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Modular Fuzzy Logic Controller for Motion Control of Two-Wheeled Wheelchair

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1. Introduction

Most of the wheelchair users are paraplegics, who are not able to move on their own due to permanent injury in their lower extremities. These wheelchairs are four-wheeled and have certain limitations due to design and control mechanism. For example, the wheelchairs cannot move to a higher level, lift the front wheel and stay in an upright position. As a result, wheelchair users cannot reach certain heights to pick and place things on the shelves, and cupboards, etc. without any assistant and also cannot have eye-to-eye conversation with normal people effectively. On the other hand, a two-wheeled wheelchair has a unique characteristic that may help disabled and elderly people who use the wheelchair as the main means of transport and can also use the wheelchair for these added advantages. Now the idea is to transform the standard four-wheeled wheelchair into a two-wheeled upright wheelchair to facilitate such maneuverability. The front wheels (casters) can be lifted up and stabilized as an inverted pendulum, thus increasing the level of height achievable while in the upright position. Similarly, when this upright position is no longer needed it may be transformed back into its normal four-wheeled position. The schematic diagram of the two-wheeled wheelchair is shown in Figure 1. The transformation will result in a highly nonlinear and complex system. Since a human has quite significant mass sitting on the wheelchair, the two-wheeled wheelchair can be modeled with double links that mimic double inverted pendulum scenario that need a clever control strategy.

Most of the classical control design methodologies such as Nyquist, Bode, state-space, optimal control, root locus, H_∞ , and μ -analysis are based on assumptions that the process is linear and stationary and hence is represented by a finite dimensional constant coefficient linear model. These methods do not suit complex systems well because few of those represent uncertainty and incompleteness in system knowledge or complexity in design. But the fact is the real world is too complex. As the complexity of a system increases, quantitative analysis and precision become difficult. The increasing complexity of dynamical systems such as this coupled with stringent performance criteria, which are sometimes subject to human satisfaction, necessitates the use of more sophisticated control approaches. However, many processes that are nonlinear, uncertain, incomplete or non-stationary have subtle and

interactive exchanges with the operating environment and are controlled by skilled human operators successfully. Rather than mathematically model the process, the human operator models the process in a heuristic or experiential manner. It is evident that human knowledge is becoming more and more important in control systems design. This experiential perspective in controller design requires the acquisition of heuristic and qualitative, rather than quantitative, knowledge or expertise from the human operator. During the past several decades, fuzzy control has emerged as one of the most active and powerful areas for research in the application of such complex and real world systems using fuzzy set theory (Zadeh, 1965).

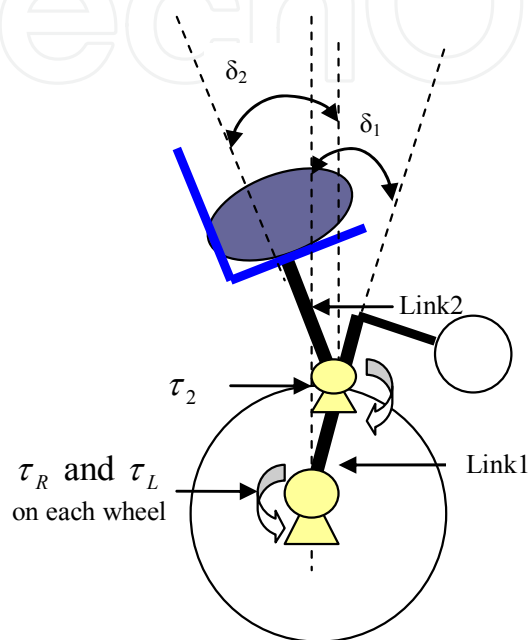


Fig. 1. Schematic diagram of wheelchair with three under actuated joints

Due to many significant advantages of wheelchair usage, this research presents findings of the research carried out on the implementation of new architecture of modular intelligent control strategies on the two-wheeled wheelchair model. The multi-objective control involves lifting and stabilizing of Link1 and Link2 of double-inverted pendulum like two-wheeled wheelchair, wheelchair backward and forward motion control as well as position. It is hoped that the proposed model, mechanisms and control could be of benefit to a wheelchair user, thus enhancing wheelchair technology for paraplegics and elderly.

2. Intelligent control approach

Intelligent control systems have evolved from existing controllers in a natural way competing demanding challenges of the time and are not defined in terms of specific algorithms. They employ techniques that can sense and reason without much *a priori* knowledge about the environment and produce control actions in a flexible, adaptive and robust manner (Harris, 1994). In general, by intelligent control approaches, it is mainly meant the methodologies of fuzzy logic, neural networks, and genetic algorithms. These methodologies have shown to be effective in controlling complex nonlinear systems. The control of complex nonlinear systems has been approached over the last few decades using fuzzy logic techniques due to the fact that fuzziness itself is easy to implement and can be

described by expert knowledge, normally possessed by human. A fuzzy logic controller (FLC) has the basic configuration illustrated in Figure 2.

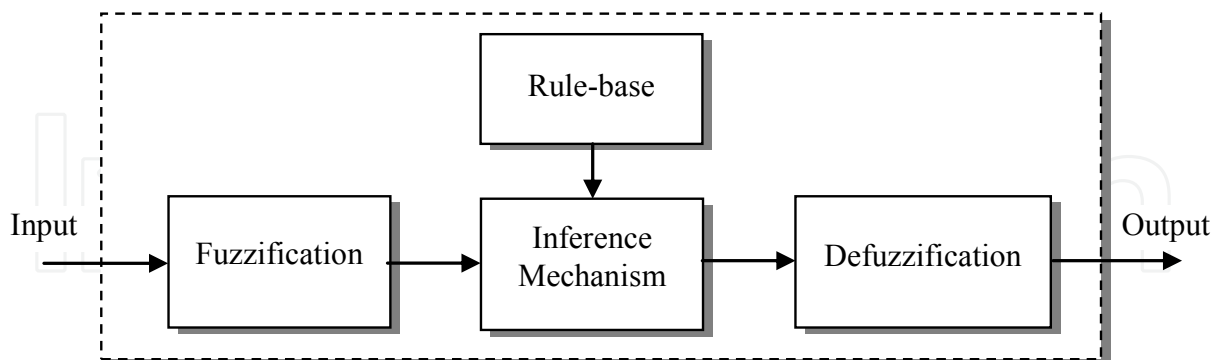


Fig. 2. Fuzzy logic control

Generally, a fuzzy logic controller consists of the following components:

- i. Fuzzification
- ii. Inference mechanism
- iii. Rule-base
- iv. Defuzzification

Fuzzification is a process of transforming an observed input space to fuzzy sets within a universe of discourse. This process consists of associating to each fuzzy set a membership function (MF). These functions can be thought of as maps from the real numbers to the interval $I = [0,1]$. If there are n fuzzy sets associated with a given quantity $x \in R$, such n maps $F_i : R \rightarrow I, i = 1, \dots, n$ are defined. They determine to what extent the linguistic label associated with fuzzy set i characterizes the current value of x . There are different kinds of MFs used in designing fuzzy controllers. The most common choices are triangular, trapezoidal, Gaussian and bell shaped MFs. There is no exact method for choosing an MF, and the designer mainly relies upon an expert knowledge or use heuristic rule.

Inference is used to describe the process of formulating a nonlinear mapping from a given input space to an output space. The mapping then provides a basis from which decisions can be taken. The process of fuzzy inference involves the MFs, fuzzy logic operators and rule-base. Generally there are three types of commonly used fuzzy inference. They differ mainly in the consequent part of their fuzzy rules, aggregations and defuzzification procedures. Thus selecting a different fuzzy inference will result in different computational time. The three common fuzzy inferences are: Mamdani fuzzy inference, Sugeno fuzzy inference and Tsukamoto fuzzy inference. The choice of a particular inference mechanism is eventually problem dependent and availability of information about the system in question.

Mamdani type fuzzy modeling was proposed as the first attempt to control a steam engine and boiler by a set of linguistic control rules by (Mamdani 1974). In this type of inference, Max-min is the most common rule of composition used. In this composition rule, the inferred output of each rule is a fuzzy set chosen from the minimum firing strength. On the

other hand, in max-product rule of composition the inferred output of each rule is a fuzzy set scaled down by its firing strength via algebraic product.

A fuzzy system is characterized by a set of linguistic statements based on expert knowledge. The expert knowledge is usually in the form of if-then rules, which are easily implemented by fuzzy conditional statements in fuzzy logic. The collection of fuzzy rules that are expressed as fuzzy conditional statements forms the rule base or the rule set of an FLC. A rule consists of two parts, antecedent and consequent. For example, typical rule in Mamdani-type fuzzy model with four-inputs and three-outputs FLC can be expressed by the following linguistic conditional statement.

If $(X_1 \text{ is } A_i) \text{ and } (X_2 \text{ is } B_j) \text{ and } (X_3 \text{ is } C_k) \text{ and } (X_4 \text{ is } D_l)$
 then $(Y_1 \text{ is } U_p) \text{ and } (Y_2 \text{ is } V_q) \text{ and } (Y_3 \text{ is } W_r)$

where $\{X_1, X_2, X_3, X_4\}$ are the inputs with linguistic terms $\{A_i, B_j, C_k, D_l\}$ and $\{Y_1, Y_2, Y_3\}$ are the outputs with linguistic terms $\{U_p, V_q, W_r\}$.

Defuzzification is basically a mapping from a space of fuzzy control actions defined over an output universe of discourse into a space of nonfuzzy (crisp) control actions. In a sense this is the inverse of the fuzzification even though mathematically the maps need not be inverses of one another. In general, defuzzification can be viewed as a function $DF: I^n \rightarrow R$, mapping a fuzzy vector x^F with n fuzzy sets to a real number. There are different methods of defuzzification. However, simple methods are available to use depending on the application, among them Centre of Gravity Method (COG), and Weighted Average Method are widely used in Mamdani-type FLC and Sugeno-type FLC. Each method is problem dependent, but the experts should know that these methods are available and should try to see which works best for the application.

