Two-Wheeled Wheelchair Stabilization Using Interval Type-2 Fuzzy Logic Controller

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***Abstract* - In this paper, an Interval Type-2 Fuzzy Logic Control (IT2FLC) is proposed to control a two-wheeled wheelchair system which mimics double-links inverted pendulum and known as highly nonlinear, unstable and complex system. The control structures of the two-wheeled wheelchair is based on IT2FLC for balancing and maintaining stability of two-wheeled wheelchair system in the upright position. This paper is aimed to develop a 3-Dimensional (3D) model of two-wheeled wheelchair using a SimWise 4D (SW4D) software, which replace a complex mathematical representation that is obtained using long equation and derivation. The movement of the system is visualized using the SW4D as it is integrated with Matlab Simulink. Simulation results show that the IT2FLC give a good performance in term of tilt angle at zero degree in the upright position.**

***Keywords* - two-wheeled wheelchair, double-link inverted pendulum, Interval Type-2 Fuzzy Logic Control.**

I. Introduction

Wheelchair is an important transportation device for disabled and elderly community to mobile from one place to another and to perform their daily routines independently. Indirectly, the feelings of self-reliance will be increased [1]. The two-wheeled wheelchair system uses the same concept as double-link inverted pendulum which has surfaced over the years for balancing control and is known as very unstable system. The inverted pendulum mechanism varies from rotational [5] and cart [2-4] to inverted pendulum system on two wheels [6-9]. Designing a control strategy of two-wheeled wheelchair is a very challenging task in order to maintain the stability in the upright position at all time on the wheels.

Several researchers have presented various control algorithms for an inverted pendulum (IP) system in their study. A nonlinear Sliding Mode Control (SMC) is used for transforming from four-wheels to two-wheels to reach the target stable state from initial state while LQR is used to stabilize the system in the inverted pendulum mode. Both controllers were used for different purposes to control a mobile robot by transforming four wheels to two wheeled system [35].

IP has been explored in a two-wheeled wheelchair system using Synthesized Pitch Angle Disturbance Observer (SPADO) recently. The SPADO was introduced in this paper to estimate the torque acting on the pitch directing. The system of wheelchair was able to balance at upright position using self-balancing dynamic system and to estimate both the disturbance effecting the pitch and the wheels direction. The Lyapunov controller was used to stabilize the wheelchair system along the pitch direction [36].

Many control approaches have been proposed in order to stabilizing a double-link inverted pendulum system on two wheels. There are including Neural Network (NN) base controller [10-11], Fuzzy Logic base controller [12-15], hybrid Linear Quadratic Regulator-Fuzzy controller (LQR-Fuzzy) [16-17] and swing-up scheme control [22]. Moreover, the existing research also worked on Proportional Derivative (PD) controller [24], cascading Proportional Integral Derivative (PID) controller [25] and group of Sliding Mode Controller (SMC) [18-21].

Fuzzy Logic Control (FLC) is one of ideal controllers to control a nonlinear system and specifically complex system [23]. However, Interval Type-2 Fuzzy Logic control (IT2FLC) is superior one of the controllers that can handle uncertainties and control very highly nonlinear system such as two-wheeled wheelchair system FLC type-1. Basically, IT2FLC has been applied in several systems, including omnidirectional mobile robots [26] and autonomous wheeled IP robot [27-31].

In addition, IT2FLC also has been compared with a FLC in order to control a delta robot trajectory. The paper discussed about the problem of systematic design method for a delta robot. The author explained how to generate the type-2 fuzzy sets form the optimized type-1 fuzzy sets by blur the type-1 fuzzy membership functions. Relationship between output control surface, blur degree and blur method of IT2FLC based on systematic analysis and the results showed that the performance of trajectory tracking was better using optimized IT2FLC have been studied in the paper [37]. However, there is none researchers control a double-link inverted pendulum using IT2FLC up to now.

Therefore, in this paper, a two-wheeled wheelchair is implements the double-link inverted pendulum concept and later the IT2FLC controller is developed. The SW4D is used to design the wheelchair and is integrated with Matlab to analyze the performance of wheel displacement, angular link 1 and angular link 2.

