Forward and Backward Motion Control of Wheelchair on Two Wheels

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***Abstract*-The challenge in designing wheelchair on two wheels involves the design and implementation of suitable control strategies for a two wheeled wheelchair to perform comparably similar to a normal four wheeled wheelchair. It is important to note that a wheelchair on two wheels is expected not to take much space during mobility as compared to when it is on four wheels. Moreover, disabled people are encouraged and expected to perform most activities that others can do and hence lead an independent life. Thus, wheelchairs on two wheels are needed for disabled persons to perform some of the essential tasks in their living and work environments. In this research a model of the standard wheelchair is developed as a test and verification platform using Visual Nastran software. Novel fuzzy logic control strategies are designed for lifting up the chair (transforming a four-wheeled wheelchair to a two-wheeled wheelchair) and maintaining stability and balance while on two wheels. Furthermore, position control for forward and backward mobility of the wheelchair on two wheels is developed using fuzzy logic control. Simulation results of the proposed control strategy are presented and discussed.**

I. Introduction

This research work is focusing on development of novel fuzzy control strategies for forward and backward motion of a two-wheeled wheelchair. The two-wheeled state of the wheelchair is realized by lifting the front wheels (casters) of the wheelchair so that it achieves an upright position with lifting the chair to a higher level. The current 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 reach certain levels of height in confined spaces, e.g. to pick and place things on shelves. Furthermore, they will be able to participate in conversations at eye-to-eye level comfortably as normal people do. Researchers have accordingly shown a great deal of interest in advancing the current technology of wheelchair to let disabled people perform most of their daily life tasks independently. They have proved that using wheelchair as a means of mobility is more efficient than walking. Thus, it is important for wheelchair users to be independent, to perform tasks similar to normal people.

It is evident from the literature that research on modeling and control of wheelchairs on two wheels is not extensive. Japanese have started the research in this field mainly for their ageing society. Many researches, on the other hand, have focused on various system types involving inverted pendulum, such as inverted pendulum on cart [1-7], rotary inverted pendulum [8-14], and inverted pendulum on two wheels [15-18]. These research works differ from one another mainly in terms of the control strategy adopted. Most of these have used conventional control methods such as linear quadratic regulator (LQR), optimal control and nonlinear control. Only a few have proposed the use of fuzzy logic, neural network and genetic algorithms.

Some limited research work on wheelchairs on two wheels has been reported in the literature [19-24]. Among them, there are a number of research reports in the literature on wheelchairs with a mechanism whereby the user can climb over a step up to about 10 cm without a helper while maintaining control as an inverted pendulum. The technique uses conventional PI control with which the wheelchair can be maintained in the inverted pendulum position for about few minutes before climbing a step on the roadside. Throughout these studies, there is no evidence of use of intelligent control approaches such as fuzzy logic control for controlling the wheelchair on two wheels. Moreover, the models reported involved only single inverted pendulum scenarios whereas the current research considers a double inverted pendulum model, which is more complex. Since fuzzy logic is known to be very ideal for control of nonlinear systems, and specifically where the system is complicated to model, this research embarks on the development of fuzzy logic control (FLC) for forward and backward movement of the wheelchair on two wheels. The controller is executed after the transformation of a wheelchair four-wheeled state to two-wheeled state by lift the front wheels and the chair, and maintaining this inverted pendulum position.

II. Wheelchair with Humanoid Model

The wheelchair with humanoid model was developed using MSC Visual Nastran 4D (VN) software. It was modeled in a basic form comprising two wheels, two casters, frames and axes connected to the seat. The main focus will be on the motor constraints connecting the two wheels to the horizontal axis, and a further motor connecting the horizontal frames to the seat. Therefore, two independent control torques are realized for controlling the system. The schematic diagram of the whole system is shown in Fig. 1. The system mimics a double inverted pendulum scenario and accordingly such a situation is the focus of this work. Torque1 represents the input torque to the wheels. For the time being and for reasons of simplicity, the torques applied

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to the two wheels will be the same in magnitude, but different in direction (sign) so that to move the wheelchair 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, and in this case an average humanoid weighing 70kg is used. The sensors are attached at the respective reference bodies for control and measurement. The control outputs fed into the wheelchair system comprise Torque1 (Nm) and Torque2 (Nm), and the outputs of the wheelchair system consists of the angular position of Link1 (degree), angular position of Link2 (degree) and Distance (m).

