

# Rejection of Yaw Disturbance in a Two-Wheeled Wheelchair System

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## Abstract

*In this paper, a virtual wheelchair (WC) model is developed within Visual Nastran (VN) software environment where the model is further linked with Matlab/Simulink for control purposes. The goal is to have stable two-wheeled WC by transforming the two front wheels (caster) to the upright position. Theoretically, when the two big wheels are fed by the same torque, the WC system will only move in one (x-) direction (with a small forward and backward movement before settlement is achieved). On the other hand, WC in VN produces action-reaction forces in terms of friction between the wheels and the defined ground that lead to small degree of rotation with respect to vertical z- axis, (yaw disturbance). Fuzzy logic control is designed in order to eliminate this unwanted rotation of the wheels during lifting and stabilizing phase. Results show that the unwanted rotation of the wheels is successfully reduced.*

## 1. Introduction

The use of wheelchair has become very important for mobility among the disabled with spinal cord injury (SCI) and the elderly people that experience difficulty with mobility. It has further been subject of a great deal of evolution in many aspects especially the control strategies to fulfil users' needs. In order to provide independence and meet the needs of disabled to function as normal people, significant research has been done world-wide [1-3].

One of the prominent research fields is the realisation of two-wheeled wheelchair that mimics inverted pendulum, and is very complex and highly nonlinear. Basically it is introduced for many reasons to fill the gap given by a normal four-wheeled wheelchair. Therefore 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. This will then help them to reach certain

level of height, for example, to pick and place objects on shelves at home or library. Furthermore, as the height of wheelchair on two wheels increased with these proposed schemes, they will be able to participate in conversations at eye-to-eye level comfortably with others as normal people do. The stability of two-wheeled wheelchair is maintained all the time using appropriate control so as to ensure safety among users. In fact it offers better efficiency and great advantages for the user as compared to walking and also it is expected not to take much space during mobility. Thus, a wheelchair on two wheels has associated design and development challenges including modelling and controller design for the system to perform comparably similar to normal four-wheeled wheelchair.

To fulfil the objectives, research has been done on development of wheelchair models and further on developing novel control strategies in order to lift the front wheel (casters) and maintain system stability in the upright position [4, 5]. The model of wheelchair has been successfully developed using Visual Nastran (VN) environment. Furthermore, the lifting and stabilizing control for the transformation of four-wheeled into two-wheeled wheelchair has been discussed in those papers. Novel fuzzy logic control (FLC) scheme with single output torque was designed and implemented and gave promising results of the system performance. On the other hand, linear motion of wheelchair system consisting of forward and backward motion as well as steering motion have been discussed in [6, 7]. Similar FLC approaches have been implemented in both papers. The advantage is that similar FLC structure has been used with this highly nonlinear system with different goals thus saving time and energy.

## 2. System Model and Parameters

Standard wheelchair has been modelled using MSC Visual Nastran 4D environment. It has been known that VN is used extensively for design and professional development of engineering products involving assemblies of 3D parts. Since VN can be linked easily

with Matlab/Simulink for developing and testing controllers, it is used in this research by providing virtual plant (system). The complete wheelchair system model is shown in Figure 1, which will be used as the plant in this work. Figure 2 shows the humanoid model as designed and approximated with reference to [8].

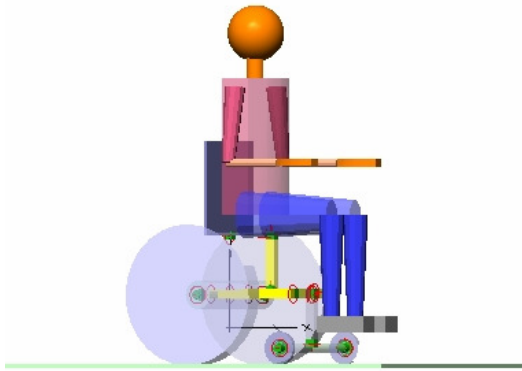


Figure 1. Complete wheelchair system model

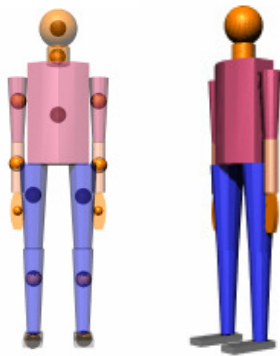


Figure 2. Humanoid model

The control of two-wheeled wheelchair system that mimics a double inverted pendulum scenario is the focus of this work. Noticeable research work has been reported on double inverted pendulum [9, 10] as well as in the area of inverted pendulum on two wheels [11]. The schematic diagram of the system considered in this work is shown in Figure 3. Wheel torque consists of right and left torques (TR and TL), and represents the input torque to the wheels. Earlier in [4, 5], for reasons of simplicity, the torques applied to the two wheels were the same in magnitude (one output torque from the controller) so as to move the wheelchair only forward or backward. Steering motion control has been introduced in [7], where two independent torques are used for the big wheels, and this configuration will be

