	**NB**

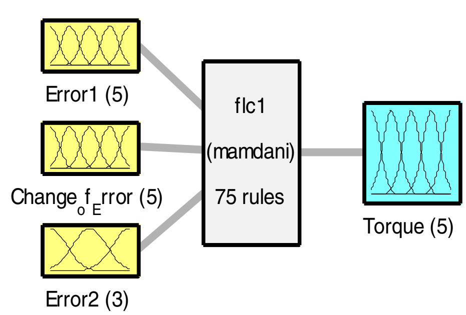

Figure 3. Structure of Fuzzy Logic Control

5. Simulation Results

The proposed locking mechanism was incorporated into lifting and stabilizing control of the two-wheeled wheelchair. The controller was designed in Matlab Simulink, interfaced with the wheelchair system in VN environment, for illustrating the effectiveness of the locking mechanism of the wheelchair on two wheels. Link2 is locked whenever both the angular position of Link2 and angular velocity of Link2 are within very small ranges. To test the effectiveness of the locking mechanism, the system is perturbed at a certain time, with and without the locking mechanism. The first part of the results show the external disturbances applied without locking while the second part demonstrates the disturbed system response with the locking mechanism.

5.1. Disturbance without locking

The system is perturbed with 1000N horizontal force (applied on the back of the chair) after 10 seconds of simulation time. This causes the wheelchair to move to the left (backward). Figures 4 to 8 show the system performance over a simulation-time period of 25 seconds. It can be seen in Figures 4 and 5 that Link1 and Link2 settled quite fast, and it took up to 3.5 seconds to settle due to the disturbance. Torque1 fluctuated about + 50Nm and -25Nm while fluctuations in Torque2 were smaller after disturbed. Both settled within nearly 4 seconds after perturbed as noted in Figures 6 and 7. Figure 8 shows that the system moved up to 0.6m to recover from the disturbance. The performance is reasonable and satisfactory with this configuration. On the other hand, the locking mechanism is expected to ensure that the system is safe in the upright position thus accounting for any sudden disturbance or even when the actuator is faulty.