The two-wheeled wheelchair model involves lifting and stabilizing the two links (Link1 and Link2) similar to a double-inverted pendulum and hence is a multi-objective control problem. Considering the complexity and non-linearity of the wheelchair, the controller has to be designed in such a way to produce the required torques, namely τ_R , τ_L and τ_2 , for acting at three different locations on the wheelchair for lifting the casters/chair and stabilizing the system. The torque τ_R and τ_L represent the input torque to the right and left wheels respectively. τ_2 represents the torque between Link1 and Link2 to cater for the whole weight of the human body. Angular positions of Link1 and Link2, δ_1 and δ_2 respectively, are measured using sensors attached to the wheelchair. This characterizes the system as a highly nonlinear multi-input multi-output (MIMO) system. Fuzzy logic control is therefore very appropriate to use in this case. To achieve upright position for the two links, they need to be lifted and stabilized to zero degree (relative to vertical axis) upright position. This may be realised with a single controller. However, this will lead to a huge fuzzy rule-base. A conventional fuzzy controller with 4 inputs $\{e_{\delta_1}, \Delta e_{\delta_1}, e_{\delta_2}, \Delta e_{\delta_2}\}$ and 3 outputs $\{\tau_R, \tau_L, \tau_2\}$ (inputs-outputs are shown in Figure 3) has significant drawback in terms of computational complexity, which increases with the dimension of the system variables; the number of rules increases exponentially as the number of system variables increases. A strategy is sought to simplify the development process and reduce the

geometric progression in the number of required rules for general purpose tracking and control situations. Moreover, it should be achieved without compromising the robustness and capability of the complete system.

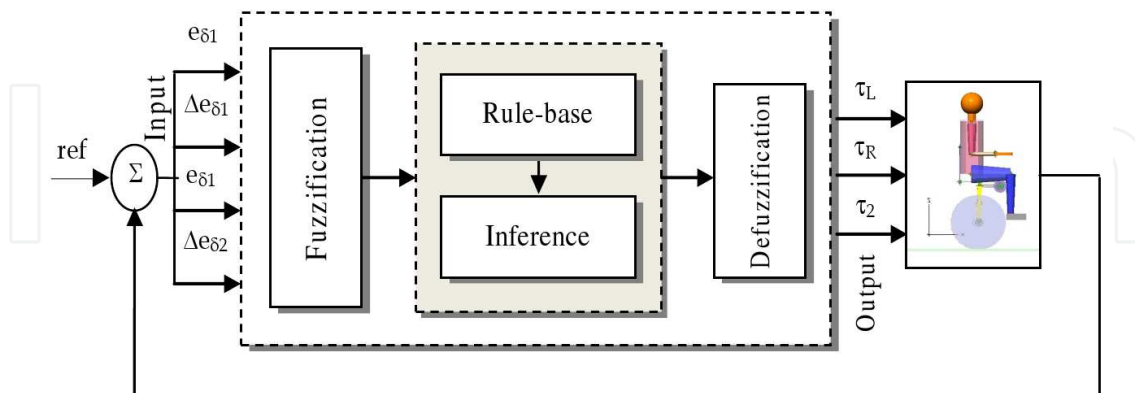


Fig. 3. MIMO FLC for lifting and stabilizing the wheelchair

A generic problem with an FLC is that the number of rules grow exponentially with the number of input-output variables and linguistic terms for each variable. For a complete rule-base with input variables $\{X_i \mid i = 1, \dots, n\}$ with linguistic terms $\{A_{ij} \mid j = 1, \dots, m_i\}$ and output variables $\{Y_k \mid k = 1, \dots, l\}$ with linguistic terms $\{B_{kj} \mid j = 1, \dots, p_k\}$, the number of rules will be

$$R = \prod_{i=1}^n m_i \quad (1)$$

The rules have the form

If $(X_1 \text{ is } A_{11})$ and ... and $(X_n \text{ is } A_{nm})$ Then $(Y_1 \text{ is } B_{11})$ and ... and $(Y_l \text{ is } B_{lp})$

This large number of rules complicates the design of an FLC, because for each of the R different premises the expert must provide a combination of term sets for the output variables, which is nearly impossible for a human expert to guess. It is possible to omit a set of rules if it could be guaranteed that a certain combination of input-output variables will never occur during control of the dynamic system. A modular structure of FLCs with minimum number of input-output variables can reduce the number of rules R .

3. Modular fuzzy control

For large scale and complex systems, the reduction in computation and design complexity remains a challenge of intelligent control systems. Hierarchical and modular methodology have gained wide popularity because of its simplicity in design and robustness. There are several approaches in decomposing a system into modules such as decentralized approach, time-scale decomposition, hierarchical system, and workspace decomposition (Siljak, 1991). For control problems with multiple objectives of different priority, sub-controller with a subset of input-output variables can be designed for each objective. Furthermore, each antecedent can be decomposed into single input modules. Each fuzzy module is designed to

handle one specific input affiliated with one of the decoupled antecedents $\{X_i | i = 1, \dots, n\}$ and produces a crisp action $\{Y_k | k = 1, \dots, l\}$ where $k = 1, \dots, l$. Such a generic modular architecture is shown in Figure 4.

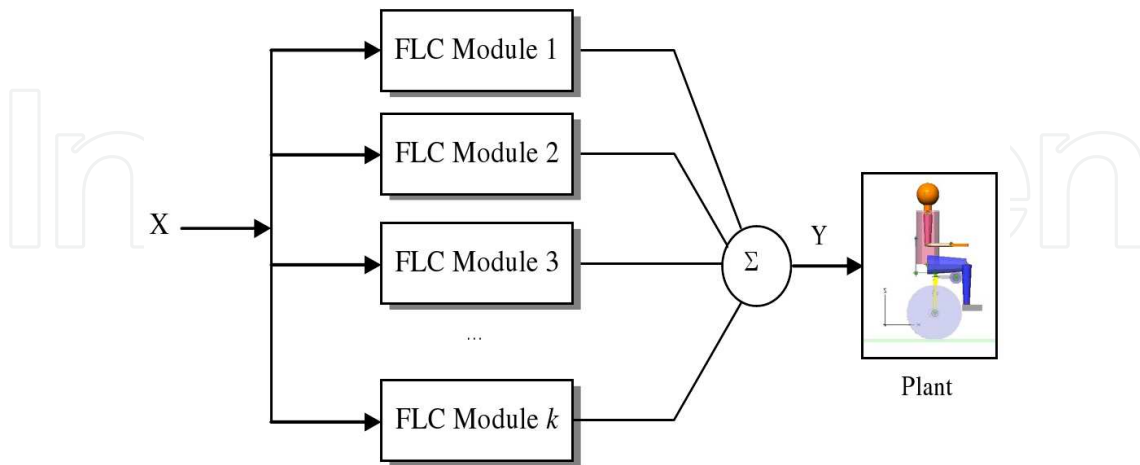


Fig. 4. Modular FLC

A typical fuzzy rule issues an appropriate output action by evaluating the related inputs from the measurement data. In the conventional IF-THEN fuzzy inference formulation, all of the system's input parameters are suggested as antecedents in the fuzzy rule. The total possible number of fuzzy rules that can be generated for the rule base is L^k where k is the number of inputs and L is the number of fuzzy linguistic terms or MFs. As compared to the modular FLC design, each input represents one fuzzy control module. The total number of rules for each module is determined by the number of MFs L . Thus, the total number of fuzzy rules for all k modules is kL . This clearly shows a significant reduction in the number of fuzzy rules from L^k to kL as well as savings in computation.

The mathematical model of the two-wheeled wheelchair incorporates three independent actuators; derived from Figure 1, corresponding to control output to be fed into the system. The angular position of Link1 and Link2, denoted as δ_1 and δ_2 respectively, are the controlled variables that will determine the system performance. The control challenge relates to the fact that there is more than one mechanism acted upon with the same actuator. For example, to transform the wheelchair into an upright two-wheeled wheelchair, the torques determined by fuzzy control are located at both right and left wheels. At the same time, if linear motion is considered, the same actuator needs to provide enough torque such that the wheelchair will still move forward or backward while in the upright position. Lifting and stabilizing consist of two system output parameters to be considered, namely angular position of Link1, δ_1 and angular position of Link2, δ_2 . Therefore a modular fuzzy logic control (MFC) is adopted to realize this multi-function two-wheeled wheelchair.

The MIMO system with an objective of achieving zero degree upright position is decomposed into small and simpler subsystems: Link1-lifting, Link1-stabilizing, Link2-lifting, and Link2-stabilizing. The structure of the modular FLC for the wheelchair is illustrated in the block diagram in Figure 5. Accordingly, this type of FLC can deal with, for example, N subsystems located at different levels, where each subsystem manages its own control strategy and communicates with the coordinator. The coordinator comprises a pair

of switches that gathers information from the subsystems and sends supervisory (threshold condition) instructions back to the subsystems. The supervisor in this case is the condition, (if the angular position error of Link1 and Link2, $-5^\circ < e < 5^\circ$, then Link1-stabilizing and Link2-stabilizing are activated). In this case, the switches coordinate the condition fulfilment of all the criteria for the activation of actuator to work accordingly. The reference position for lifting and stabilizing of both links is 0 degree at the upright position. The parameters 'a' and 'b' in the figure show the fuzzy input scaling factors (input gain) such that if the stabilizing subsystem of Link1 or Link2 is activated, the sensitivity of the fuzzy inputs is increased by giving higher gain (about 10 times) of a and b. The outputs from the system that are fed back to the controller are the angular position of Link1 (δ_1) and the angular position of Link2 (δ_2). The control approach using this modular strategy is believed to work well with the independently allocated tasks. In the figure, e_{δ_1} shows the angular position error of Link1, Δe_{δ_1} represents the change of angular position error of Link1. The effect of Link2 onto Link1 is taken into account by using the angular position error of Link2, e_{δ_2} as the fuzzy input for FLC1 and FLC2. In these two controllers, e_{δ_2} represents the angular position error of Link2, while Δe_{δ_2} represents the change of angular position error of Link2. Similarly the effect of Link1 onto Link2 is taken into account by using the angular position error of Link1, e_{δ_1} as the input for FLC3 and FLC4.