used in this work. T2 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 the right torque, TR (Nm), left torque, TL (Nm) and torque between Link1 and Link2, T2 (Nm). The measured outputs from the wheelchair system that consist of the angular position of Link1 (Degree), angular position of Link2 (Degree) as well as WC rotation about the vertical axis (Degree) are compared with the target reference, which in this case is to be 0 degrees. Recall that the normal four-wheeled WC is transformed to two-wheeled WC by lifting Link1 (actuated by TR and TL) while Link2 (actuated by T2) is mainly used to cater for the human weight. After both Link1 and Link2 are within small range of angular position, the stabilizing controller is activated, by giving more sensitivity to the input scaling prior to feeding into the controller.

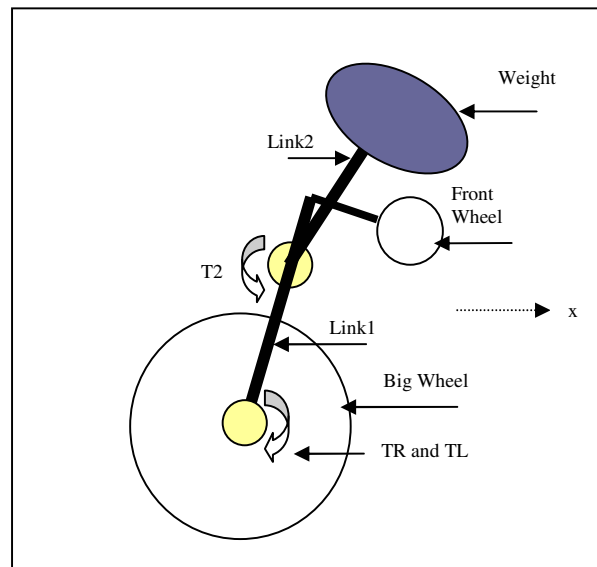


Figure 3. Schematic diagram of wheelchair system

### 3. Wheelchair Rotation (Yaw) Disturbance Rejection

Figure 4 shows the 3D motion diagram of the plant. There are several motions that are possible for the WC to experience. Those are along the x-axis (longitudinal for forward and backward motion), as well as along the y-axis (lateral when the WC is considered on a slope) as discussed in [12], while motion along the z-axis (vertical) is not permissible at all. Rotation-wise, only

rotation around the z-axis (yaw) is permissible. When lifting and stabilizing is taken place, three degrees of freedom are involved; angular rotation of Link1 ( $\phi_1$ ), angular rotation of Link2 ( $\phi_2$ ), and linear motion (x) due to rotation of wheels that cause the WC to move backward and forward in a small distance along the x-axis before settling. In the previous work, for lifting and stabilizing purposes, only one output torque has been considered, which means that similar output torque ( $TR = TL$ ) is fed into the two wheels to simplify the control. Then FLC with two outputs was later designed with independently-controlled torques for each right and left wheels, ( $TR$  and  $TL$ ). During lifting and stabilizing, the fuzzy rules will give similar output torques for both  $TR$  and  $TL$ , thus no rotation around z-axis (yaw) is expected. Theoretically, the same amount of torque with the same direction will lead to linear motion of the wheelchair system (forward and backward) along the x-axis. Unfortunately, due to the nature of VN that mimics real condition of the plant, the friction between wheels and defined ground will cause losses on some forces, torques and energy, causing the system to rotate (yaw disturbance). This rotation is not favoured in the lifting and stabilizing phase unless steering motion is required. Thus, this type of disturbance needs to be eliminated. Since steering motion control has been discussed in detail for the same system in [7], and the same controller structure with 0 degree reference of rotation can be implemented in order to eliminate the yaw disturbance. In the current work, the unwanted yaw disturbance that leads to wheels' rotation around z-axis is reduced by adding a disturbance rejection control together with lifting and stabilizing controllers of Link1. Therefore, there are three controllers active at the same time; one for lifting or stabilizing Link1, one for lifting or stabilizing of Link2 and one for yaw disturbance rejection control.