This paper is organized as below. In section II, the two-wheeled wheelchair is designed using SW4D. In section III, the IT2FLC is designed. In section IV, the heuristic is applied to get the optimal value of parameters. In section V, the results of the simulation are analyzed. The conclusion is explained in section VI.

II. System Model And Parameters

Model of two-wheeled wheelchair is highly nonlinear and complex because it has a very complicated feature to be modelled and controlled. This includes control of stabilization, extension of linear actuator, external disturbances, linear and steering motion. In this research, SW4D software is used to replace a complex derivation of mathematical modelling and long equations. The importance of replacing a mathematical with SW4D is to reduce the time used to obtain the correct equations of the system. It also can avoid any mistakes during mathematical derivation because in SW the two-wheeled wheelchair is modeled by using the provided shapes and some of components is imported and reconfigured from another CAD software. The modelling of wheelchair is depended on parameter of each part of the two-wheeled wheelchair.

SW4D is an upgraded version from MSc Visual Nastran 4D software and can simulate assemblies in a unique virtual environment. Moreover, the system was designed to become more creative, robust and able to reduce cycle time. It combines several tasks including motion, displacement, FEA, measurement, control, and provides an analysis capabilities and wide range of modelling.

Generally, SW4D is divided into three: SW Motion, SW FEA and SW4D (combination of Motion and FEA). SW Motion is a kinematic and dynamic performance assembly that evaluates using 3D motion simulation. SW FEA is structural characteristics (stress and deflection) that evaluate using 3D FEA. The FEA analysis comprises: linear-elastic stress and deflection (static), steady state thermal, natural frequency & mode shapes and linear-elastic buckling. SW4D is a simultaneously solution of 3D and FEA. It can be used for FEA only, motion only or both FEA and motion.

In this paper, the SW4D software environment is used to model the two-wheeled wheelchair system for motion visualization when executing the Matlab Simulink program as shown in Figure 1. The SW4D allows integration of the two-wheeled wheelchair model with control strategies in Matlab Simulink platform. The two-wheeled wheelchair system is modelled using double links inverted pendulum system. It comprises with a load using humanoid model (approximated human weight with 70kg) on top of the link2, link1, link2, three independent motors and linear actuator. The schematic diagram of two-wheeled wheelchair is shown in Figure 2. The model of two-wheeled wheelchair in SW4D is used as a plant and integrated with IT2FLC in Matlab Simulink 2015b environment.

The basic wheelchair dimensions were taken from a standard wheelchair in the market by making some changes to produce a compact two-wheeled wheelchair, lightweight and use less space to move. The torques τ_R and τ_L represent right and left wheels respectively, while τ_2 represents torque between link1 and link2. The entire torques are used to cater for the whole human body weight and the linear actuator is used to extend the seat to reach an optimal higher level. Table 1 shows dimension and specification of two-wheeled wheelchair developed in SW4D while the parameters of two-wheeled wheelchair is shown in Table 2.

TABLE I. Basic dimension and specification of two-wheeled wheelchair

Description	Dimension (m)
Diameter of wheel	0.6
Distance between both wheels	0.55
Chair seat	0.4 x 0.05 x 0.43
Back rest	0.4 x 0.5 x 0.101
Link1	0.04 x 0.04 x 0.2
Link2	0.04 x 0.04 x 0.22
Height of the chair from the ground	0.72