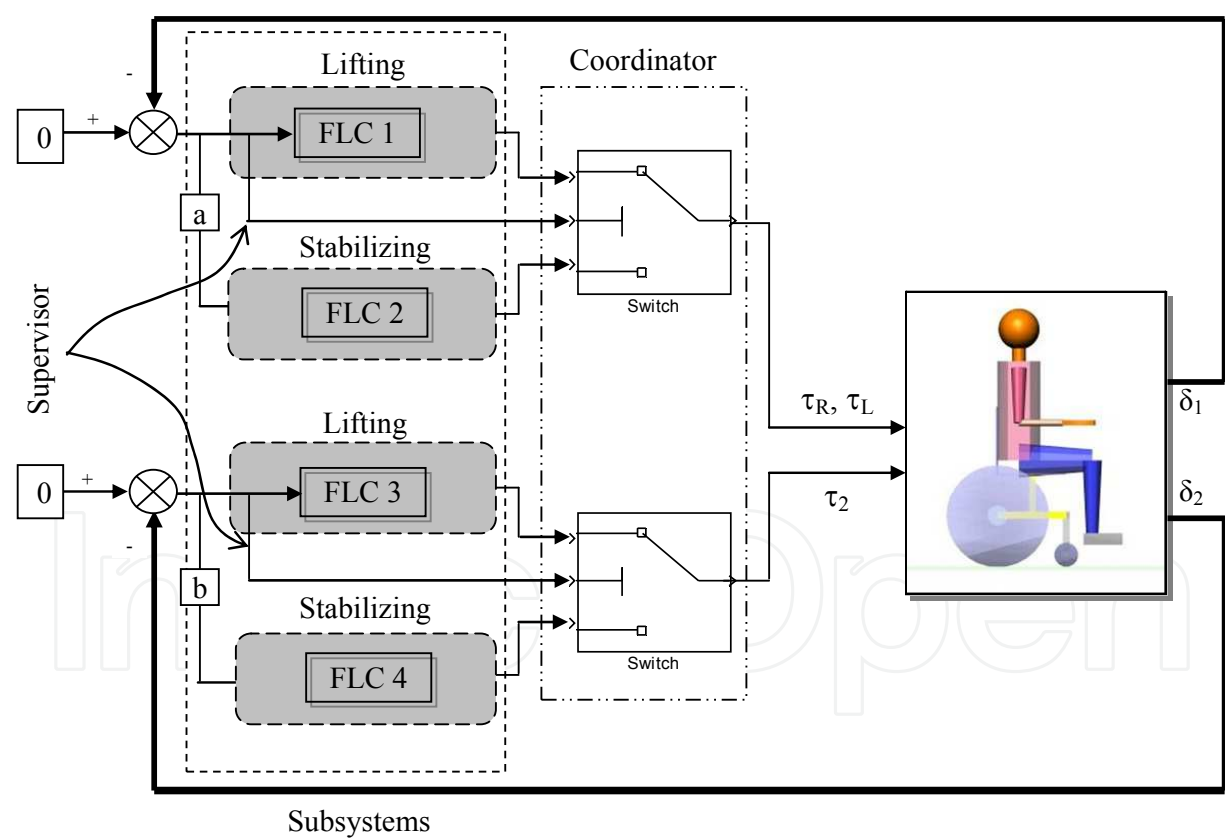


Fig. 5. Modular FLC for Two-wheeled wheelchair.

4. MFC for two-wheeled wheelchair

The MFC is also known as hierarchical fuzzy control (HFC), and the two terms are used interchangeably. It is discussed in detail for two-wheeled application in (Ahmad et al. 2011).

The goal of the controller is to produce the required torques, namely τ_R , τ_L and τ_2 , for acting at three different locations on the wheelchair for lifting and stabilizing. The torques τ_R and τ_L represent the input torque to the right and left wheels respectively. On the other hand, τ_2 represents the torque between Link1 and Link2 to be used to cater for the whole weight of the human body. Angular positions of Link1 and Link2, δ_1 and δ_2 respectively, are measured using sensors attached to the wheelchair in Visual Nastran (VN). To achieve upright position of the two links, they need to be lifted and stabilized at zero degree upright position. The goal may be treated as a single objective control that is having Link1 and Link2 at the 0 degree upright position with one controller. This will increase significantly the computational complexity, which increases with the number of system variables; the number of rules increases exponentially as the number of system variables increases.

4.1 Rules reduction strategy for general purpose tracking and control situations

The strategy is sought without compromising the robustness and capability of the system. Such a strategy relies mainly on three concepts, (Ahmad et al. 2011).

- Independence
- Functional Relationship
- Command Manipulation

To assess the effect of coupling in the fuzzy control, the system is tested with two different configurations, which mainly differ at the input side of the controller, as shown in Table 1.

	With coupling effect	Without coupling effect
Link1 (Lifting & Stabilizing)	- Angular position error of Link1, e_{δ_1} - Change of angular position error of Link1, Δe_{δ_1} - Angular position error of Link2, e_{δ_2}	- Angular position error of Link1, e_{δ_1} - Change of angular position error of Link1, Δe_{δ_1}
Link2 (Lifting & Stabilizing)	- Angular position error of Link2, e_{δ_2} - Change of angular position error of Link2, Δe_{δ_2} - Angular position error of Link1, e_{δ_1}	- Angular position error of Link2, e_{δ_2} - Change of angular position error of Link2, Δe_{δ_2}
Rules of each lifting and stabilizing	$5 \times 5 \times 3 = 75$ rules	$5 \times 5 = 25$ rules

Table 1. Different input configurations of modular fuzzy logic controller

The system was tested with both configurations and the performances, with and without coupling were comparably similar, see Figure 6. Therefore, as seen the second configuration performed well with fewer fuzzy rules fired, and this configuration is used in implementing the motion control for two-wheeled wheelchair.

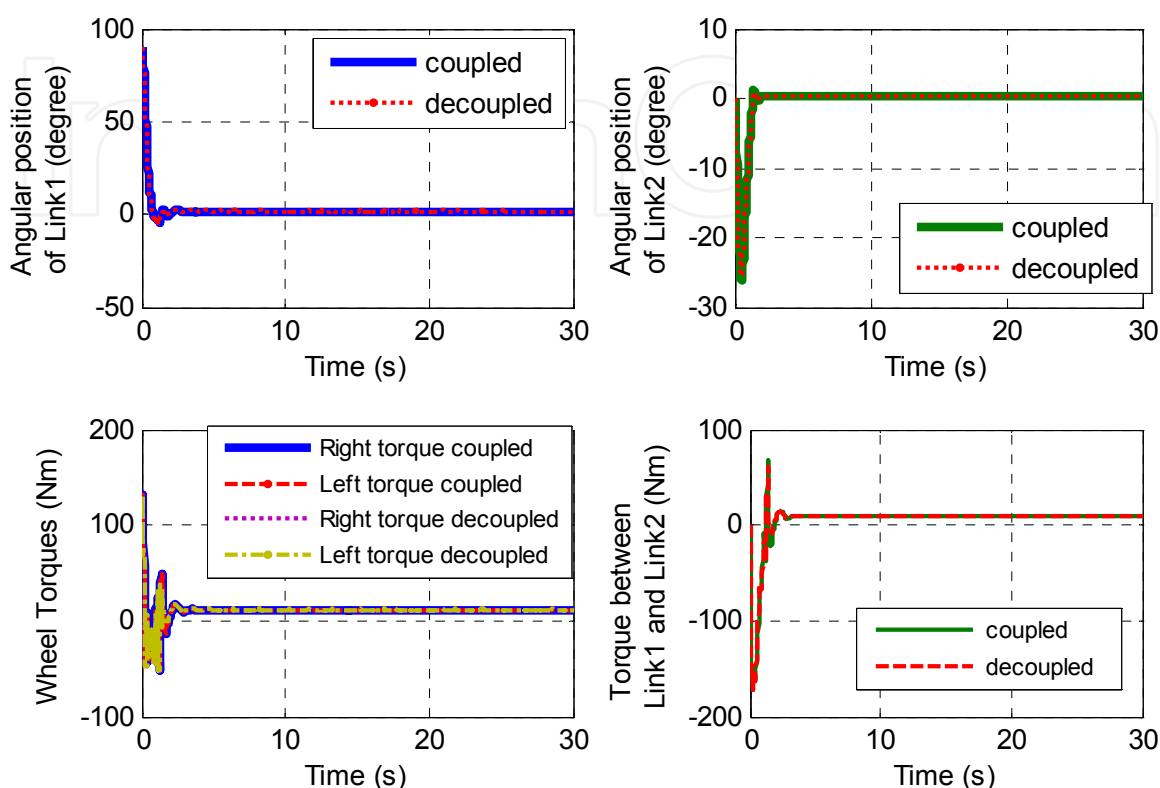


Fig. 6. System performance comparison between coupled fuzzy inputs and decoupled fuzzy inputs in terms of δ_1 , δ_2 , τ_R , τ_L and τ_2 .

The MFC is thus adopted for the two-wheeled wheelchair mechanisms, and the corresponding research objectives are:

- Lifting and stabilizing control
- Linear motion control (forward or backward)
- Steering motion control

The MFC can be divided into two significant categories, primary and secondary (Bessacini and Pinkos 1995). The controller is categorized according to different objectives. The control structure for achieving an upright two-wheeled maneuverable wheelchair is depicted in Figure 7. The general function of MFC is to minimize the errors in system responses considered. The primary goal unit caters for the upright control, which consists of lifting and stabilizing to the upright position and the transformation back to normal four-wheeled position of Link1 and Link2. These controllers are active most of the time even during maneuver. The secondary unit is activated by the coordinator (switch), with certain condition pre-set for output activation. It consists of different unique objectives involving linear motion control, steering control, additional chair height extension control. Each objective in the secondary goal unit is discussed in detail in the following sections.