The control scheme for the proposed disturbance rejection is shown in Figure 5. The disturbance rejection controller introduced consists of two-output Mamdani-type FLC. Therefore, all three controllers are activated in fulfilling the transformation of four-wheeled normal wheelchair to two-wheeled wheelchair, without any rotation around the z-axis (yaw).

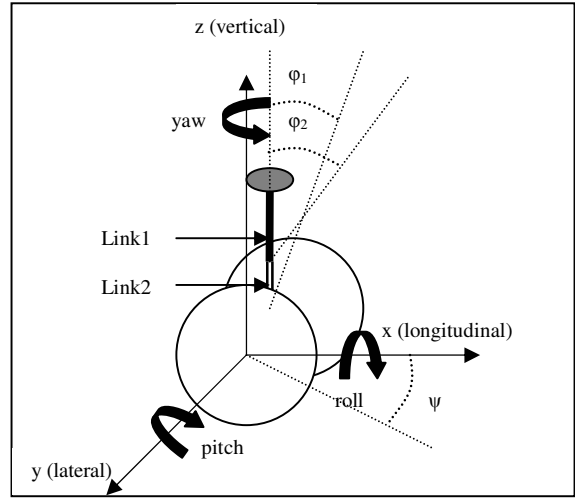


Figure 4. 3D motion diagram

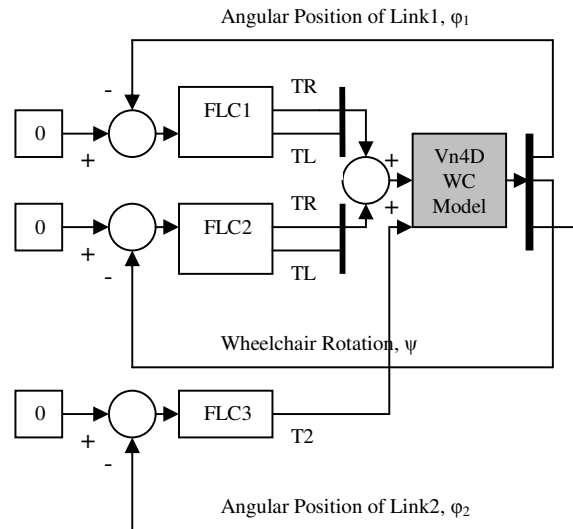


Figure 5. Control scheme

For lifting and stabilizing controller of Link1 (FLC1), the controller inputs are angular position error in Link1, change in angular position error in Link1 and angular position error of Link2. For yaw disturbance rejection controller (FLC2), the two controller inputs are wheelchair rotation error and change in wheelchair rotation error. The output torques for both right and left of the two controllers (FLC1 + FLC2) are added to give final output torques to the WC system. On the other hand, the lifting and stabilizing controller of Link2 (FLC3) will control the lifting and stabilizing of Link2, where the controller inputs are angular position error in Link2, change in angular position error in Link2 and angular position error of Link1. Gaussian membership functions were 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). FLC1 and FLC3 both consist of  $5 \times 5 \times 3 = 75$  rules. Right and left torques are set to have the same fuzzy rules for FLC1 while for FLC2, the left torque has different rules. On the other hand, FLC2 has  $5 \times 5 = 25$  rules. Table 1 shows the implemented fuzzy rules for FLC1, FLC2 and FLC3.

Table 1: The fuzzy rules  
a) FLC1

$E \backslash \Delta E$	NB	NS	Z	PS	PB
NB	PB <i>PB</i>	PB <i>PB</i>	PB <i>PB</i>	PS <i>PS</i>	Z <i>Z</i>
NS	PB <i>PB</i>	PB <i>PB</i>	PS <i>PS</i>	Z <i>Z</i>	NS <i>NS</i>
Z	PB <i>PB</i>	PS <i>PS</i>	Z <i>Z</i>	NS <i>NS</i>	NB <i>NB</i>
PS	PS <i>PS</i>	Z <i>Z</i>	NS <i>NS</i>	NB <i>NB</i>	NB <i>NB</i>
PB	Z <i>Z</i>	NS <i>NS</i>	NB <i>NB</i>	NB <i>NB</i>	NB <i>NB</i>

