

Lifting and stabilizing of two-wheeled wheelchair system using interval type-2 fuzzy logic control based spiral dynamic algorithm

N. A. A. Razali¹, Nor Maniha Abdul Ghani², Bifta Sama Bari³

^{1,2}Department of Electrical Engineering, College of Engineering, Universiti Malaysia Pahang, Malaysia

³Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang, Malaysia

Article Info

Article history:

Received Dec 27, 2020

Revised Jun 14, 2021

Accepted Oct 9, 2021

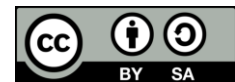
Keywords:

IT2FLC
Stability
System optimization
Vibration
Wheelchair control

ABSTRACT

The current study emphasizes on improving an interval type-2 fuzzy logic control (IT2FLC) system through the use of spiral dynamics algorithm (SDA) optimization in stabilizing a transformational two-wheeled wheelchair. The main contribution of this research is to reduce vibrations while performing the lifting and stabilization of a wheelchair from its standard four-wheeled to two-wheeled transformation. IT2FLC based SDA was used to enhance the system's stability performance by obtaining the optimized value for input and output controller gains and IT2FLC parameters for IT2FLC. System modeling was done through development within the SimWise 4D software environment, which was then integrated with MATLAB/SIMULINK for control purposes. The proposed algorithm has demonstrated improved tilt angle performance with reduced noise and lower torque when various disturbances were applied, as compared to a system solely controlled by IT2FLC without any optimization. Moreover, the proposed algorithm has also comprehensively outperformed previous controllers in terms of system's stability, further demonstrated its superiority as a system controller within transformational wheelchairs.

This is an open access article under the [CC BY-SA](#) license.



Corresponding Author:

Nor Maniha Abdul Ghani
Department of Electrical Engineering
College of Engineering
Universiti Malaysia Pahang
Lebuhraya Tun Abdul Razak, 26300 Kuantan, Malaysia
Email: normaniha@ump.edu.my

NOMENCLATURE

c	: Fuzzy logic control	M	: Number of rules in the rule base
$IT2FLC$: Interval type-2 fuzzy logic control	R_{MIMO}^i	: Group of multiple-input-multiple-output $r_{k_{miso}}^i$ rules
PID	: Proportional integral derivative	ρ	: Inputs
LQR	: Linear quadratic regulator	k	: Outputs
SDA	: Spiral dynamics algorithm	y_{lk}	: Utmost left points right point
IP	: Inverted pendulum	y_{rk}	: Utmost right point
$MIMO$: Multiple-input-multiple-output	r	: Radius/radius of the spiral
$MISO$: Group of multiple-input-multiple-output	θ	: Angle of rotation
τ_L	: Left torque	i	: Number of points

τR	: Right torque	I_n	: A matrix
$\tau 2$: Second torque	χ^*	: The center of the spiral
$\delta 2 (\theta 1)$: Tilt angle for Link1	k	: Number of iterations
$\delta 2 (\theta 2)$: Tilt angle for Link2	m	: Maximum point
x	: Crisp inputs	E_1	: Error for the orientation angle of Link1
$\tilde{A}\chi$: Type-2 fuzzy sets	ΔE_1	: Change of error for the orientation angle of Link1
$\mu \tilde{A}\chi$: Sum of type-2 fuzzy sets	E_2	: Error for the orientation angle of Link2
y	: Crisp outputs	ΔE_2	: Change of error for the orientation angle of Link2

1. INTRODUCTION

Based on their functions and capabilities, wheelchairs have practically been used by the elderly and disabled people alike as transportation and mobile tools. Often, limited flexibility has been seen within a standard four-wheeled wheelchair due to its bulky exterior and limited transformational capability. Such limitation is overcome by the development of a transformational wheelchair (four-wheeled \rightarrow two-wheeled). The later system which mimicked the concept of an inverted pendulum has enabled greater satisfactions to users' mobility requirements; yet, it has also uncovered new challenges in stability, often due to its complexity and non-linearity [1]-[13].

In seek of resolution to the fore-mentioned challenge, the current study focuses on the control strategy to lift and stabilize a transformational two-wheeled wheelchair, with the transformation mechanism of four-wheeled to two-wheeled wheelchair. Herewith, two links mechanism have been incorporated within the studied two-wheeled wheelchair with additional dynamics and disturbances as same as a double link inverted pendulum scenario. Thus, this signifies the need for a powerful control strategy towards maintaining system's stability via reduced vibrations, thereby ensuring user's well-placed security. A number of controllers have been involved in fulfilling such requirements [14]-[26]. Compared to other controllers, linear quadratic regulator (LQR) [27] as well as proportional integral derivative (PID) [28] were the most commonly adopted controllers in balancing two-wheeled wheelchairs with a transformation mechanism. Whereas, some have adopted the applications of intelligent control algorithms, like fuzzy logic and neural network, in achieving system's stability-fuzzy logic type-1 has often been the basic fuzzy logic system found within other published research [29], [30]. Fuzzy logic is well-suited for approximating the nonlinearities [31]. Studies have shown that fuzzy strategies are an effective and relatively simple tool to use for nonlinear problems [32], [33]. Apart from the nonlinearity of the systems, the significant other consideration is that it imposes difficulties to the solution of control problem. An excellent controller for nonlinear systems and complex control problems is the fuzzy logic control (FLC) that has been considered as an ideal controller for mitigating complexity in the control system. Interval type-2 fuzzy logic control (IT2FLC) can take into consideration the uncertainties in a two-wheeled wheelchair system, such as whether it is currently moving or not, and respond effectively on nonlinear complex systems such as type-1 FLC wheelchair system [34]-[37]. Therefore, intelligent control approaches following nature-inspired algorithms (e.g., optimized fuzzy logic), despite being minimally explored within previous literatures, have hereby been highlighted in catering the inherent nonlinearity of a transformational two-wheeled system.