Figure 1. Complete two-wheeled wheelchair model with human

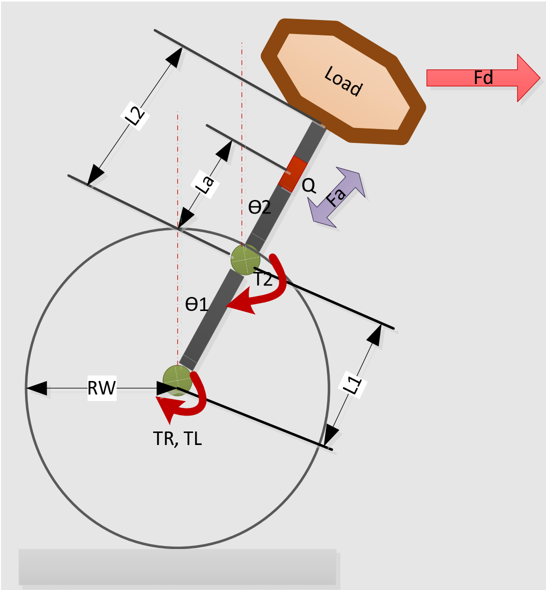

Figure 2. Schematic diagram of two-wheeled wheelchair system

TABLE II. PARAMETERS OF THE TWO-WHEELED WHEELCHAIR

Symbol	Description	Parameter
M_W	Mass of the wheel	1.5kg
M_L	Mass of the load	70kg
M_B	Mass of the axle	20kg
M_1, M_2	Mass of link 1 and link 2	3kg
R_W	Radius of wheel	0.3m
L_1	Length of link 1	0.2m
L_2	Length of link 2	0.22m
J_1, J_2	Moment of inertia link 1 and link 2	$(M_iL_i^2)/3$
J_R, J_L	Moment of inertia both side of wheel	$(M_iL_i^2)/2$
g	Gravitational acceleration	9.81 m/s^2
Q	Displacement of the linear actuator	m
L_a	Length of linear actuator from the upper link	m
F_d	External disturbance force	N

III. INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER (IT2FLC)

The main purpose of using the IT2FLC is to overcome the nonlinearities of the nonlinear system. Besides, the proposed controller is able to control the system with uncertainties and the environmental disturbances. Generally, IT2FLC was introduced in 1975 by Lotfi Zadeh [38] and recently become popular among researchers in 2001 onwards. It has been used by researchers in several systems to control a difficult and complex systems [25-30]. However, it is not easy to design an IT2FLC because there are many choices to be made based on the controller's law. The IT2FLC uses an Interval Type-2 Fuzzy Set (IT2FS) and its architecture consists of 5 components; fuzzifier, rule base, inference engine, type-reducer and defuzzifier as shown in Figure 3.

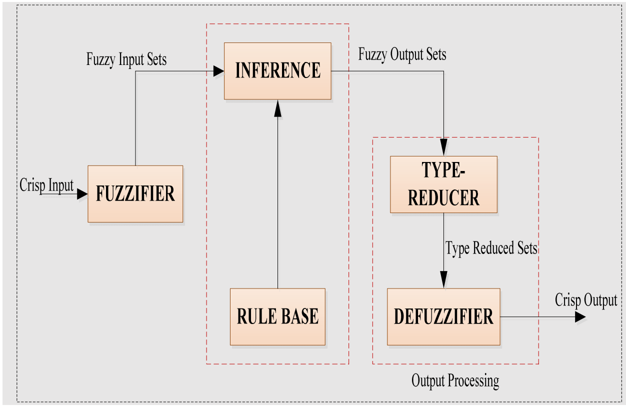

Figure 3. Architecture of IT2FLC [37]
Figure 4.

A. 1st Component: Fuzzification.

The crisp parameter of input sensor is fuzzified into IT2FS using singleton fuzzifiers due to its simplicity and more popular in practice and real time application. The fuzzy set contains two inputs and one output for the membership function. There are error (e), change of error (Δe) and torque (u). The output of IT2FLC will be produced when the rule base and the inference engine are activated by the input of IT2FS.

B. 2nd Component: Rule base.

The rules of IT2FLC will remain the same as in Fuzzy Logic Control (FLC). The different is antecedents or consequents will be presented by IT2FLC. Basically, IT2FS is activating the rule base and it is a blurred version of the FLC fuzzy set (FLCFS) that is bounded from top and bottom by FLCFS. The term of footprint of uncertainty (FOU) is used for the area between these fuzzy sets as shown in Figure 4.

Theoretically, in each input domain of IT2FS can use one an arbitrary number of FOUs like FLCFS. However, the best suggestion in each input domain is ≤7 membership functions (MFs) due to facilitate understanding and to reduce computational cost. The Gaussian shape is recommended to choose in MFs due to the simplicity, guarantee of continuity and it is easier to represent and optimize.

C. 3rd Component: Inference engine.

The inference engine is also activated by IT2FS as the rule base to produce output. The input of IT2FS and output of IT2 are mapped by combining the fired rules using inference engine and type-reducer will process the outcome from inference engine. The output sets will combine by the type-reducer and performs a centroid calculation which leads to FLCFS called the type-reduced sets.