b) FLC2

$E \backslash \Delta E$	NB	NS	Z	PS	PB
NB	PB <i>NB</i>	PB <i>NB</i>	PB <i>NB</i>	PS <i>NS</i>	Z <i>Z</i>
NS	PB <i>NB</i>	PB <i>NB</i>	PS <i>NS</i>	Z <i>Z</i>	NS <i>PS</i>
Z	PB <i>NB</i>	PS <i>NS</i>	Z <i>Z</i>	NS <i>PS</i>	NB <i>PB</i>
PS	PS <i>NS</i>	Z <i>Z</i>	NS <i>PS</i>	NB <i>PB</i>	NB <i>PB</i>
PB	Z <i>Z</i>	NS <i>PS</i>	NB <i>PB</i>	NB <i>PB</i>	NB <i>PB</i>

c) FLC3

$E \backslash \Delta E$	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

## 5. Simulation Results

The proposed yaw disturbance rejection scheme 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 approach.

### 5.1. System performance without disturbance rejection controller

The system performance without the disturbance rejection controller is shown in Figures 6 to 8. It can be seen that all errors were reduced to zero in less than 5 seconds. However, as noted in Figure 8 the WC rotates from about  $-10$  degrees to about  $7$  degrees, which is not favoured.

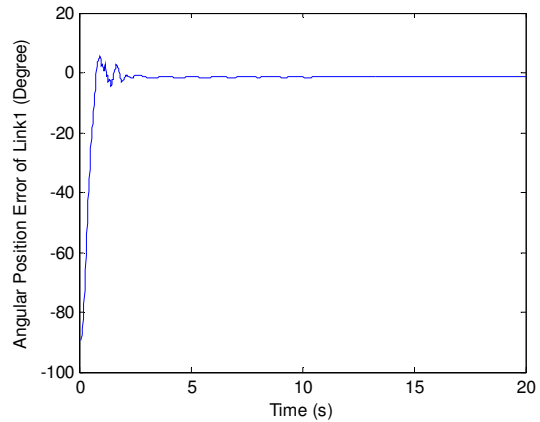


Figure 6. Angular position error of Link1 (Degree) as a function of time

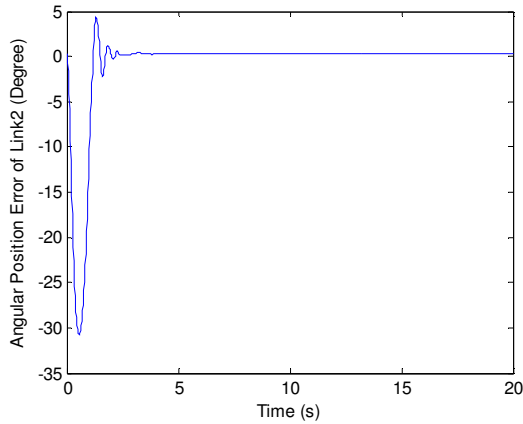


Figure 7. Angular position error of Link2 (Degree) as a function of time

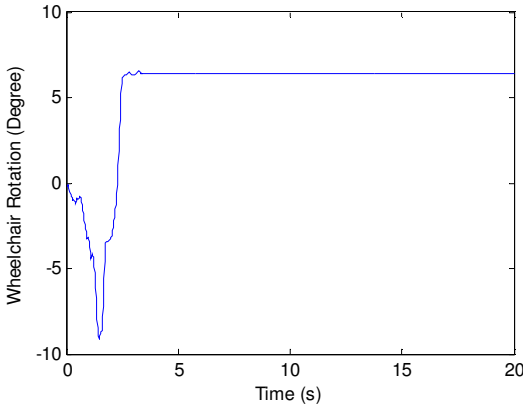


Figure 8. Wheelchair Rotation-Disturbance (Degree) as a function of time

### 5.2. System performance with disturbance rejection controller

The system performance incorporating yaw disturbance rejection controller is shown in Figures 9 to 13. It is noted the system settled in less than 5 seconds. It can be noted in Figure 10 that about 2.5Nm was produced by the disturbance rejection controller before incorporating into the lifting and stabilizing of Link1 controller. The resultant torques in Figure 11 show that in order to eliminate the disturbance, the right and left torques were no longer equal in magnitude. Figure 13 shows that the unwanted wheelchair rotation was eliminated and the system maintained at about 0 degree. Therefore, it can be noted that the system performance with independent controller for the unwanted wheelchair rotation was better than that without disturbance rejection controller.

## 6. Conclusion

A yaw disturbance rejection controller has been introduced to eliminate disturbance that can cause the wheelchair to rotate when it is not requested to. In this controller, fuzzy logic control with two inputs and two outputs has been designed and implemented. The results presented prove that the disturbance rejection controller introduced helps the wheelchair to be in its normal position and direction as expected. Future work will look at further improvements of the control mechanism at the unstable point (upright position) and the optimisation of the control parameters.