Following the discussions above, an integration of IT2FLC with spiral dynamics algorithm (SDA) optimization, has been adopted within this study as its intelligent control approach. As introduced by Tamura and Yasuda [38], SDA optimization follows a logarithmic spiral algorithm which possesses a converging spiral motion towards the center. It hereby fulfills the diversification and search strategies [39]. Not to mention, such optimization method has been applied towards optimizing the scaling factors including output and input gain of a stair climbing wheelchair [40], which proven its applicability within a fuzzy logic control algorithm (fuzzy logic type-1), as being currently investigated.

The main focus of this research is placed on developing an IT2FLC-based control system, through the application of SDA optimization, in reducing vibrations and handling disturbances, further achieving stability during the transformation process of a transformational two-wheeled wheelchair from its standard four-wheeled configuration. To evaluate the system's performance, the proposed model has been investigated in the Simwise 4D environment for the purpose of visualization, and then integrated with MATLAB/SIMULINK. Herewith, the remainder of the paper is arranged as follows: The transformational two-wheeled wheelchair system modeling methodology is presented in section 2. Section 3 contains the results along with a brief discussion, while the conclusion is represented in section 4.

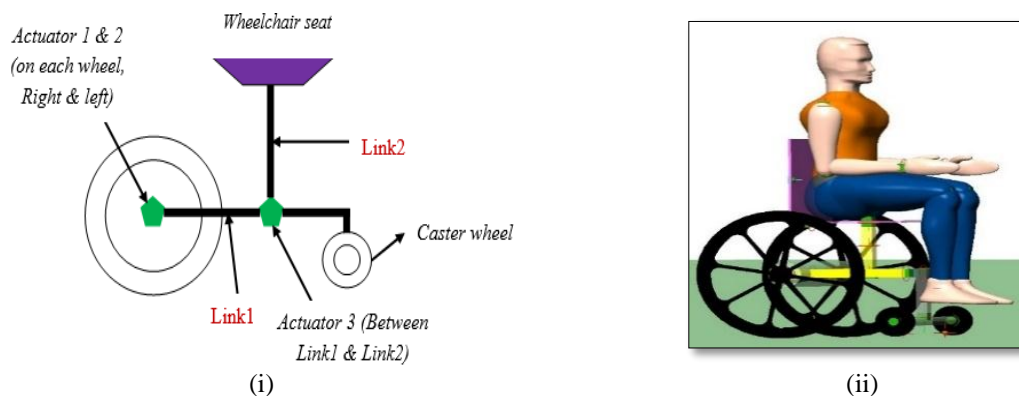
2. METHODOLOGY

2.1. System model and parameters

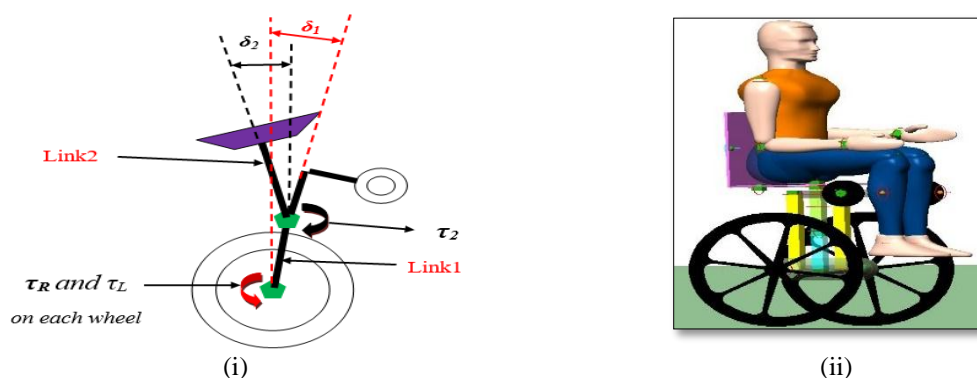
Based on a double links IP system, wheelchair with transformational mechanism between four and two wheels was designed using SimWise 4D software. Similar techniques were employed on the previous research that utilized type-1 fuzzy logic controller (T1FLC) as its movement controller [18]. However, such system was being improved within the current research, by integrating IT2FLC as its controller. Such improvements were further verified by making performance comparison between both the former and current controllers.

This model's design had been inspired by previous works [18]-[22]. Basically, three independent actuators were involved, which were located on each of the two wheels in generating torque-left (τ_L) and right (τ_R); with the third one being situated in between Link1 and Link2 as the second torque (τ_2). The wheelchair's design was largely consisted of two wheels driven by the left and right motors, individually. Whereas, another two caster wheels (front wheels), classified as the second group wheels, will be lifted during the transformation process. In particular, the wheelchair's mechanism actually consists of two links, the first of which was the rod that attached the axle to the left and right motors; and the second of which was the seat of the wheelchair that was connected to the first link. Herewith, tilt angle for Link1 and Link2 were called δ_1 (θ_1) and δ_2 (θ_2), respectively. The schematic diagrams for the system in normal position (Figure 1 (a)), as well as when the wheelchair is transformed (Figure 1 (b)), are hereby illustrated in Figure 1. Figure 1 also figured out the turbulence for 360-degree rotation for the wheelchair in real simulation with the human load [41].