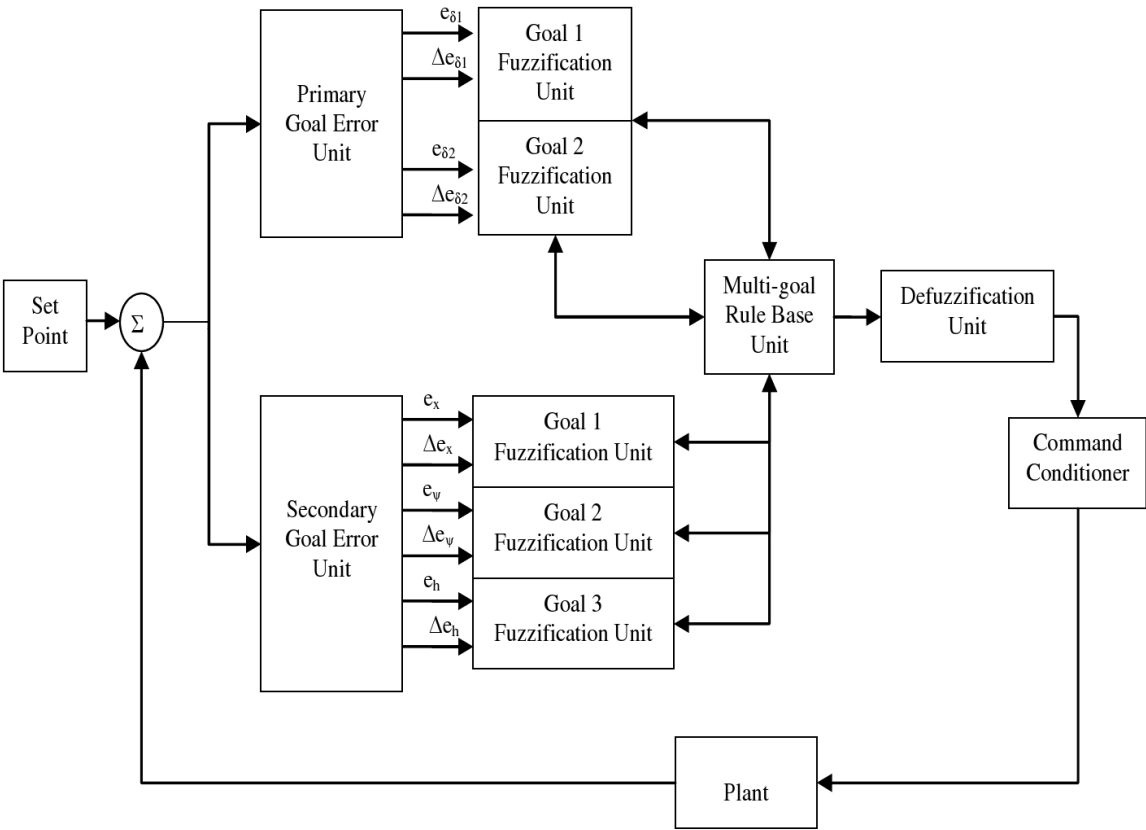


Fig. 7. Adapted modular intercepts fuzzy logic system (Bessacini and Pinkos 1995)

4.2 Simulation based performance analysis

The overall motion control for two-wheeled wheelchair is represented in Figure 8.

a. FLC for linear motion

The linear motion control generally consists of forward and backward (reverse) motion control. They are both characterized as secondary systems (Bessacini and Pinkos 1995) since the system needs to fulfill the primary target to achieve the upright position for both links. Therefore MFC as discussed in Section 4 is very appropriate to implement.

Similar structure of FLC used for lifting and stabilizing is adopted for linear motion control. The controls differ in terms of input and output scaling factors due to different reference points executed. The control strategy designed in Matlab/Simulink was integrated with wheelchair model, which was developed in VN software environment as a plant. The motion (forward, backward or steering) takes place after lifting and stabilizing has been achieved. Results show that the MFC strategy designed works very well and gives good system performance.

In the current studies of wheelchair mobility, much research has been conducted on wheelchair mobility in large spaces (outdoor mobility) (Vries et al. 1999; Wong et al. 2007). In those researches, the distance and angle are considered at the same time to give output torque of the wheels. On the other hand, note that the two-wheeled wheelchair is designed for use in confined spaces, such that the linear motion and the steering motion are independent.

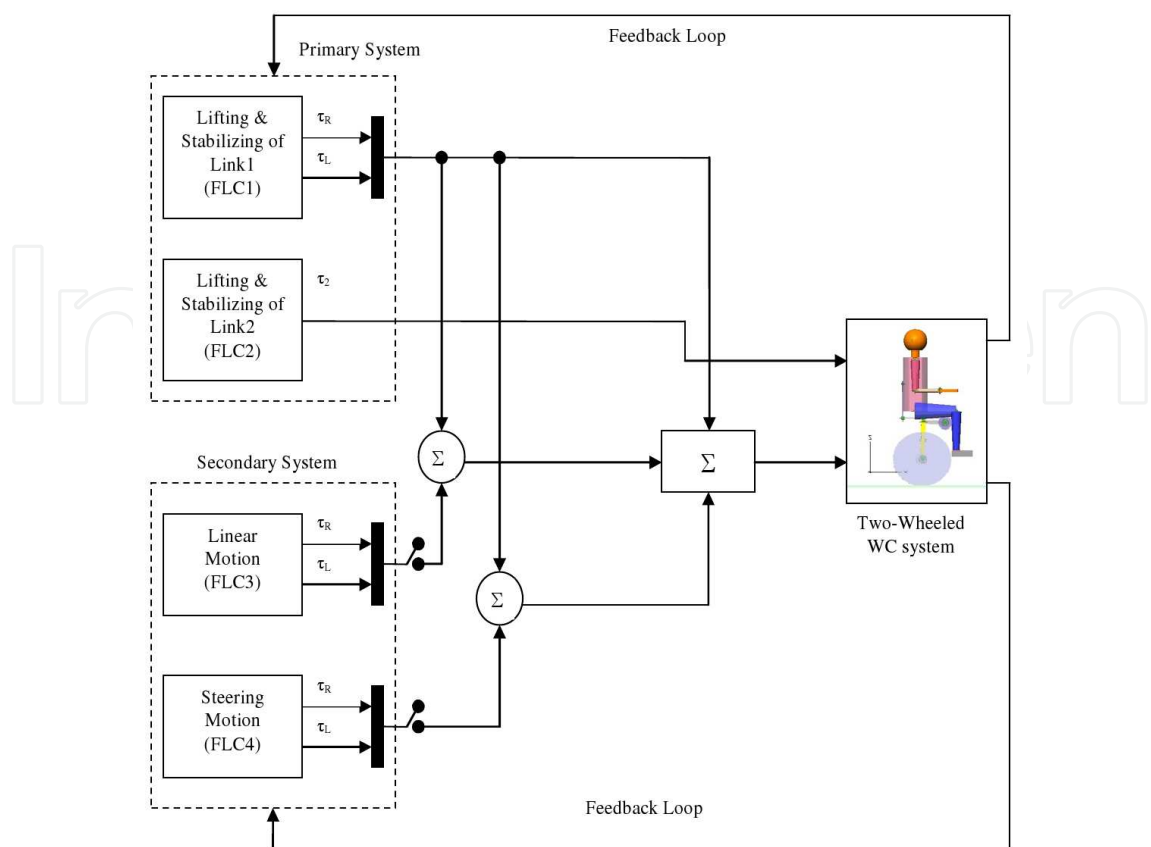


Fig. 8. Block diagram of two-wheeled wheelchair system motion

This confined space is normally found in the domestic environment (home, office and library). Within such environment, linear motion is executed alone before steering is done and vice versa. The block diagram for linear motion control of two-wheeled wheelchair is shown in Figure 9.

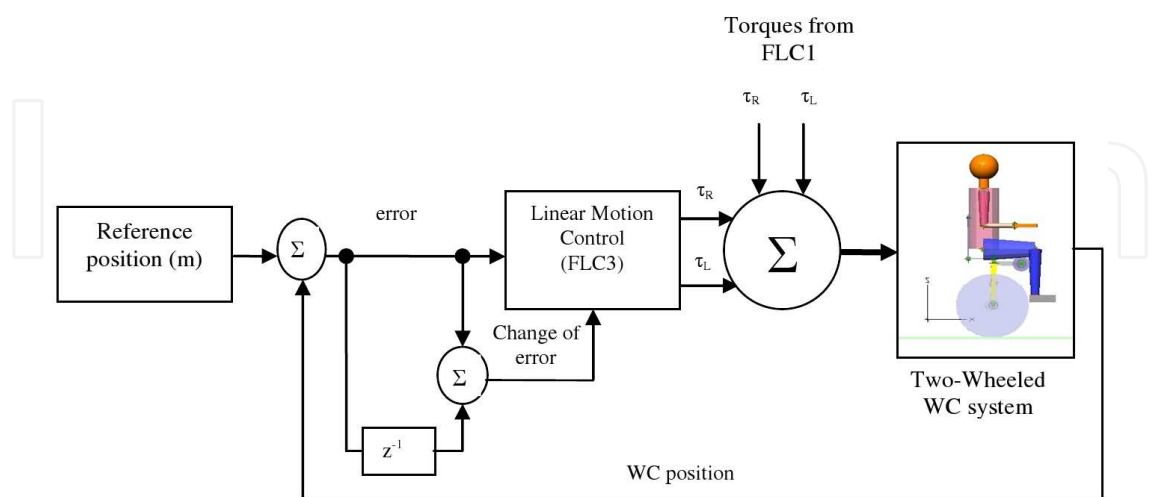


Fig. 9. Block diagram for linear motion control

The FLC for linear motion (FLC3) consists of two inputs and two outputs. The controller inputs are the position error, e and the change of position error, Δe , while the controller

outputs are the torques, τ_R and τ_L . The fuzzy inputs are normalized so that they can be generalized and then processed using the fuzzy rules. Moreover, the input normalization is done due to the complexity of predetermining the range of change of position error, Δe . Gaussian (bell shaped) type membership functions with default parameters given by Matlab/Simulink are used for all inputs and outputs. The membership levels for each input and outputs are five in total. These comprise Negative Big (NB), Negative Small (NS), Zero (Z)

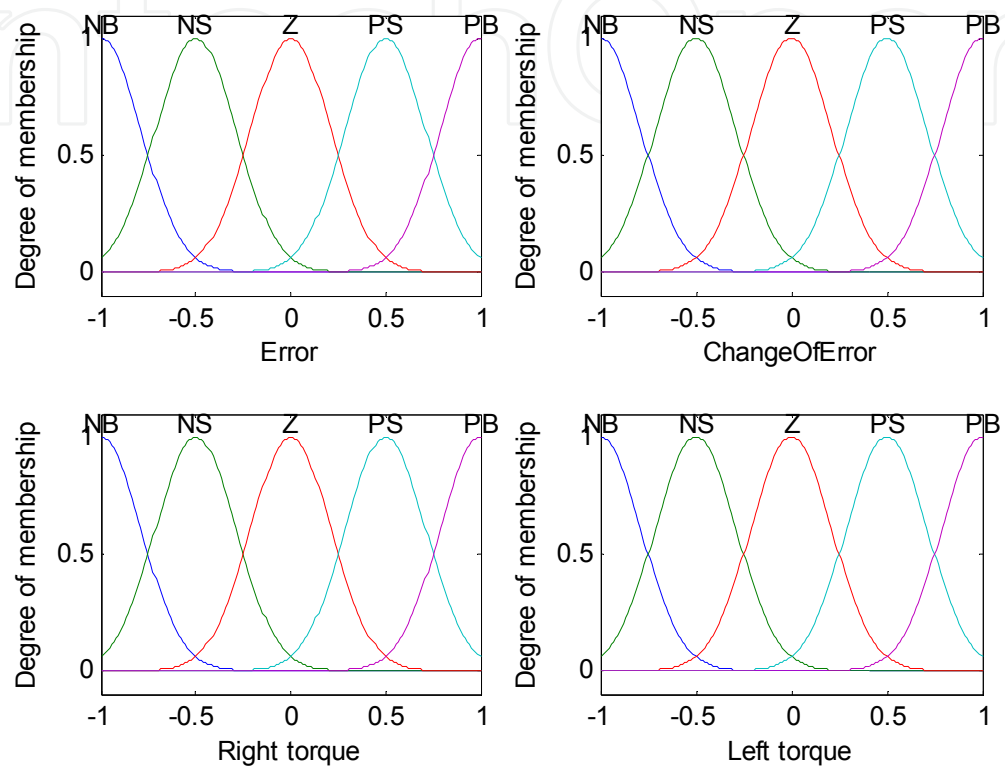


Fig. 10. Membership functions for inputs and outputs for FLC3 of linear motion control