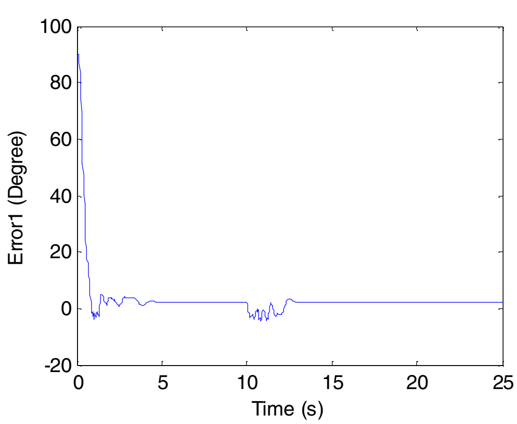

Figure 4. Angular position error of Link1 (Error1) as a function of time

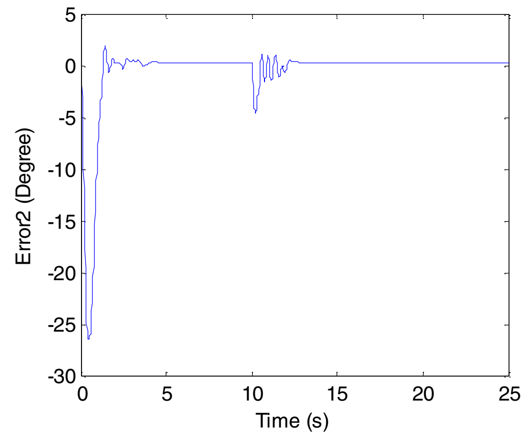

Figure 5. Angular position error of Link2 (Error2) as a function of time

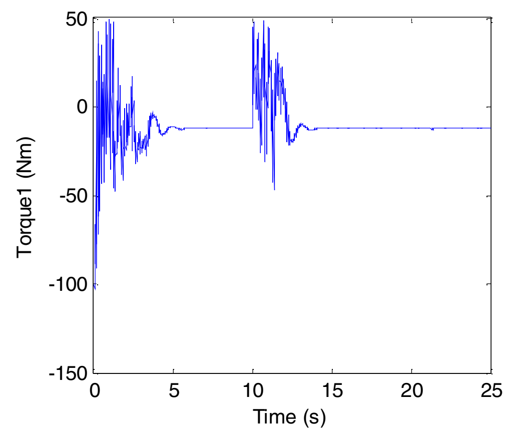

Figure 6. Wheel torque (Torque1) as a function of time

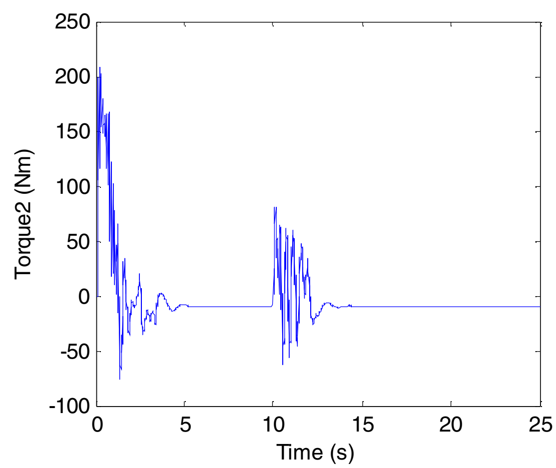

Figure 7. Torque of motor between Link1 and Link2 (Torque2) as a function of time

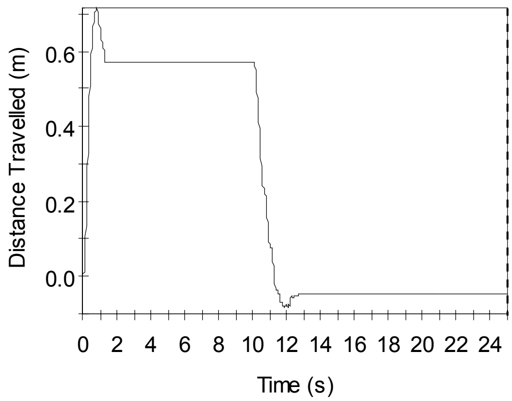

Figure 8. Distance travelled by the wheelchair as a function of time

5.2. Disturbance with locking

The system performance with the locking mechanism applied is shown in Figures 9 to 13. Figure 9 shows that Error1 settled within 3 seconds after the system was disturbed by 1000N force at 10 second. Error2 also settled quite fast as shown in Figures 10. On the other hand, both Torque1 and Torque2 settled after fluctuating for about 3 seconds, due to the disturbance. Torque1 did not oscillate as high as compared to without the locking configuration. These can be observed in Figures 11 and 12. Apart from very small oscillation of Torque2 due to switching effect, the result is within acceptable range. It can also be seen that the lock helped the system settle faster and the wheelchair travelled up to 0.6m to recover from the disturbance, as noted in Figure 13. Therefore, it can be noted that the system performance with the locking mechanism was better than that without locking.