III. FUZZY LOGIC CONTROL

Fuzzy logic control (FLC) is widely used by researchers for control of complex systems that are difficult to model. A fuzzy logic algorithm is derived using human expert knowledge. Accordingly, it 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. There are three errors to be reduced with respect to three independent reference inputs and the corresponding three output responses of the wheelchair system.

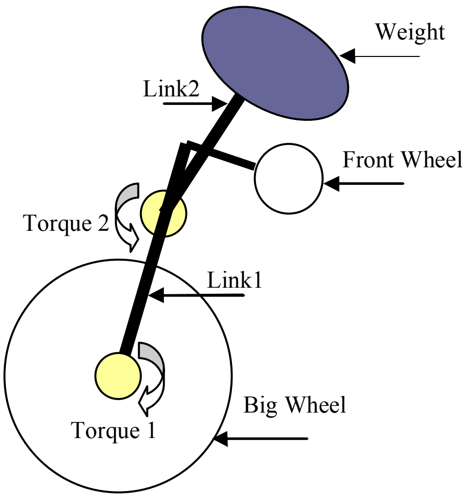


Fig. 1. Schematic diagram of wheelchair system

For the first 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 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 that of Error1 is taken into account in FLC2. This will account for the cross-coupling effects of the dynamics of the links in the control design. These two controllers are mainly for lifting and stabilizing Link1 and Link2. The third controller (FLC3), on the other hand, is designed for position control of the two-wheeled wheelchair. The same structure of FLC is used. Three controller inputs are considered including distance error (Error3), change in distance error (Change of Error3) and angular position error of Link1 (Error1). Error1 and Error3 are considered in FLC3 as both uses the same actuator (Torque1) in the wheelchair system.

The two links and distances are controlled independently with FLC algorithms that have the same rule bases. For each angular position control, a stabilizing FLC has been incorporated, which is activated within small region of the upright position ($\pm 5^0$). The only difference of the stabilizing FLC with the other FLC algorithms is the scaling factor, which is made relatively larger so that the controller is more sensitive within this region. The advantage of this fuzzy logic approach is that the same fuzzy logic algorithm is implemented in different situations. Therefore, only one FLC algorithm was designed but implemented for five different purposes; two controllers for lifting, two for stabilizing the system, and one for position control. The inputs are normalized so that they can be generalized and then processed using the fuzzy rules. Gaussian (bell shaped) type membership functions were used, which is believed to give smooth and steady response of the system. These comprise, for Error3 and Change of Error3 in FLC1, for instance, five levels of membership, and only three levels of membership of Error1, resulting in 25×3 = 75 rules. For the output torque, five levels of membership function are used. 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). Since the fuzzy logic controllers designed are the same and applied at different places, only the distance error (Error3) controller will be presented in detail as it is the main focus in this paper. Details of the lifting and stabilizing control and results are given in [25]. Table 1 show the implemented fuzzy rules for FLC3 controller when Error1 is negative (N). The same rules are applied when Error1 is Zero (Z) and positive (P). The rules are typically fired as:

*If Error3 is **PB**, and Change of Error3 is **PB** then The Torque is **NB**.*

TABLE 1
TABLE OF FUZZY RULES

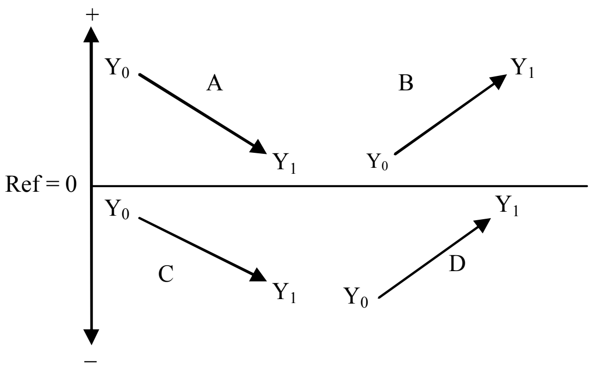
E3 \ ΔE3	**NB**	**NS**	**Z**	**PS**	**PB**
NB	**PB**	**PB**	**PB**	**PS**	**Z**
NS	**PB**	**PB**	**PS**	**Z**	**NS**
Z	**PB**	**PS**	**Z**	**NS**	**NB**
PS	**PS**	**Z**	**NS**	**NB**	**NB**
PB	**Z**	**NS**	**NB**	**NB**	**NB**

Fuzzy rules are designed based on the following set of equations. Further details are given in Fig. 2.

$$E3_0 = Y_0 - Ref \quad (1)$$

$$E3_1 = Y_1 - Ref \quad (2)$$

$$\Delta E3 = E3_1 - E3_0 = Y_1 - Y_0 \quad (3)$$



Fig, 2. Transformation diagram of Error3 and Change of Error3

Case A
E3 is positive, ΔE3 is negative and thus the action (Torque1) is zero. This happens because the error is moving toward the target reference.