<div><div><div><div></div><div>Δe</div><div>e</div></div></div></div>	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	Z
	PB	PB	PB	PS	Z
NS	PB	PB	PS	Z	NS
	PB	PB	PS	Z	NS
Z	PB	PS	Z	NS	NB
	PB	PS	Z	NS	NB
PS	PS	Z	NS	NB	NB
	PS	Z	NS	NB	NB
PB	Z	NS	NB	NB	NB
	Z	NS	NB	NB	NB

Table 2. Fuzzy rules for linear motion

(Z), Positive Small (PS) and Positive Big (PB). The membership function for inputs and outputs of FLC3 is shown in Figure 10. Table 2 shows the implemented fuzzy rules for FLC3 controller. The two consecutive rows in the output part represent two fuzzy outputs, τ_R (first row) and τ_L (second row). The rules developed are predetermined using expert knowledge available such that all the errors should be brought back to the reference point immediately.

Forward Motion

The system was commanded to move forward after 4s, where at this time the two links had been stabilized at the upright position. Figure 11 shows the final position of forward mechanism execution while Figure 12 to Figure 18 show the results over 15s of simulation time for forward movement of the two-wheeled wheelchair. The wheelchair was set to move 1.5m forward from its initial position. The results show that the FLC approach worked very well with the wheelchair system on two wheels. Figure 11 shows the final wheelchair position when it was set to move forward to 1.5m from the origin. It is noted from Figures 12 and 13 that both links settled after 4s from starting time of linear motion, which can be considered quite good performance for the initial attempts of parameters setting. Link1 tilted with a positive angle from the 0° upright position. This configuration was automatically adjusted to initiate the forward motion. The corresponding wheelchair position is shown in Figure 14. It is noted that as much as 0.1m of the steady state error appeared when it settled. Figure 15 shows the wheel torques (τ_R and τ_L) from the lifting and stabilizing controller of Link1 (FLC1), and the wheel torques from the linear motion control is shown in Figure 16. The torques vary from +40Nm to -40Nm during the forward motion with positive slope during initial phase of travel. The resultant wheel torques contributed by the lifting and stabilizing control as well as the linear motion control are shown in Figure 17. The torque between Link1 and Link2 (τ_2) given by (FLC2) is shown in Figure 18.

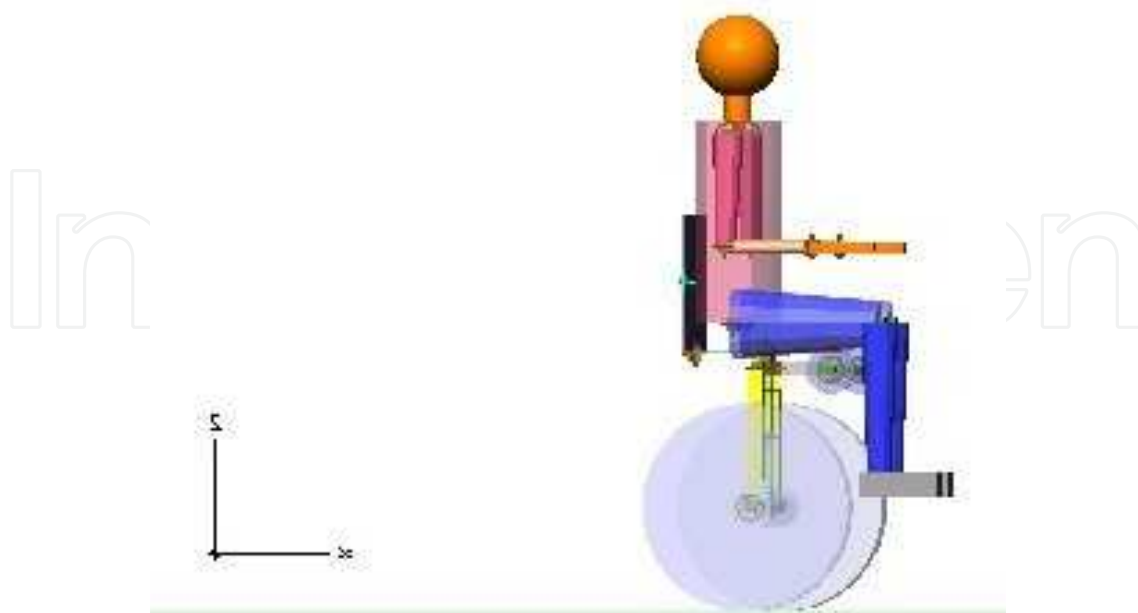


Fig. 11. Final position of 1.5m forward motion

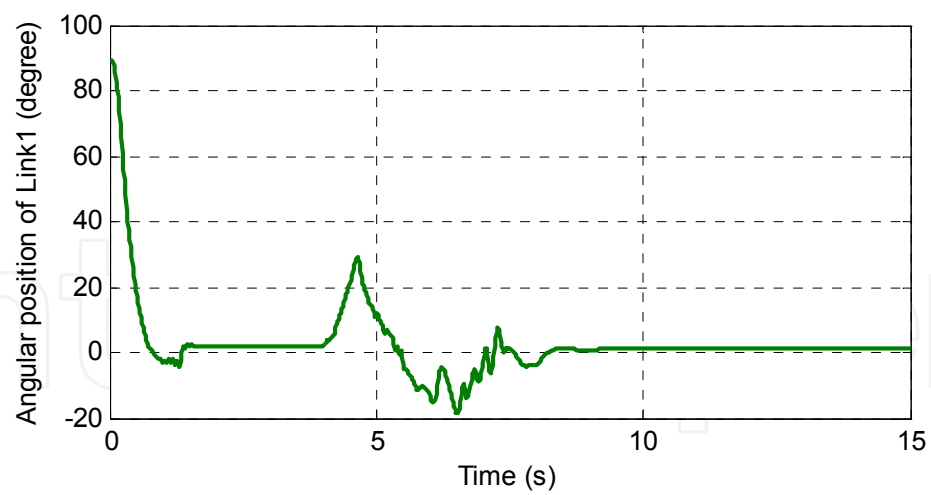


Fig. 12. Angular position of Link1, δ_1 (degree)

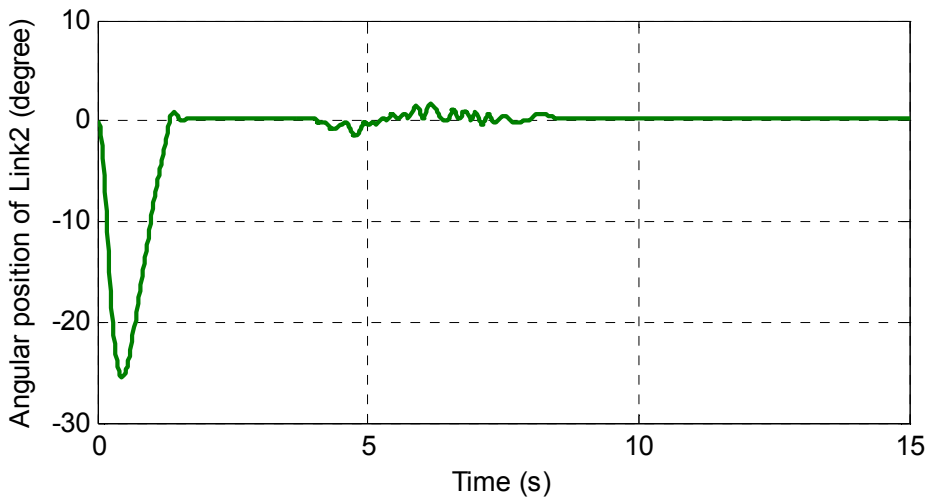


Fig. 13. Angular position of Link2, δ_2 (degree)

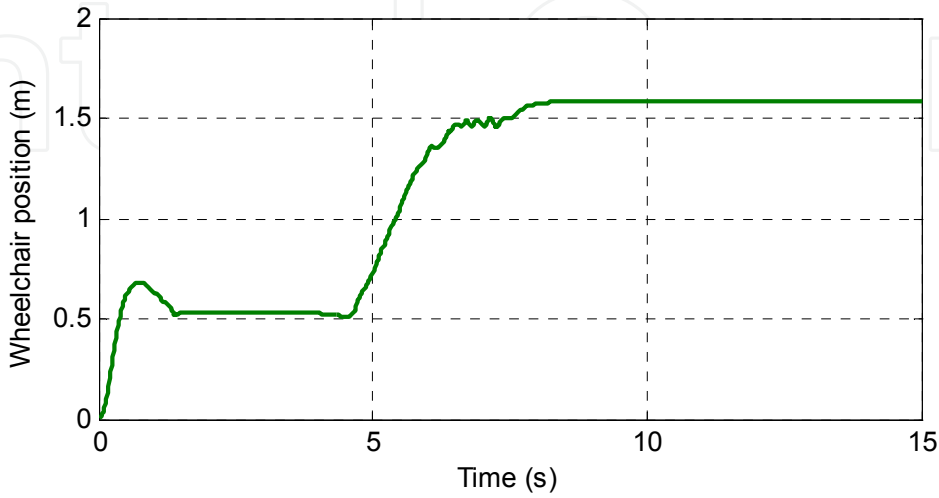


Fig. 14. Wheelchair position, x (m)