D. 4th component: Type-reducer.

There are about 10 different types of type-reduction methods [33]. In this paper, the Center-Of-Sets type-reduction is used instead of the simplified type-2 reduction operation. The reason to use the Center-Of-Sets because it has reasonable computational complexity that lies between the computationally expensive centroid type-reduction and the simple height and modified height type-reductions which have problems when only one rule fires [32].

E. 5th Component: Defuzzification.

Defuzzification is the last component in the architecture of the IT2FLC after the type-reduction process. The type-reduced sets are defuzzified after previous steps are complete to obtain crisp outputs that are sent to the actuators by taking the average of the type-reduced set.

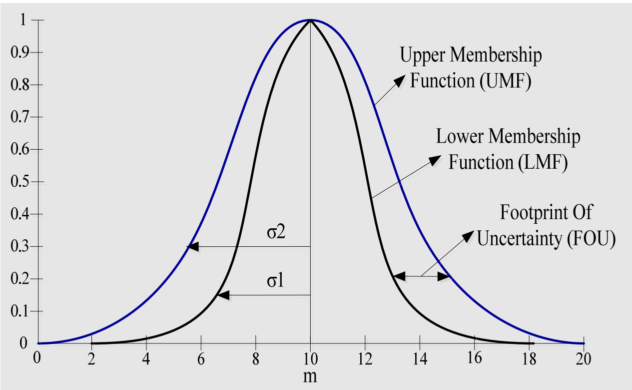

Figure 5. An IT2FLC fuzzy set [32]

In this paper, a Sugeno-type fuzzy rules are adopted and two inputs to the IT2FLC are considered. The controller of IT2FLC is divided by two subsystems as there are two links considered in this work, the first subsystem IT2FLC1: the controller inputs are the change of error angular position of link1 ($\Delta e\Theta_1$) and the error of angular position link1 ($e\Theta_1$). The second subsystem IT2FLC2: the controller inputs are the change of error angular position of link2 ($\Delta e\Theta_2$) and the error of angular position link2 ($e\Theta_2$).

Table 3 shows 5 levels of membership functions using Gaussian resulting in 25 rules (5 x 5) comprises of $e\Theta_i$ and $\Delta e\Theta_i$ in IT2FLC and the IF-THEN rules is applied. The Gaussian shape was used to represent the Sugeno-type IT2FLC algorithm because it gives smooth and steady response of the system [34] as shown in Figure 5. The levels of membership function are negative big (NB), negative small (NS), zero (Z), positive small (PS) and Positive Big (PB).

The two-wheeled wheelchair system in this paper is a multi-input multi-output (MIMO) system as it consists of several inputs and need to control several outputs. The block diagram of MIMO is shown in Figure 6. Figure 7 shows the overall view of integration between SW4D and IT2FLC in Matlab Simulink.