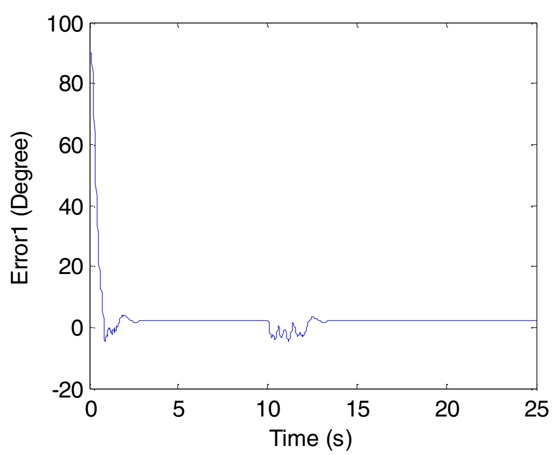

Figure 9. Angular position error of Link1 (Error1) as a function of time

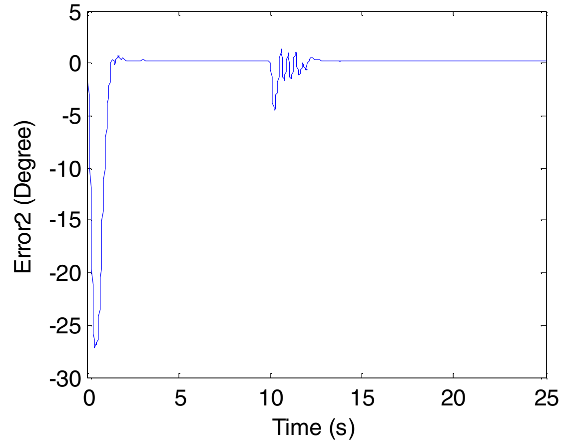

Figure 10. Angular position error of Link2 (Error2) as a function of time

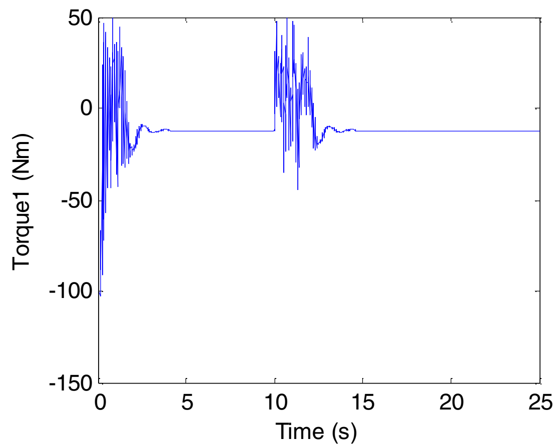

Figure 11. Wheel torque (Torque1) as a function of time

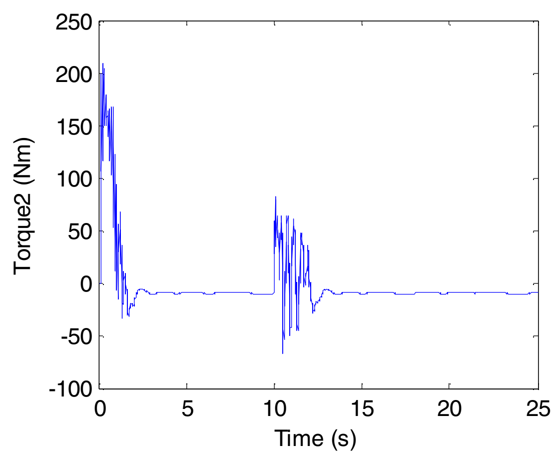

Figure 12 .Torque of motor between Link1 and Link2 (Torque2) as a function of time

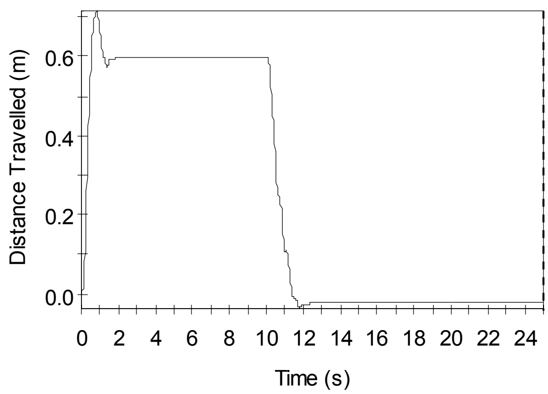

Figure 13. Distance travelled by the wheelchair as a function of time

6. Conclusion

A locking mechanism has been introduced as a precaution towards unexpected disturbance on a two-wheeled wheelchair, particularly when the system is at the stationary state. The lock will be applied at the upright position and will be inactive automatically when it is not needed. Simple fuzzy logic control for lifting as well as stabilizing the wheelchair has been successfully implemented and tested. The proposed locking mechanism has been successfully incorporated into a very highly non-stable, nonlinear wheelchair system. The results presented prove that the locking mechanism introduced helps to reduce the number of degrees of freedom of the system, and thus enhances the system resistance to sudden external disturbances and leads to good system performance. Future work will look at further improvements of the control mechanism at modelling and simulation of the system as well as optimisation of the control parameters.

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