The system used SimWise 4D for designing the model as a software module, as it is a powerful tool in which 3D multibody dynamic motion simulation was performed by analyzing and optimizing of 3D finite element, yet manageable simulative domain (Motion+FEA=4D) [41]. The integration of MATLAB/SIMULINK2015b considered as the second software to develop the system's controller towards controlling the wheelchair's performance, it worked as representative of the mechanical system in SimWise 4D where the whole system, inclusive of hydraulics, electronics, and controls, could be tested. As such, the full design of the four to two-wheeled wheelchair model with load had been previously shown in [41], which covered basic dimensions and specifications of the system.



(a) During wheelchair in normal position; (i) basic sketch for wheelchair before transformed, (ii) real simulation for wheelchair before transformed



(b) During wheelchair in transformation; (i) basic sketch for wheelchair during transformation (ii) real simulation for wheelchair after transformed

Figure 1. Schematic diagram of the wheelchair in, (a) normal position, (b) during transformation [41]

2.2. Interval type-2 fuzzy logic controller

There are five different components that are utilized in type-2 FLC including rule base, fuzzifier, fuzzy inference engine, type-reducer, and defuzzifier. The inputs as well as outputs of the system can be presented by interval the type-2 fuzzy sets, towards developing type-2 FLC within the control of a mobile robot [42], [43]. In general, the process for type-2 FLC starts off with the crisp inputs from input sensors being fuzzified into type-2 input fuzzy sets. This first step only considers singleton fuzzification, which would then activate the fuzzy inference engine and rule base towards producing type-2 output fuzzy sets. Following this, the type-2 output fuzzy sets will be processed by type-reducer through undertaking centroid calculation. Then they are combined with the gained type-1 fuzzy sets to further generate the type-reduced sets. Lastly, defuzzifier takes on the role to defuzzify the type-1 reduced fuzzy outputs, in attaining the crisp outputs to be fed to the actuators [44]. In view of clarification, Figure 2 depicts the block diagram of the entirety of the process undertaken for a type-2 FLC system.

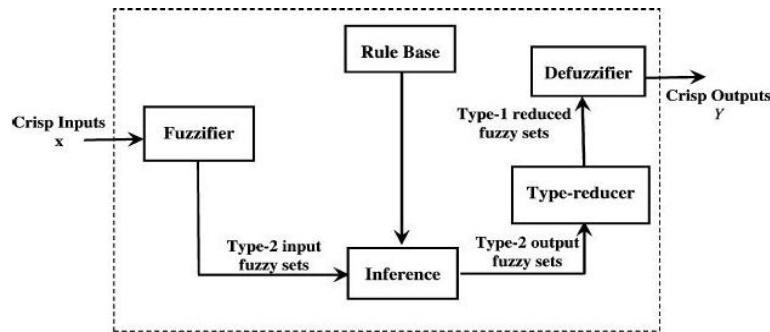


Figure 2. Type-2 block diagram [44]

2.2.1. Fuzzifier

A fuzzifier gives a crisp input vector with p inputs, into the input fuzzy sets, which can then be generalized as the type-2 fuzzy sets (\tilde{A}_X).

$$\mathbf{x} = (\chi_1, \dots, \chi_p)^T \in X_1 \times X_2 \times \dots \times X_p \equiv \mathbf{X} \quad (1)$$

In view of singleton fuzzification's ability in enabling swift computing, and its ability to be applied on robots in real-time application, it has been heavily recommended for the current research. One notable point of non-zero membership is that there is only a single point of non-zero membership in the input fuzzy for the Singleton fuzzification; \tilde{A}_X (type-2 singleton) with a coefficient, μ if [44]

$$\mu_{\tilde{A}_X}(\mathbf{x}) = 1/1 \text{ for } \mathbf{x} = \mathbf{x}' \quad (2)$$

and,

$$\mu_{\tilde{A}_X}(\mathbf{x}) = 1/0 \text{ for all other } \mathbf{x} \neq \mathbf{x}' \quad (3)$$

2.2.2. Rule base

By considering a type-2 FLC robot have p inputs,

$$\chi_1 \in X_1, \dots, \chi_p \in X_p \quad (4)$$

and c outputs;

$$y_1 \in Y_1, \dots, y_c \in Y_c \quad (5)$$

The i th rule in the multiple-input-multiple-output (MIMO) FLC can be written as:

$$R_{\text{MIMO}}^i: \text{IF } \chi_1 \text{ is } \tilde{V}_1^i \text{ and } \dots \chi_p \text{ is } \tilde{V}_p^i \quad (6)$$

Then,

$$y_1 \text{ is } \tilde{E}_1^i \dots y_c \text{ is } \tilde{E}_c^i, i = 1, \dots, M \quad (7)$$

Here, the number of rules in the rule base is denoted by M [38]. Type-2 FLC has a rule base that is very similar to type-1 FLC, as shown by [45]. Therefore, by satisfying this condition, R_{MIMO}^i can be classified as a group of multiple-input-multiple-output (MISO) R_{kMISO}^i rules, whereas R_{kMISO}^i is a rule relating multiple p inputs and the k th single output with $k=1, \dots, c$ [44].