Case B
E3 is positive, ΔE3 is positive and thus the action (Torque1) is negative, in order to bring the error back to the target reference.

Case C
E3 is negative, ΔE3 is negative, and thus the action (Torque1) is positive, in order to bring back the error to the target reference.

Case D
E3 is negative, ΔE3 is positive, and thus the action (Torque1) is zero. This happens because the error is already moving toward the target reference.

IV. SIMULATION RESULTS

The proposed control approach was implemented in Matlab Simulink for illustrating the effectiveness of the method for position control of the wheelchair on two wheels after it has been lifted. The control objective is to move the wheelchair forward or backward while maintaining the upright position after the lifting stage. The main effort was on the scaling of normalized parameters. There are as much as fifteen input scaling factors needed to be determined. At first, heuristic tuning was applied to the controller. Further optimization of the parameters will help to obtain the best system performance.

A. Forward Movement

Fig. 3 to Fig. 8 shows the results after 20 seconds of simulation time for forward movement of the two-wheeled wheelchair. The wheelchair was set to move 2.5m forward from its initial position. The result shows that the FLC approach works very well with the wheelchair system on two wheels. From the figures, it can be observed that Error1, Error2 and Error3 settled after about 5 second, which can be considered quite good performance for the initial attempts of parameters setting. Fig. 3 and Fig. 4 show that the angular position error of Link1 and Link2 reduced to zero after about 5 seconds. This is considered rather fast settling time. On the other hand, the distance error settled without overshoot, as noted in Fig. 5. Fig. 6 and Fig. 7 show the torque corresponding to Torque1 and Torque2 respectively. It can be seen that Torque1 settled after about 6 seconds, which is within acceptable range. It settled a bit slower due to the need for adequate amount of torque for balancing the upright position as well as maintaining the distance error to be zero. On the other hand, Torque2 overshoots up to 190Nm at the start in order to cater for the human weight. The result in Fig. 8 proves that the velocity of the wheel was decreasing and settled within about 5 seconds. The human body moved up by up to 0.2 meters, which can help a disabled person to reach heights of up to 1.5m. Further height extension can be incorporated with suitable mechanical designs of the wheelchair system.