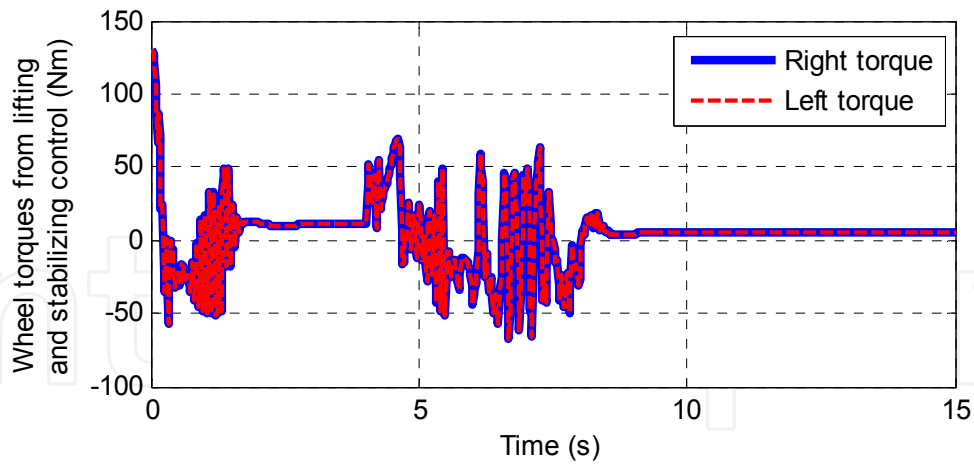


Fig. 15. Wheel torques, τ_R and τ_L due to lifting and stabilizing control, FLC1 (Nm)

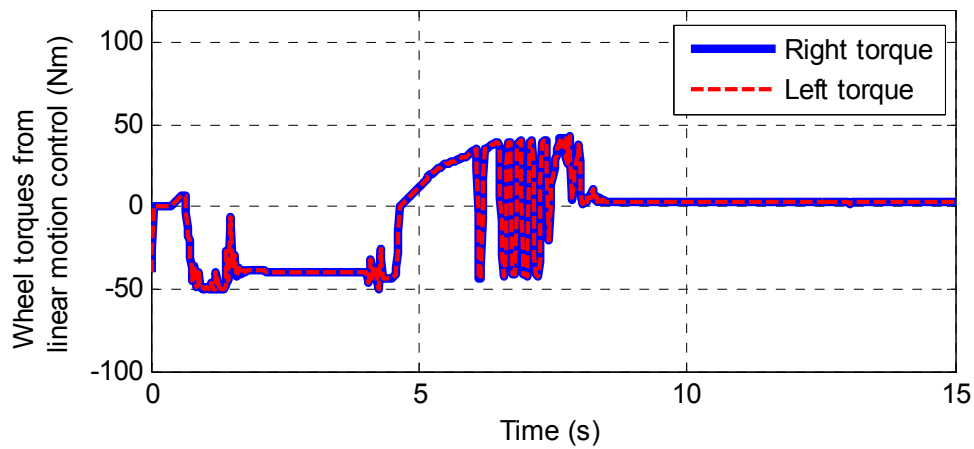


Fig. 16. Wheel torques, τ_R and τ_L due to linear motion control, FLC3 (Nm)

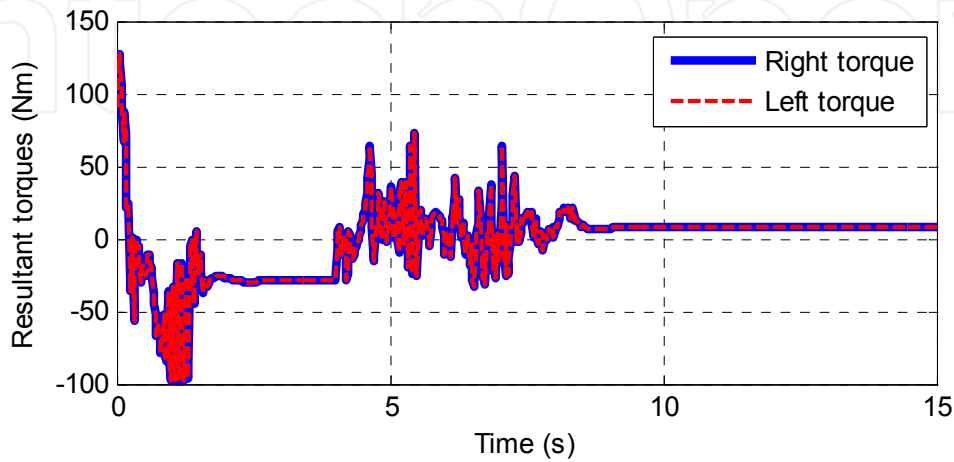


Fig. 17. Resultant wheel torques due to FLC1 and FLC3 (Nm)

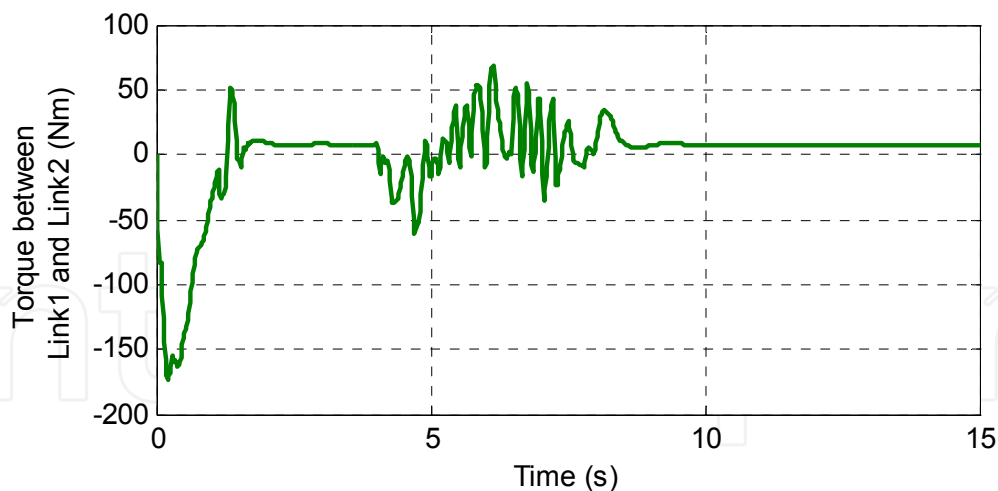


Fig. 18. Torque between Link1 and Link2, τ_2 , FLC2 (Nm)

b. FLC for steering motion

A steering motion is needed when the two-wheeled wheelchair needs to change its direction. The two-wheeled wheelchair can rotate to the right or to the left depending on which direction it is commanded. There are two different approaches where steering could be realized (Tanimoto et al., 2009). Similar direction of wheel rotation with different magnitudes could lead to steering motion (moving both wheels forward with different magnitudes). The first approach causes bigger turning radius as compared to the second approach. The second approach to realize steering motion is by giving different direction of wheel rotation (moving right wheel forward and left backward). The output torques in this work given by the FLC used for steering motion covers both approaches according to the steering error and the change of the steering error. In contrast to normal steering for mobile robots, steering motion for the two-wheeled wheelchair is executed after the upright position has been achieved; Link1 and Link2 at the 0° upright position. Therefore the complexity in this configuration is higher than the steering motion using four wheels, since other motion controls are active at the same time.

A block diagram for steering motion control of two-wheeled wheelchair is shown in Figure 19. As discussed earlier, for reasons of simplicity, the torques applied to the two wheels are the same in magnitudes (one output torque from the controller) so as to move the wheelchair only forward or backward. Then each right and left wheel torque is made independent to realize the steering motion. The weight here represents the human body weight, for which an average 70kg human is used. Sensors are attached at the respective reference bodies for control and measurement. The control signals applied to the wheelchair model comprise the right torque, τ_R (Nm), left torque, τ_L (Nm) and torque between Link1 and Link2, τ_2 (Nm). The measured outputs from the wheelchair system that consist of the angular position of Link1, δ_1 , (degree), angular position of Link2, δ_2 , (degree) and wheelchair rotation angle about the vertical axis, ψ (degree) are compared with the target references.

The wheelchair system modeled in VN software environment was used as a plant and controlled with the developed FLC in the Matlab/Simulink environment. The steering motion introduced takes place after the lifting and stabilizing mechanism has been achieved.

This new capacity increased the number of DOF of the two-wheeled wheelchair. Thus, it is noticeable challenge to control the two-wheeled wheelchair where limited actuators are available for different functions. Therefore, suitable controllers are needed, and FLC is adopted. Results show that the FLC strategy works well and gives good system performance.

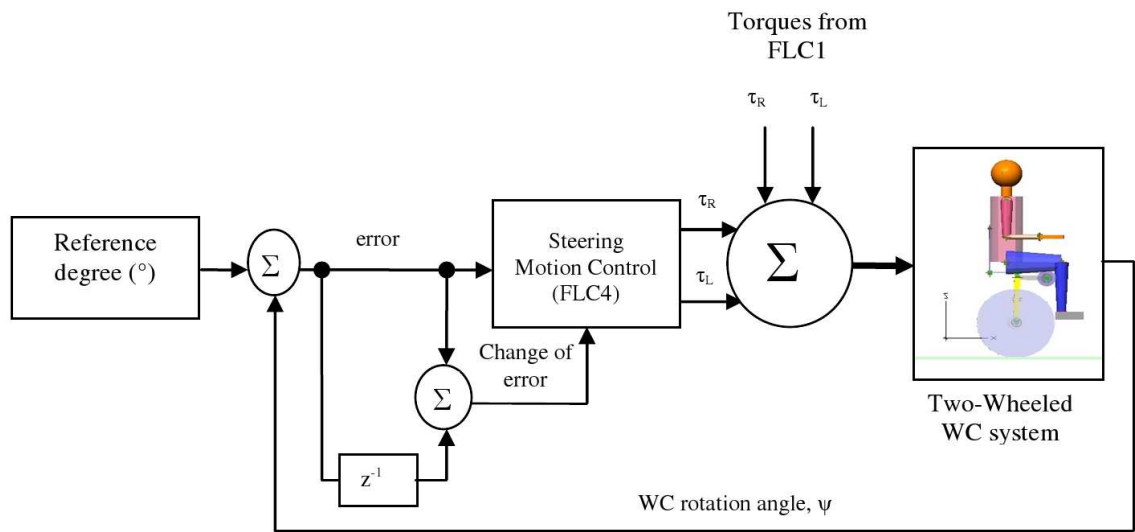


Fig. 19. Block diagram for steering motion control

Two inputs and two outputs FLC is developed to control the steering motion. The membership functions used are shown in Figure 20. The membership levels for each input