2.2.3. Fuzzy inference engine

Mappings for the output type-2 sets are obtained from the type-2 input by combining the fuzzy inference engine rules. The different antecedents are connected inside the fuzzy inference engine by using the *Meet* operation. The next step is to execute a combination operation known as *Join*. In more detail, the input and output membership grades are combined through the use of the extended sup-star composition. The MISO fuzzy rule base comprised of M rule contains p inputs for each rule,

$$\chi_1 \in X_1, \dots, \chi_p \in X_p \quad (8)$$

and one output,

$$y_k \in Y_k \quad (9)$$

can be written as,

$$R_{\text{kMISO}}^i : \tilde{V}_1^i \times \dots \times \tilde{V}_p^i \rightarrow \tilde{E}_k^i = \tilde{A}^i \rightarrow \tilde{E}_k^i, \quad i = 1, \dots, M \quad (10)$$

According to [39], R_{kMISO}^i is described by the membership function,

$$\mu R^i(\mathbf{x}, y_k) = \mu R^i(\chi_1, \dots, \chi_p, y_k) \quad (11)$$

and,

$$\mu R^i(\mathbf{x}, y_k) = \mu \tilde{A}^i \rightarrow \tilde{E}_k^i(\mathbf{x}, y_k) \quad (12)$$

can be written as,

$$\mu R^i(\mathbf{x}, y_k) = \mu \tilde{V}_1^i(\chi_1) \Pi \dots \Pi \mu \tilde{V}_p^i(\chi_p) \Pi \mu \tilde{E}_k^i(y_k) = [\Pi_a^p = 1 \mu \tilde{V}_a^i(\chi_a)] \Pi \mu \tilde{E}_k^i(y_k) \quad (13)$$

A type-2 fuzzy input set, A_χ comprises of a single element \mathbf{x}' in the Singleton fuzzification. Each of $\mu_{\tilde{X}_a}(\chi_a)$ is non-zero solely at a single point, which is $\chi_a = \chi'_a$. The *meet* under t-norm is employed in the interval type-2 FLC. The outcomes of the input along with the antecedents operations in an interval type-1 set are represented by,

$$V^i(\mathbf{x}') = [v^i(\mathbf{x}'), v^{-i}(\mathbf{x}')] \equiv [v^i, v^{-i}] \quad (14)$$

where,

$$\underline{v}^i(\mathbf{x}') = \underline{\mu}_{\tilde{V}_1^i}(\chi'_1) * \dots * \underline{\mu}_{\tilde{V}_p^i}(\chi'_p) \quad (15)$$

and

$$\overline{v}^i(\mathbf{x}') = \overline{\mu}_{\tilde{V}_1^i}(\chi'_1) * \dots * \overline{\mu}_{\tilde{V}_p^i}(\chi'_p) \quad (16)$$

In the firing set, the input and the operations are included that can be expressed as [38],

$$\Pi_a^p = 1 \mu \tilde{V}_a^i(\chi'_a) = V^i(\mathbf{x}') \quad (17)$$

2.2.4. Type reduction

In the type-2 FLC system, two stages of type reduction are applied. The first stage would be to calculate centroid of the rule consequents. For any output of k ($t=1, \dots, T$, where T =number of output fuzzy sets), Type-2 interval consequent set of i th rule, \tilde{E}_k^i will be one of the outputs of type-2 interval fuzzy sets \tilde{E}_k^i . Calculation of the consequent centroid, while not being part of the control cycle, would be done once prior to

the robot's primary movements. In this case, the two end points, y_{lk} and y_{rk} , would need to be computed for any output k in the main equation in order to obtain the type-reduced sets. Following this, the type-reduced sets shall be defuzzified, in delivering crisp outputs to the actuators.

2.2.5. Defuzzification

As previously described in [44], the utmost left and right points, y_{lk} and y_{rk} will be determined following the type reduction step. Herewith, the interval set based upon average between both y_{lk} and y_{rk} is defuzzified, which then generates the crisp output for each output k . In (18) describes the crisp output defuzzification as:

$$Y_k(x) = \frac{y_{lk} - y_{rk}}{2} \quad (18)$$

In the proposed system, there are three inputs and two outputs that are observed. These include the torque for Link1 at the left and right wheels being the first and second input, the torque for Link2 being the third input; whereas, the angle of body orientation for Link1 (left and right wheels) as a whole, and Link2 being the two outputs, respectively. The first subsystem includes controller inputs for the orientation angle of Link1 which are error (E_1) and change of error (ΔE_1). Similarly, the second subsystem includes the controller inputs for the orientation angle of Link2, which are error (E_2) and change of error (ΔE_2).

In general, there are 5 separate levels that have been included in the membership function including negative big (NB), positive big (PB), positive small (PS), negative small (NS) and zero (Z). By following the IF-THEN rule, then it generates 25 rules (5x5) altogether. Table 1 illustrates these 25 rules by using the inputs E and ΔE in IT2FLC. Thus, Figure 3 describes the entirety of integration for SimWise 4D, alongside the controller in MATLAB/SIMULINK.

Table 1. 25 rules for IT2FLC for the input torques

$\begin{matrix} E \\ \Delta E \end{matrix}$	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	Z
NS	PB	PB	PS	Z	NS
Z	PB	PS	Z	NS	NB
PS	PS	Z	NS	NB	NB
PB	Z	NS	NB	NB	NB

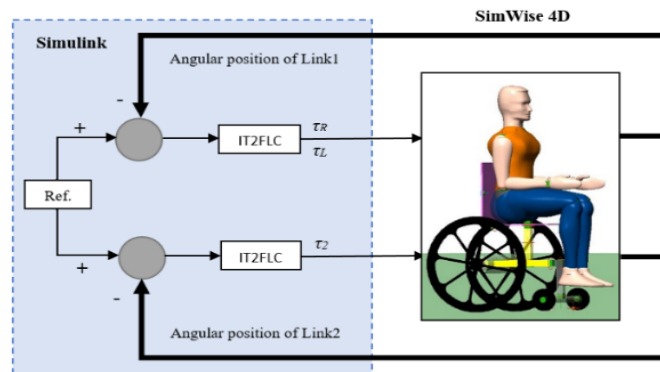


Figure 3. Integration between SimWise 4D and MATLAB/SIMULINK

2.3. Spiral dynamic algorithm

As understood from Tamura and Yasuda, the SDA approach is based on the metaheuristic optimization, which draws inspiration from natural spiral patterns including galaxy, hurricanes and tornado [38]. As a basic criterion, SDA optimization would establish a balance in combining both the exploration and exploitation strategies. Basically, the search agents for this spiral-inspired algorithm would move from the outer part area of a spiral, slowly towards its centre in a twirling manner, following the gradual increase in the number of iterations. Also known as the intensification phase, such occurrence is taken place within the spiral, with the centre as its destination. Thus, the equation of mathematical modeling for SDA is represented by,

$$\chi_i(k+1) = S_n(r, \theta)\chi_i(k) - [S_n(r, \theta) - I_n]\chi^*, i = 1, 2, 3, \dots, m. \quad (19)$$