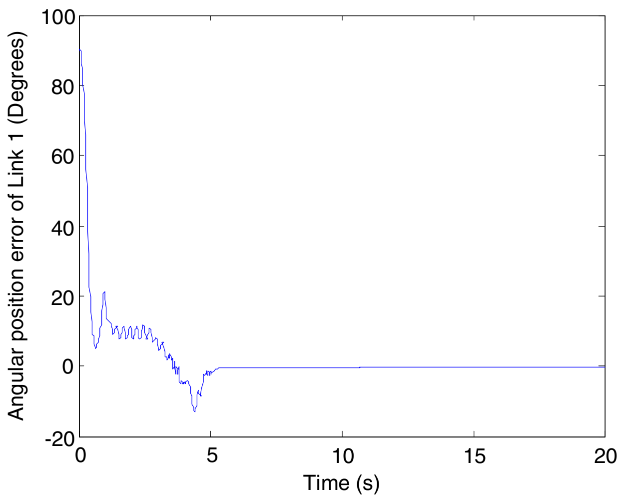


Fig. 3. Angular position error of Link1 (Error1) as a function of time

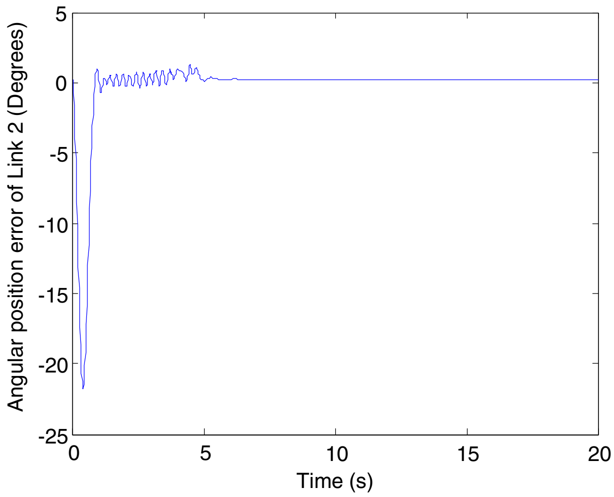


Fig. 4. Angular position error of Link2 (Error2) as a function of time

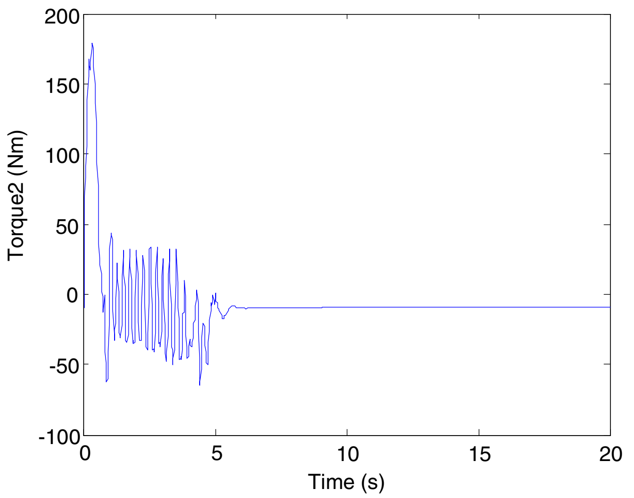


Fig. 7. Torque between Link1 and Link2 (Torque2) as a function of time

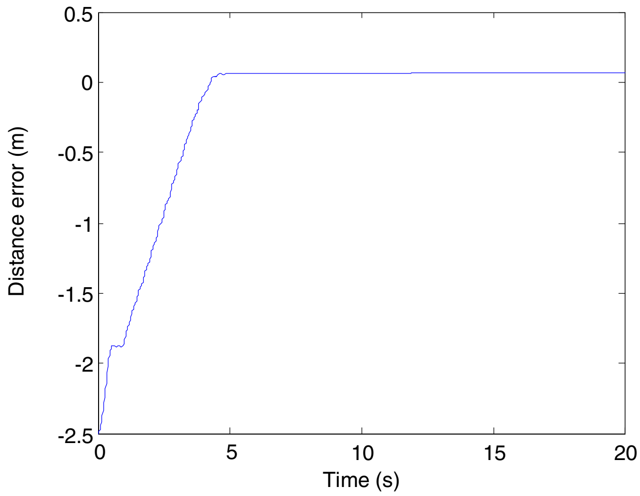


Fig. 5. Distance error (Error3) as a function of time

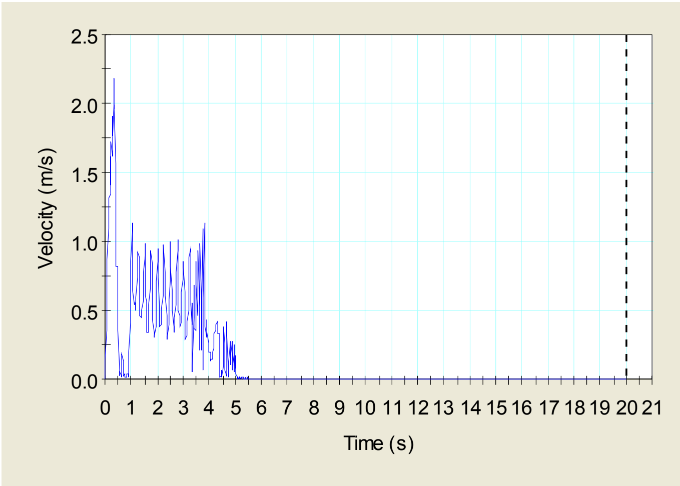


Fig. 8. The wheel velocity as a function of time

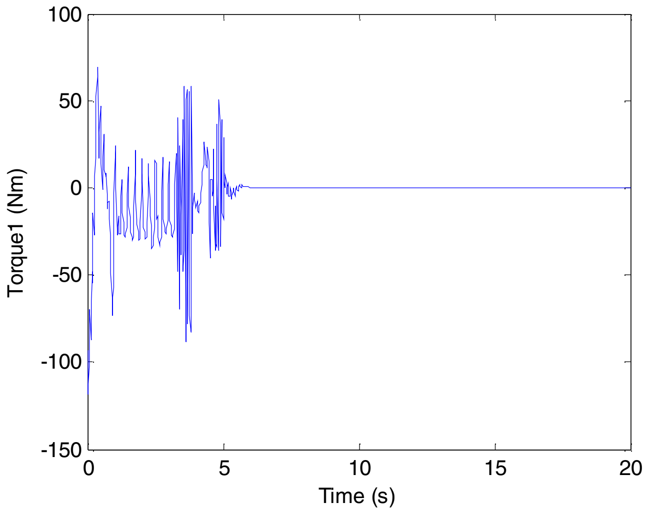


Fig. 6. Wheel torque (Torque1) as a function of time

B. Backward Movement

Fig. 9 to Fig. 14 shows the results after 20 seconds of simulation time for backward movement of the two-wheeled wheelchair. The wheelchair was set to move 2.5m backward from its initial position. It can be seen that the system requires relatively more time in the backward motion to settle. This is caused by different dynamics needs to be accounted for by the wheelchair from lifting up the front wheels, stabilizing stage as well as backward maneuvering stage, which forces the system to take extra time. However, the results show that the FLC approach works well to move the wheelchair system on two wheels backwards, and it takes the system about 10 seconds to travel 2.5m backwards and settle. It is noted in Figs. 9 and 10 that Error1 and Error2 settled after about 11 seconds. On the other hand, Error3 settled with small offset after 10 seconds as noted in Fig. 11. The offset value is not that significant in this case since precision is not the core target as compared to stability control of the two-wheeled wheelchair. On the other hand, the smaller the offset the better the system performance and this can be further improved through optimization. Fig. 12 and Fig. 13 show the corresponding torques Torque1 and Torque2 respectively. It can be seen that both Torque1 and Torque2 settled after 11 seconds. The result in Fig. 14 demonstrates that the velocity of wheel was decreasing and settled within about 10 seconds. In fact the system moved at below 2 m/s throughout the trajectory although it shoots up to 2 m/s in the first stage of motion.