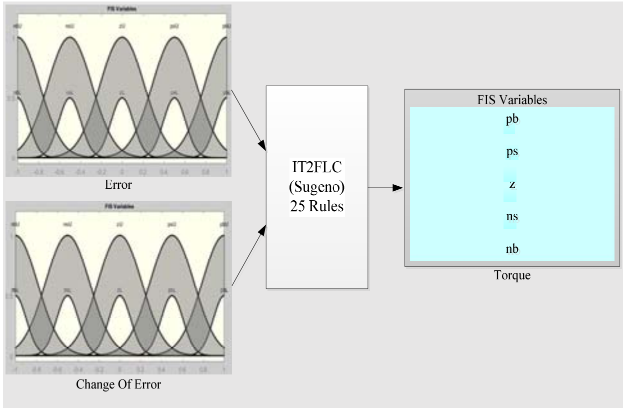

Figure 6. Inputs and output of IT2FLC

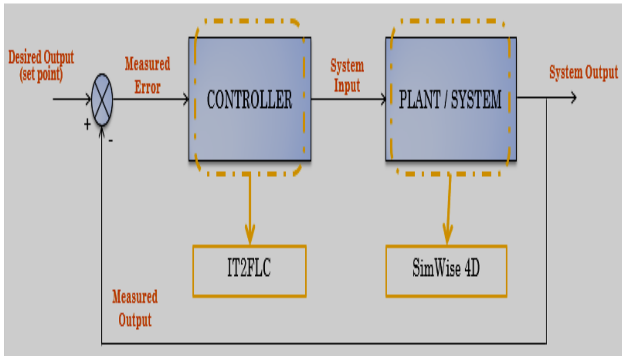

Figure 7. Block diagram of MIMO system of two-wheeled wheelchair system

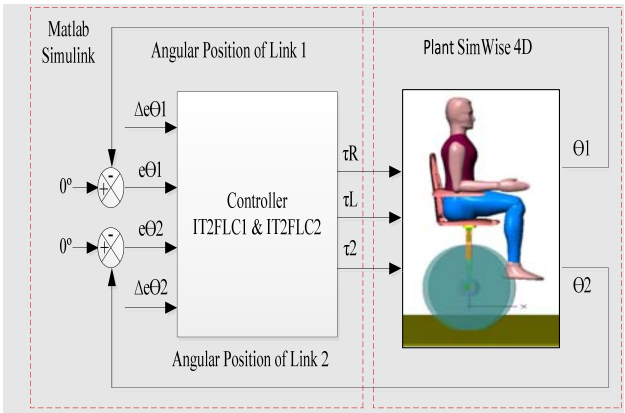

Figure 8. Matlab Simulink integrated with SW4D

Figure 9. IT2FLC rules for the control input of system

e\Δe	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

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IV. SIMULATION RESULTS

There are 12 control parameters that need to be added in this research, and the value of IT2FLC inputs scaling factor (*K1, K2, K4, K5, K7, K8, K10, K11*) is used as the lowest value of gains and outputs scaling factor (*K3, K6, K9, K12*) as higher value of gains to stabilize the two-wheeled wheelchair in the upright position. The range of lowest gains used are between 0.04 to 7.25 and the highest gains used are between 63 to 213.

Figure 10, Figure 11 and Figure 12 show the wheel displacement of the system, the angular displacement of link1 and the angular displacement of link2 respectively. The performance output data of the system was tabulated in Table 4 including torque of wheels (τ_w), torque between link1 and link2 (τ_2), rise time, settling time, peak overshoot and peak undershoot.

Based on the simulation result, the torques on both wheels and the torques between link1 and link2 are low in range of -0.961 Nm and -0.175 Nm as shown in Figure 8 and Figure 9 respectively. The two-wheeled wheelchair produce on torque because the system only performs a stabilization at upright position without any external disturbances. The wheel displacement shows only minimal distance range with ±0.0075m. the wheelchair does not travel far from the initial position as shown in Figure 10 even though both wheels of the two-wheeled wheelchair is not maintained at 0m.

Table 5 is clearly stated all the information based on performance in Figure 11 and Figure 12. The angular link1 is remain at -0.198° until 50s and the angular link2 is remain at 0.0118° until 50s. The visualization movement in SW4D show that the two-wheeled wheelchair is maintain stabilize in the upright position and both links is less than ±0.2° for tilt angle.

The settling time for the system is less than 3.5s for angular link1 and less than 2.74s for angular link2 respectively. It shows that the system is stabilized with a good settling time. The graph shows that the angular link1 and angular link2 have less oscillation with the peak overshoot and undershoot also give a minimum value with less than 0.4º.