Here, θ is defined as the angle of rotation, which rotates with a variation from 0 to 2π . The center of the spiral is denoted by χ^* , whereas the number of iterations is denoted by k . I_n is a matrix. The radius of the spiral is denoted by r , ranging from 0 to 1. The number of points and the maximum point is denoted by i and m , respectively [39]. The implementation flowchart of SDA has been illustrated in Figure 4 [38].

In the proposed work, for the spiral dynamic trajectory; radius, $r=0.95$ and $\Theta=\pi/4$ were employed since they provide the optimum performance [38]. The number of search agents was applied as 30, while the number of iterations employed in this work was measured at 30. This optimization was sought to minimise the error in the angular position while mitigating external disturbances. Most importantly, the total of the 14 inputs and output gains as a whole, as well as δ and σ , were applied to determine the size of membership function within IT2FLC.

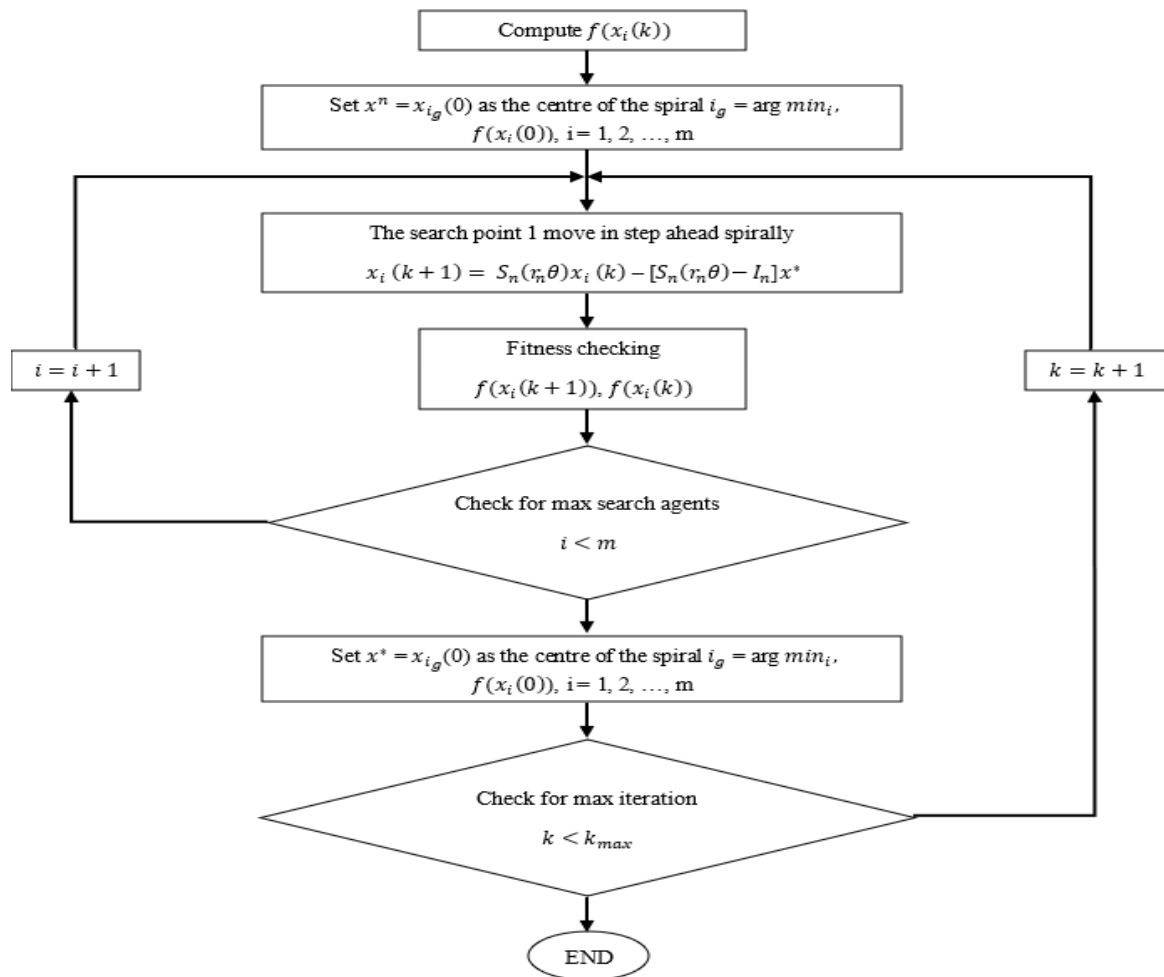


Figure 4. SDA flowchart

3. RESULTS AND DISCUSSION

3.1. Spiral dynamic algorithm optimization

The research objectives have hereby been achieved, following the completed results obtained from the trial and error method, as demonstrated in the previous paper [41]. All of the values obtained were then used for the purpose of optimization towards improving the controller. The SDA approach has been selected for optimization within the current study as it has been tested to be one of the best optimization methods for this type of system. Overall, the Simulink block diagram with SDA for the system's optimization is shown in Figure 5. Figure 5 also describes throughout the optimization stage when SimWise 4D was chosen as the replication of the real application, all the parameters involved were taken into consideration in order to design a 4-to-2 wheelchair. To gain the best 14 parameters, SDA MATLAB/SIMULINK and visual