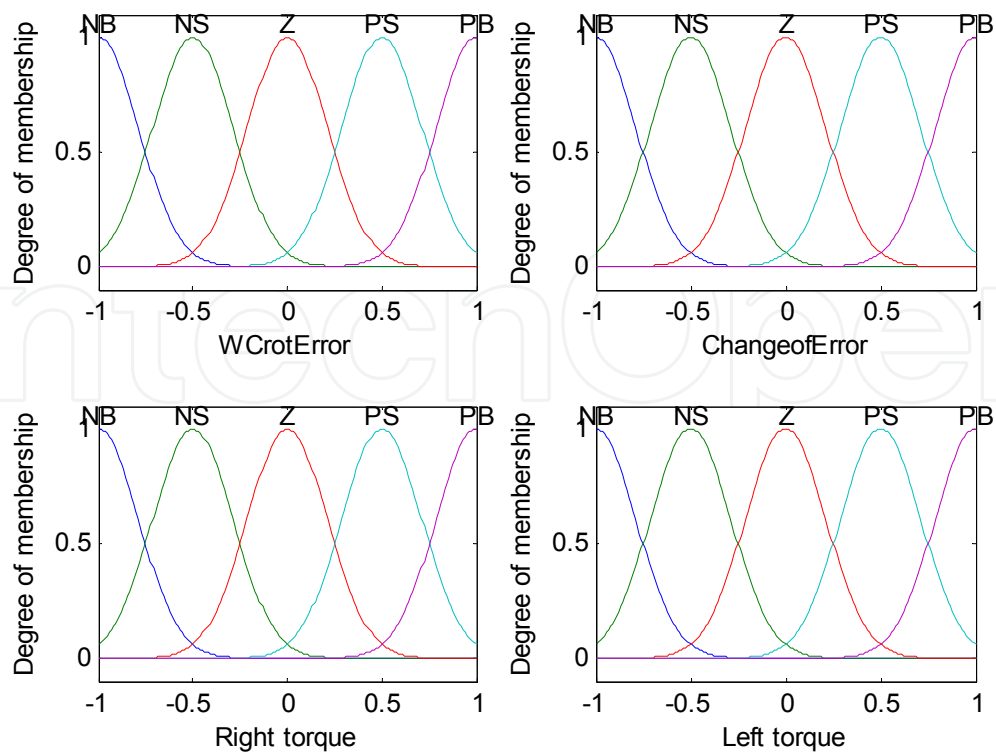


Fig. 20. Membership levels for inputs and outputs of steering control

and output comprise Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB). The two inputs used were the wheelchair rotation error (e_ψ) and the change of wheelchair rotation error, Δe_ψ . The controller outputs are the right and left wheel torques, τ_R and τ_L . All membership functions of input and output parameters are normalized for ease of control. Table 3 shows the implemented fuzzy rules for steering motion control (FLC4), where the first row relates to right-wheel torque and the second (shaded) row relates to the left-wheel torque.

$\Delta e_\psi \backslash e_\psi$	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
	PB	PB	PB	PS	Z
NS	NB	NB	NS	Z	PS
	PB	PB	PS	Z	NS
Z	NB	NS	Z	PS	PB
	PB	PS	Z	NS	NB
PS	NS	Z	PS	PB	PB
	PS	Z	NS	NB	NB
PB	Z	PS	PB	PB	PB
	Z	NS	NB	NB	NB

Table 3. Fuzzy rules for steering motion

Steering to 30°

The final position of the wheelchair system can be seen in Figure 21. Figures 22 and Figure 23 show the angular positions of Link1, δ_1 and Link2, δ_2 respectively when the system was set to steer at 30° causing the two-wheeled wheelchair to rotate to the left from its initial position. Both links settled with small steady state error after the steering settlement was achieved. As noted, they settled in less than 4s. As noted in Figure 24, the wheelchair rotated very near to 30°, with < 0.1° of the steady state error. The output torques from each lifting and stabilizing control of Link1 as well as the steering control are shown in Figures 25 and 26 respectively. Note that the output torques from FLC1 had the same magnitude and direction for both right and left wheels. On the other hand, the output torque from FLC4 had the same magnitude but different in direction representing the fuzzy rules output for steering motion. The torque between Link1 and Link2 can be seen in Figure 27. As noted, it changed between +30Nm and -20Nm to maintain the upright stability of Link2 with human payload during the steering motion. The resultant torques for both fuzzy controllers (FLC1+FLC4) is shown in Figure 28. The system was then tested to rotate at a different angle (negative angle leading to rotation to the right).

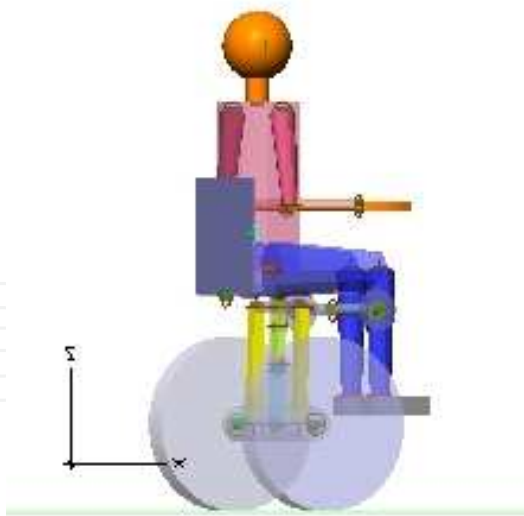


Fig. 21. Final steering position for 30° reference point

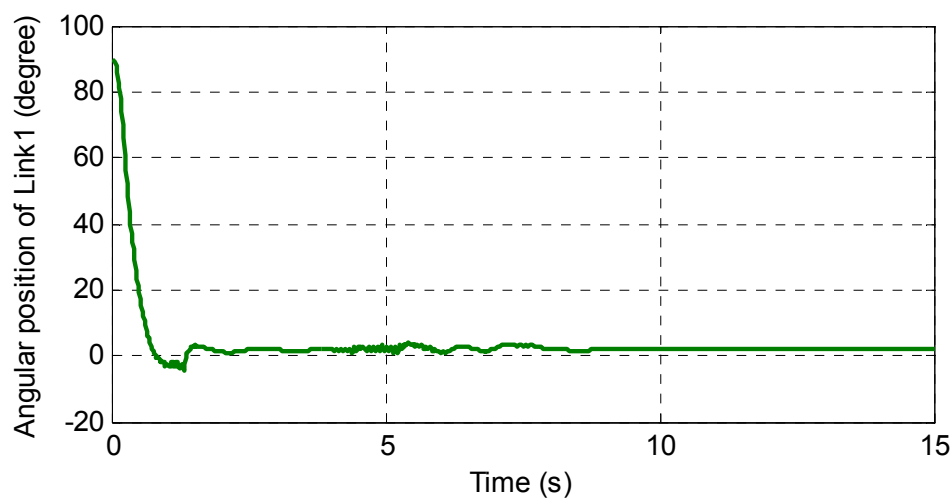


Fig. 22. Angular position of Link1, δ_1 (degree)

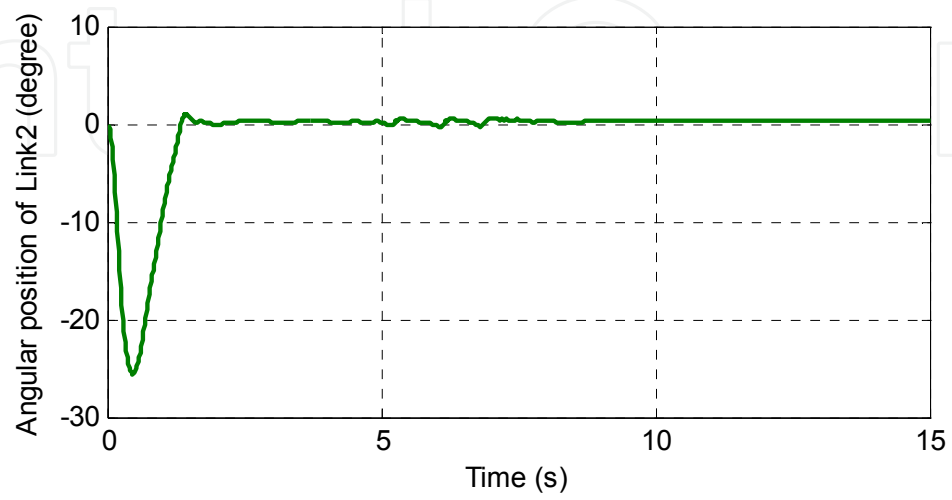


Fig. 23. Angular position of Link2, δ_2 (degree)

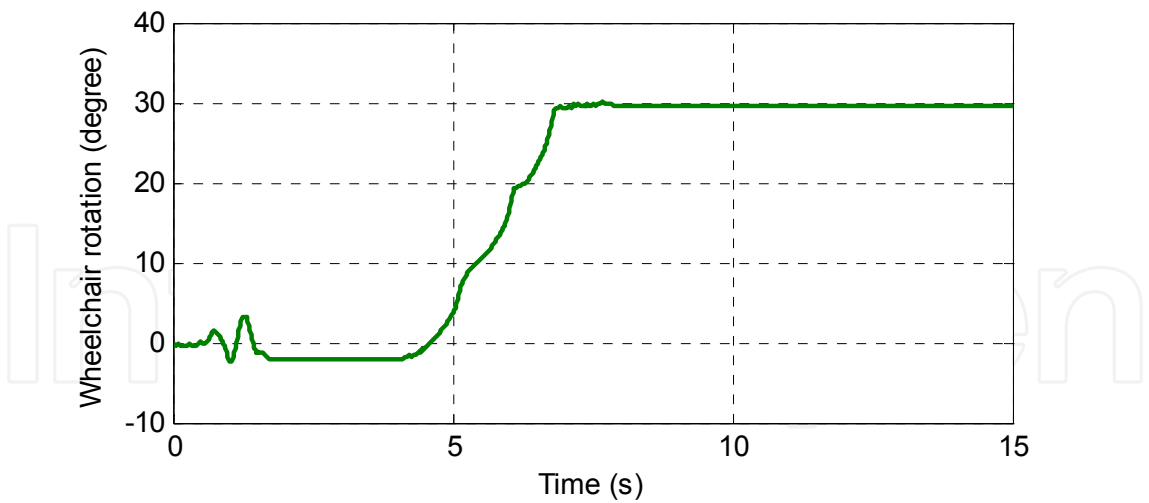


Fig. 24. Wheelchair rotation, ψ (degree)