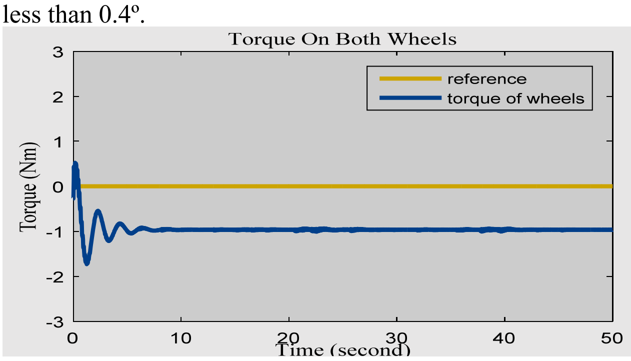

Figure 10. Torque on both wheels

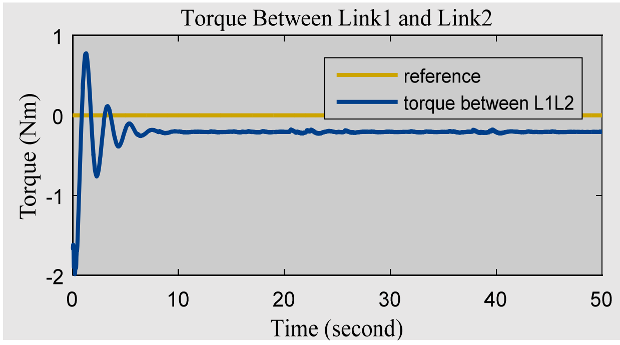

Figure 11. Torque between link1 and link2

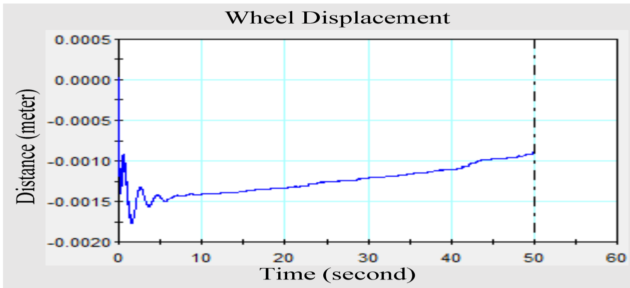

Figure 12. Wheel displacement of the system (x)

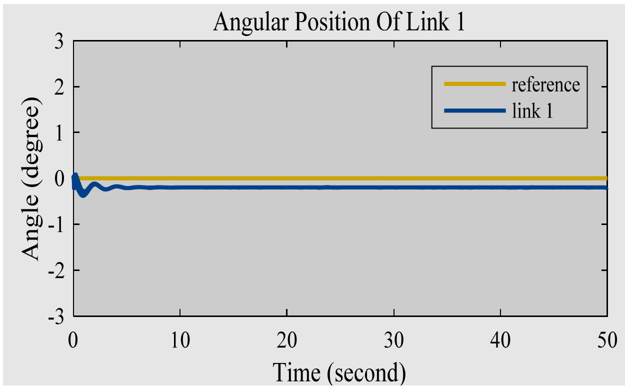

Figure 13. Angular position of link 1 of the system (Θ_1)

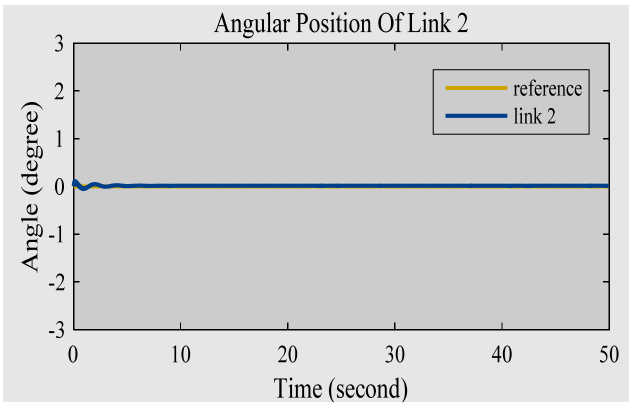

Figure 14. Angular position of link 2 of the system (Θ_2)

TABLE III. INFORMATION OF THE SYSTEM

	τ_w	τ_2	Rise Time (s)	Settling Time (s)	Peak Overshoot (deg)	Peak Undershoot (deg)
Angular Link1, Θ_1	-0.961	-0.175	0.12	3.25	0.09	-0.38
Angular Link2, Θ_2			0.08	2.74	0.08	-0.05

V. CONCLUSION

A control approach based on IT2FLC of a two-wheeled wheelchair has been presented in this paper. The model of two-wheeled wheelchair is designed based on a double-link inverted pendulum structure using SW4D environment. Then, the model of two-wheeled wheelchair is integrated with Matlab Simulink block diagram to visualize the motion of the system when the program in Matlab Simulink is executed. Based on the simulation result, shows that the system is able to maintain stability in the upright position within ±0.2° for both angular of link1 and link2 using IT2FLC controller. The parameters of the system were tuned using heuristic method and it can be improved using any optimization methods to get optimal values with a less computational time. The system also can be extended for another feature of wheelchair such as extending the seat and applying any disturbances to observe the performance against uncertainties for future work.

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