representation were conducted at the same time during optimization process. The specifications include length, weight, mass, gravity, friction, angles, distance, velocity, joints, motors and uncertainties have been considered in this work. $K1$ until $K14$ were hereby optimized to achieve a stable performance. Noted that $K1$ until $K12$ were the input and output gains; whereas, $K13$ and $K14$ were known as the corresponding delta and sigma, which were controller used to control the system's parameters. Following optimization being implemented within the investigated system, the data was recorded, similar to that of the trial and error method. The vibrations were reduced by the IT2FLC and remain stable as the system was able to achieve zero-degree tilt angle in the upright position.

3.2. Comparison with other controllers

In order to demonstrate the excellence of IT2FLC-SDA as a controller during the transformational process of a two-wheeled wheelchair, SDA optimization results were then verified and compared against other controllers—FLC Type-1 by Chotikunnan [29], and FLC Type-1 and PID by Ghani [16], [17]. Specifically, three sorts of external disturbances were employed to the system during the lifting and stabilizing tasks, towards assessing the robustness of the controllers; which consisted of positive, negative and positive-negative disturbances. The results, alongside condition without any disturbance, is presented as:

3.2.1. Without disturbances signals

Under the absence of external disturbance, the obtained data for the system implemented with IT2FLC-SDA, and other tested controllers have been presented in Table 2. As seen, IT2FLC-SDA has prevailed to be the second best option when it comes to traveling distance following the simulation, with a recorded travelling distance of 0.6 meters which bested that of FLC type-1 and PID by Ghani [16], [17]; yet, felt short behind FLC Type-1 by Chotikunnan [29] at a traveling distance of merely 0.36 meters. However, such shortfall has been overshadowed by the shortest settling time recorded for IT2FLC-SDA, at a mere 1.5 seconds. Despite its slightly further traveling distance, the settling time of the proposed controller has outshined that of Chotikunnan [29] as recorded at 4.6 seconds; thus, supporting IT2FLC-SDA as the best controller, among others, under the absence of external disturbance.

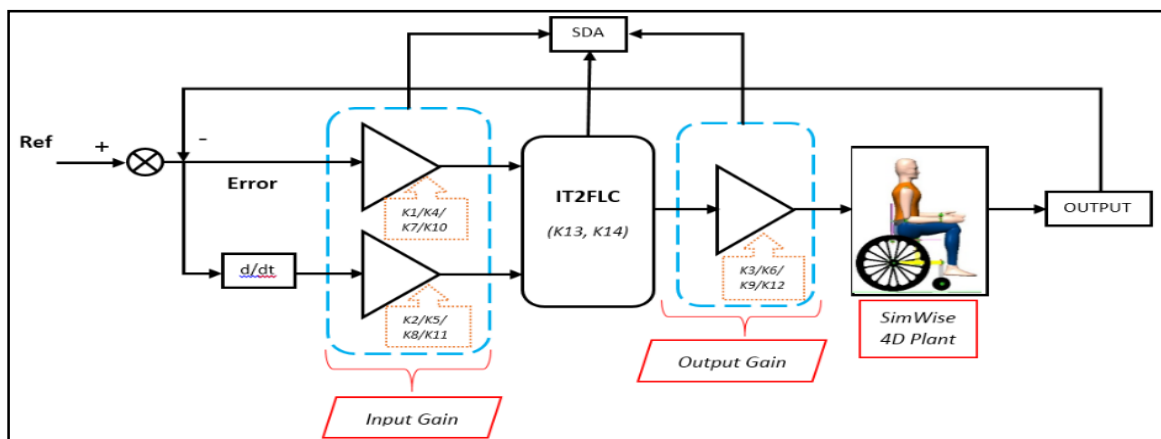


Figure 5. Simulink block diagram with SDA

Table 2. Comparison for IT2FLC with other controllers without disturbance signals

		N.A.A. Razali (IT2FLC- SDA)	Phichitphon Chotikunnan (FLC Type-1)	N.M.A. Ghani (FLC Type-1)	N.M.A. Ghani (PID)
Position of the WC/ WC travelled distance (m)		0.6	0.36	6.5	3
Settling time (s)		1.5	4.6	N/A	2.3
Velocity (m/s)		0.000893	N/A @ 0	N/A	N/A
Torque reduction at Link1 (Nm)	Max	+110	N/A	N/A	+270
	Min	-105	N/A	N/A	-100
Torque reduction at Link2 (Nm)	Max	+25	N/A	N/A	N/A
	Min	-112	N/A	N/A	N/A
Angular Link1 (deg)		-0.835	N/A @ 0	N/A	N/A
Angular Link2 (deg)		-0.747	N/A @ 0	N/A	N/A

3.2.2. Positive-negative disturbance signals

As for the condition of positive-negative disturbance, external disturbances were concurrently applied from both directions as per being previously tested independently in testing the system's compatibility to uncertain situations. Unlike disturbances from a single direction, the current simulation started off with impulses injected from the 3rd second mark, which then consecutively applied within a 10 seconds interval (13th, 23rd, 33rd second marks). Accounting for both positive and negative directions, positive disturbances with a magnitude of 1260 N were applied at the 3rd and the 23rd second marks; whereas, negative disturbances with a magnitude of -470 N were applied at the 13th and 33rd second marks, as illustrated in Figure 6. Following the simulation, the input torques for Link1 and Link2 are separately presented in Figure 7 and Figure 8; while, Figure 9 and Figure 10 represent the output angles of the wheelchair for both Link1 and Link2 respectively.