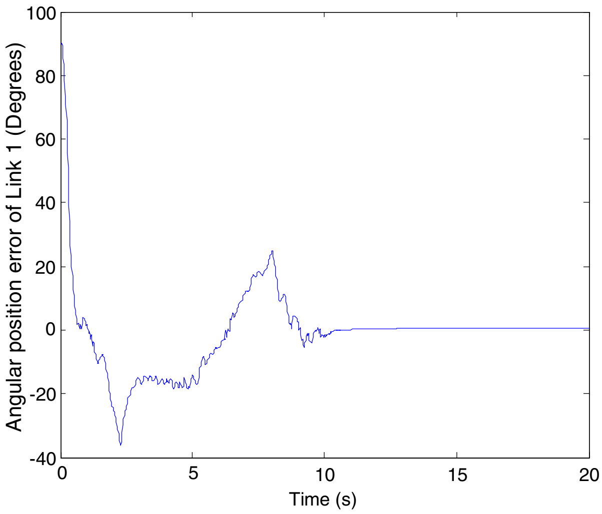


Fig. 9. Angular position error of Link1 (Error1) as a function of time

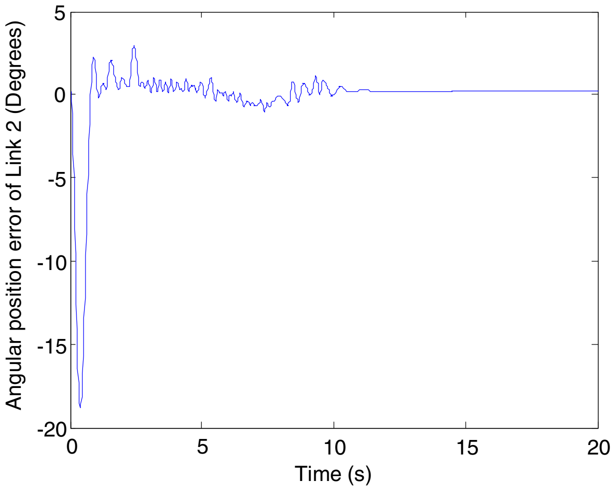


Fig. 10. Angular position error of Link2 (Error2) as a function of time

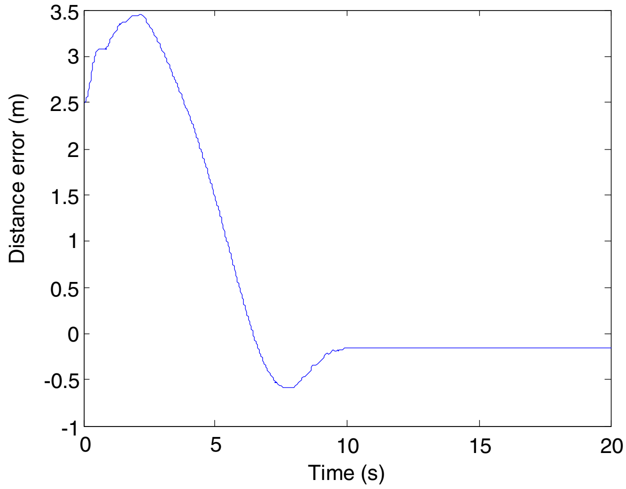


Fig. 11. Distance error (Error3) as a function of time

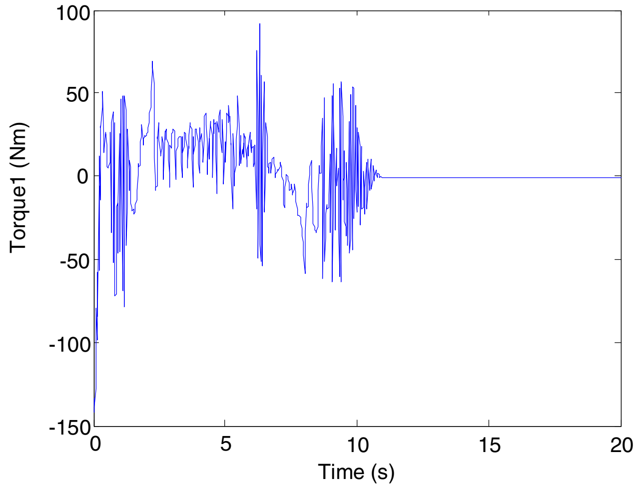


Fig. 12. Wheel torque (Torque1) as a function of time

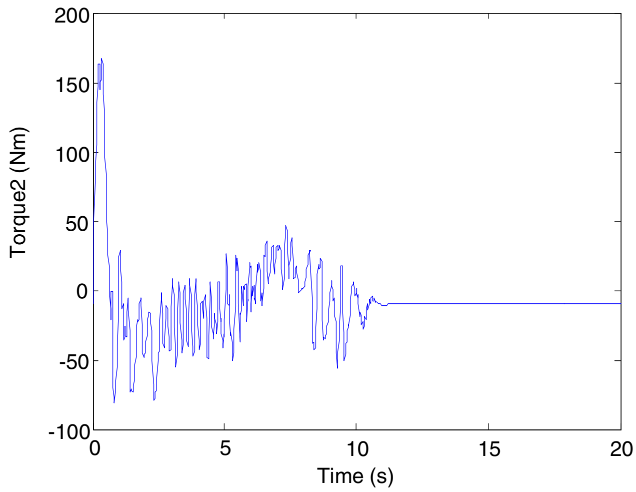


Fig. 13. Torque between Link1 and Link2 (Torque2) as a function of time

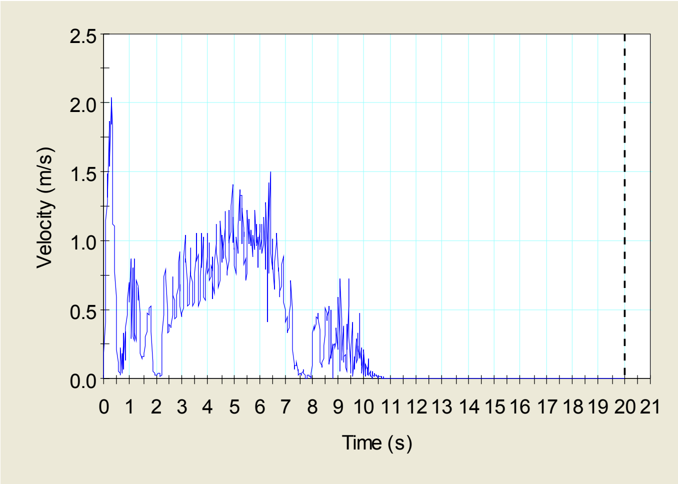


Fig. 14. The wheel velocity as a function of time

IV. CONCLUSION

In this paper an FLC strategy for forward and backward motion of two-wheeled wheelchair has been developed. The proposed FLC has been successfully incorporated into the control scheme with predetermined membership type and related parameters. The results presented demonstrate that the FLC approach works very well on highly nonlinear systems such as the wheelchair system on two wheels and gives good system performance. It can also be concluded that backward movement takes more time to settle as compared to normal forward movement of the two-wheeled wheelchair. Due to this, at later stage the forward movement might be favored in contrast to backward movement once steering motion is introduced. Future work will concentrate on further improvement of system model and parameter optimization of the fuzzy logic controllers.

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