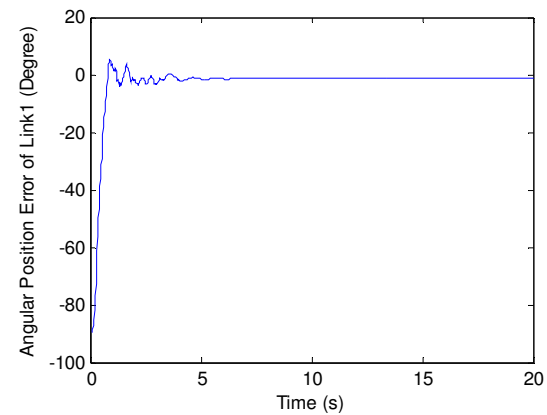


Figure 9. Angular position error of Link1 as a function of time

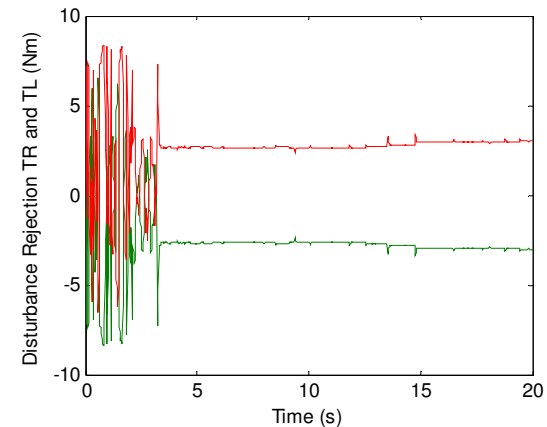


Figure 10. Torques produced to eliminate disturbance (Nm) as functions of time

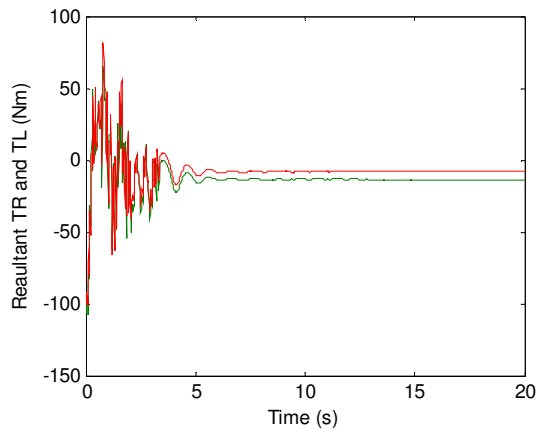


Figure 11 .Resultant torques for right and left wheels (Nm) as functions of time

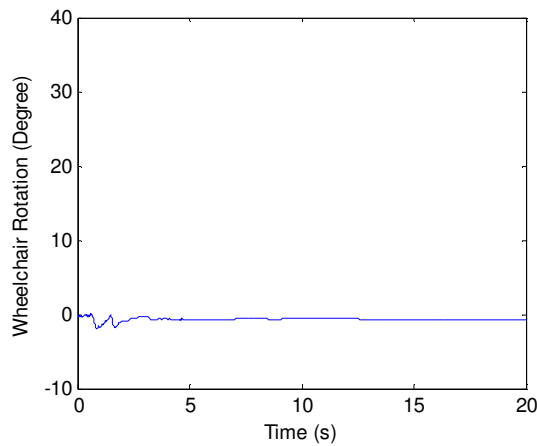


Figure 12. Wheelchair rotation-disturbance (Degree) as a function of time

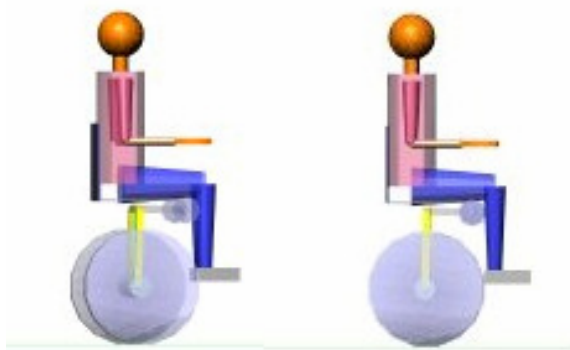


Figure 13. Final Wheelchair Position  
 Left: Without disturbance rejection controller  
 Right: With disturbance rejection controller

## 7. References

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