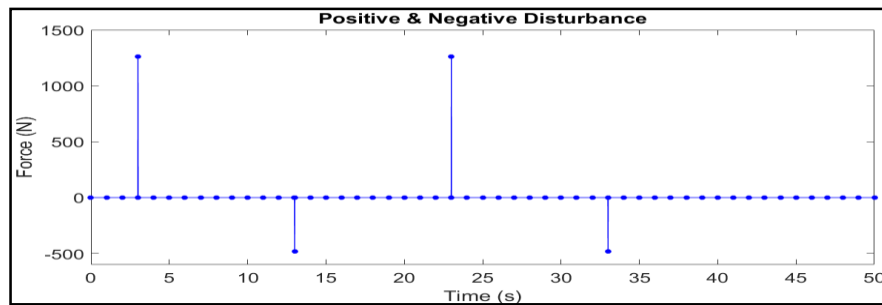


Figure 6. Positive-negative disturbance impulse

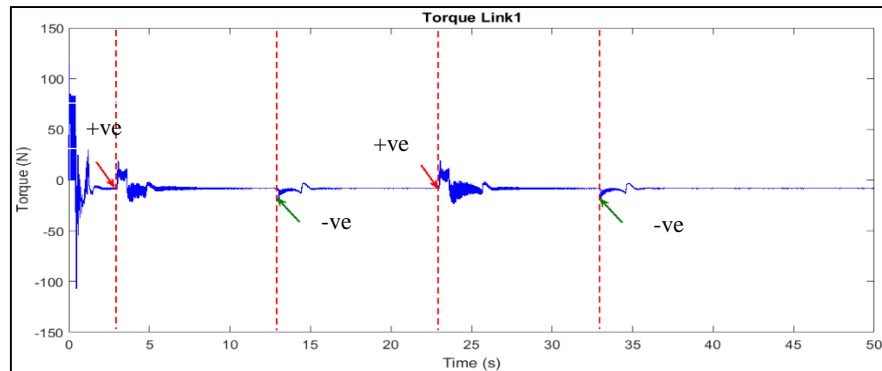


Figure 7. Torque Link1 with positive-negative disturbance

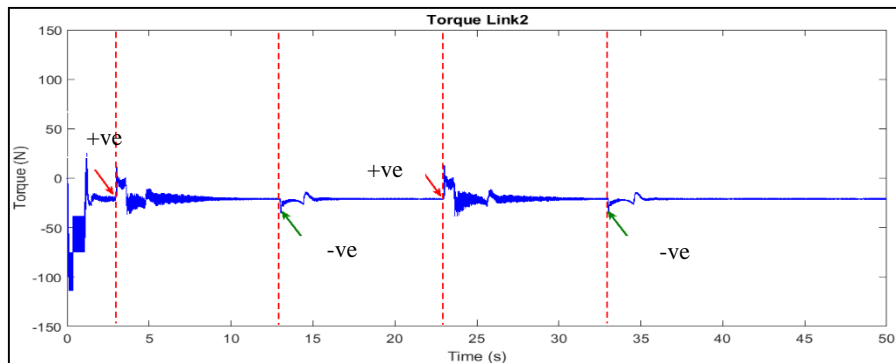


Figure 8. Torque Link2 with positive-negative disturbance

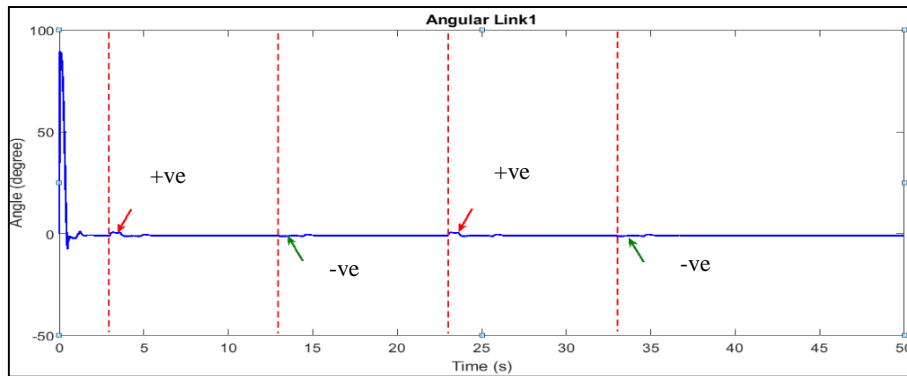


Figure 9. Angular Link1 with positive-negative disturbance

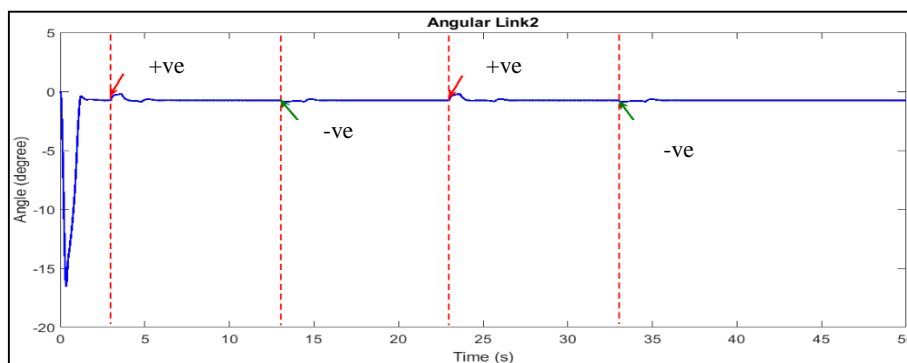


Figure 10. Angular Link2 with positive-negative disturbance

Comparatively, IT2FLC-SDA has yielded a massively closer wheelchair position to the initial point, following the influence of external stimulus – a difference in travel distance of 9.899 meters. This has also been the case for settling time, where IT2FLC-SDA settled 3.4 seconds faster than that of Type-1 FLC; a settling time of less than 2 seconds indicating higher stability. Besides, smaller values have been recorded for both maximum and minimum torques on both positive and negative disturbances as shown in Table 3.