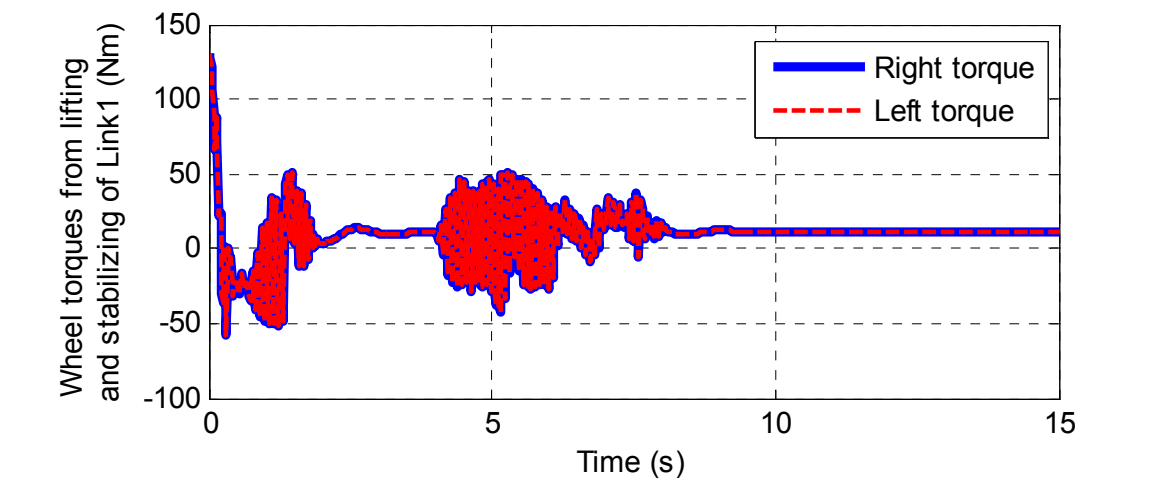


Fig. 25. Wheel torques (τ_R and τ_L) from FLC1 (Nm)

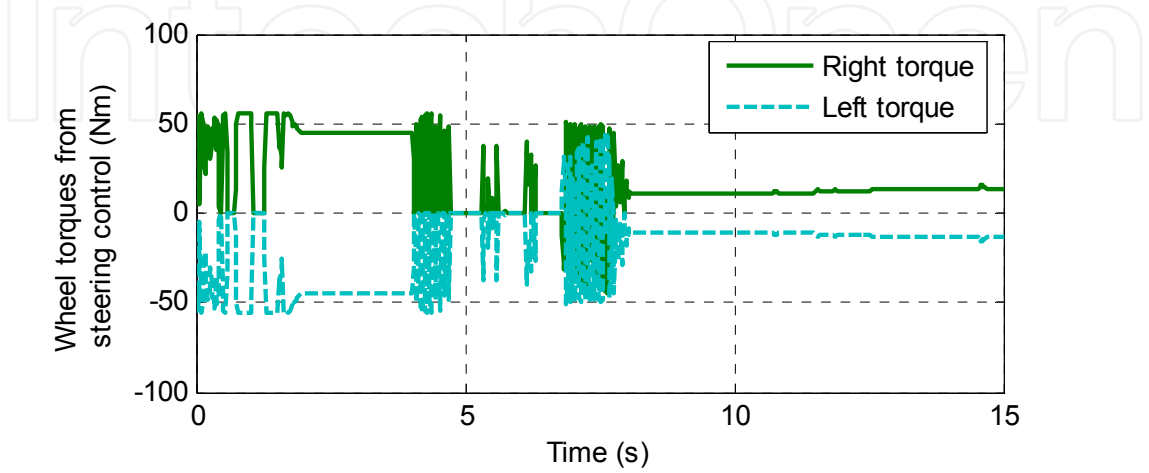


Fig. 26. Wheel torques (τ_R and τ_L) from steering motion control, FLC4 (Nm)

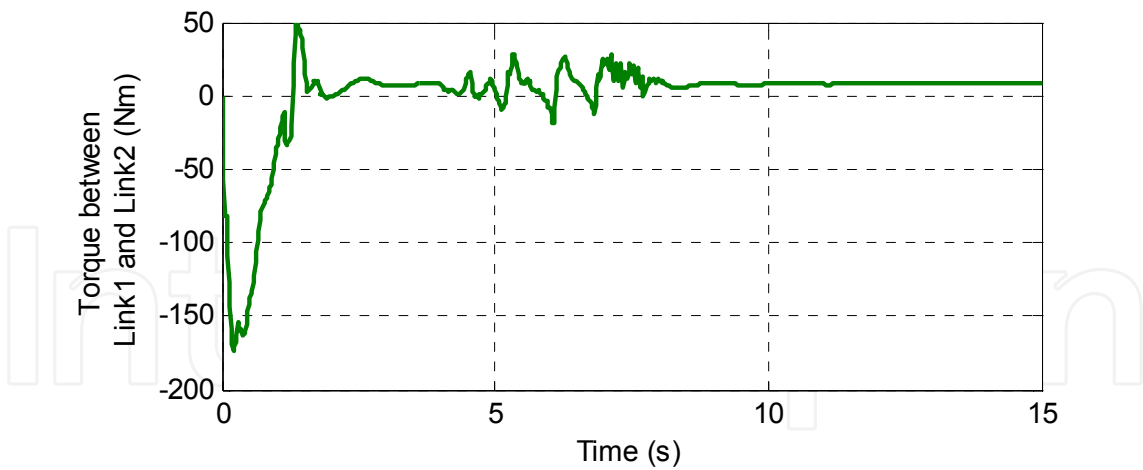


Fig. 27. Torque between Link1 and Link2, τ_2 (Nm)

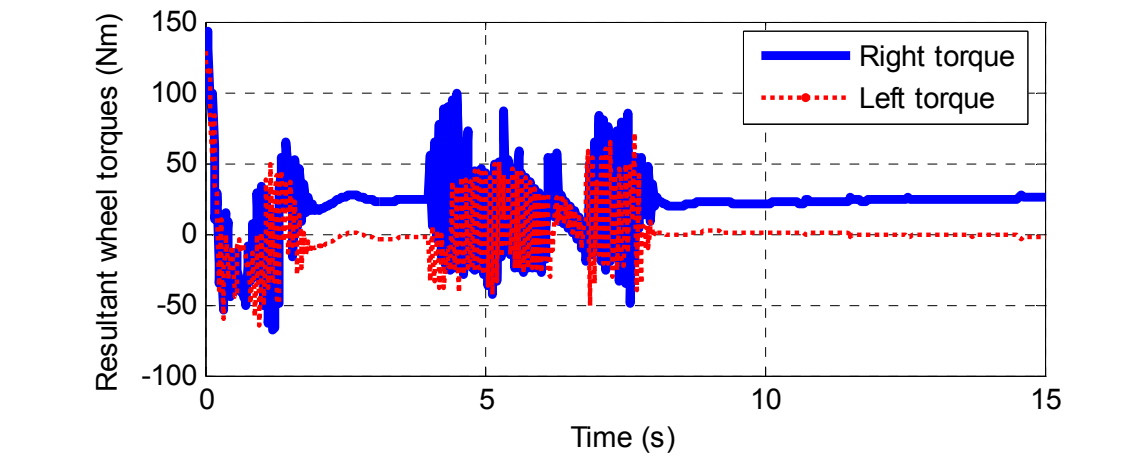


Fig. 28. Resultant wheel torques (Nm)

5. Conclusion

Fuzzy logic is one of the control techniques that is very close to human feelings and expressions. It can be easily understood and implemented although the knowledge about classical or conventional control system is not much identified. Nevertheless the general knowledge of the system involved must be generally known otherwise it is difficult to formulate a fuzzy controller for such system. If the system involved is known to be linear, and simple thus it is more worth to start with conventional Proportional-Integral-Differential (PID) controller. Otherwise if the system is known to be very complex, nonlinear and ill-defined type of system, then it is suggested to use one of the computational approaches such as fuzzy logic. This method was successfully implemented in the two-wheeled wheelchair system where a modular fuzzy control (MFC) was developed and implemented for controlling lifting and stabilizing mechanism, linear and steering motion control. Note that since a wheelchair is a main means of transport for disabled and elderly people, this two-wheeled wheelchair system would allow the user to achieve a higher level of height without assistance and hence independence. The wheelchair has been modeled as a double inverted pendulum. The integrated two-wheeled wheelchair with a human model

has been imported as the plant into Matlab/Simulink environment for control and evaluation purposes. Therefore, fuzzy logic techniques have been found suitable for control of the two-wheeled wheelchair.

A Modular Fuzzy logic Control (MFC) approach has been adopted, where the control tasks are divided into primary and secondary tasks (subsystems), and FLC modules have been designed and executed for the various control tasks accordingly. Among the control tasks, lifting and stabilizing in the upright position are considered as the primary control system task. Secondary system tasks include linear motion and steering motion. The MFC strategy developed is based on a hierarchical approach whereby the primary subsystem must be executed followed by selection of secondary subsystems. Both linear and steering motions have been successfully controlled independently using a two-input two-output PD-type FLC.

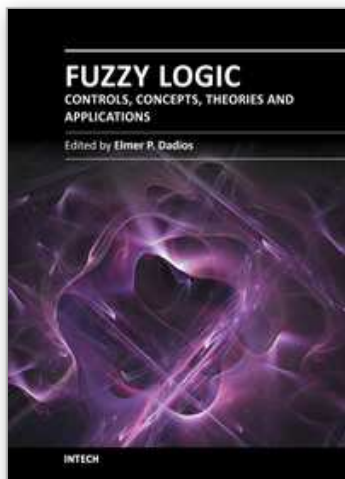
The proposed MFC has been successfully implemented and tested within simulated exercises for two-wheeled wheelchair application. The results presented proved that the MFC approach works very well in controlling highly nonlinear systems such as a wheelchair on two wheels and significantly reduces the number of rules.

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