Table 3. Comparison for IT2FLC with type-1 FLC for positive-negative disturbance signals

		N.A.A. Razali (IT2FLC-SDA)	S. Ahmad (FLC Type-1)
Position of the WC/ WC travelled distance (m)		0.611	10.5
Settling time (s)		1.6	5
Velocity (m/s)		0.000893	N/A
Torque reduction at Link1 (Nm)	Max	-5	+100
	Min	-10	-75
Torque reduction at Link2 (Nm)	Max	-18	+70
	Min	-25	-200
Angular Link1 (deg)		-0.917	N/A
Angular Link2 (deg)		-0.774	N/A

4. CONCLUSION

In this paper, IT2FLC with SDA optimization has been implemented as the control algorithm for tuning both the controller's input and output gains, as well as its control parameters within a transformational two-wheeled wheelchair system. Following this, comprehensive comparisons have been conducted in term of tilt angle and stability performance under several disturbance conditions. The results hereby indicated that IT2FLC based SDA has managed to improve both the wheelchair's settling time and traveling distance when undertaking its transformation system from four-wheeled to two-wheeled. As such, the proposed algorithm has also demonstrated its superiority in performance during the case of independent positive and negative disturbances, with 50% greater robustness in both traveling distance and settling time, as compared to the

former controllers. This has further demonstrated the proposed controller's ability to withstanding greater disturbances from both directions. However, as effective as it is, future work with regards to IT2FLC-SDA can place emphasis on additional features, with the like of vertically extendable seat on the wheelchair. Since this work is the first stage of the research, SimWise 4D acts as the replicator of the real application and almost likely to be real because the software includes the variation of needed for a real situation such as type of material used, gravity, and friction. Therefore, the second stage of this work will be including the real hardware application and predictably to be in success rate in the future work.

ACKNOWLEDGEMENTS

This work has been funded by the Fundamental Research Grant Schemes FRGS/1/2019/ICT02/UMP/02/10 with the university reference RDU1901196. The fundings have been granted by the Ministry of Higher Education via the Research and Innovation Department, UMP.

REFERENCES

- [1] H. O. Wang, K. Tanaka and M. F. Griffin, "An approach to fuzzy control of nonlinear systems: stability and design issues," *IEEE Transactions on Fuzzy Systems*, vol. 4, no. 1, pp. 14-23, 1996, doi: 10.1109/91.481841.
- [2] J. Q. Yi, N. Yubazaki and K. Hirota, "Upswinging and stabilization control of inverted pendulum system based on the SIRMs dynamically connected fuzzy inference model," *Conference Proceedings of IEEE International Fuzzy Systems (FUZZ-IEEE '99)*, vol. 122, no. 1, pp. 139-152, 1999, doi: 10.1109/FUZZY.1999.793273.
- [3] J. Q. Yi and N. Yubazaki, "Stabilization fuzzy control of inverted pendulum systems," *Artificial Intelligence in Engineering*, vol. 14, pp. 153-163, 2000, doi: 10.1016/S0954-1810(00)00007-8.
- [4] S. Yurkovich and M. Widjaja, "Fuzzy controller synthesis for an inverted pendulum system," *Control Engineering Practice*, vol. 4, no. 4, pp. 455-469, 1996, doi: 10.1016/0967-0661(96)00026-3.
- [5] A. Blankespoor and R. B. Roemer, "Experimental verification of the dynamic model for a quarter size self-balancing wheelchair," *Proceeding of American Control Conference Boston, Massachusetts*, vol. 1, pp. 488-492, 2004, doi: 10.23919/ACC.2004.1383650.
- [6] F. Grasser, A. D'Arrigo, S. Colombi and A.C. Rufer, "JOE: A mobile, inverted pendulum," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 1, pp. 107-114, 2001, doi: 10.1109/41.982254.
- [7] K. Pathak, J. Franch and S. K. Agrawal, "Velocity and position control of a wheeled inverted pendulum by partial feedback linearization," *IEEE Transactions on Robotics*, vol. 21, no. 3, pp. 505-513, 2005, doi: 10.1109/TRO.2004.840905.
- [8] S. H. Jeong and T. Takahashi, "Wheeled inverted pendulum type assistant robot: design concept and mobile control," *Intelligent Service Robotics*, vol. 1, no. 4, pp. 313-320, 2008, doi: 10.1007/s11370-008-0024-5.
- [9] D. L. Kamen, D. Field and R. K. Heinzmann, "Control of a balancing personal vehicle," *U.S. Patent*, vol. 6, 443 250, 2002.
- [10] J. Rubi, A. Rubio and A. Avello, "Swing-up control problem for a self-erecting double inverted pendulum," *Proceeding of IEE -Control Theory and Applications*, vol. 149, no. 2, pp. 169-175, 2002, doi: 10.1049/ip-cta:20020326.
- [11] Y. Takahashi and O. Tsubouchi, "Modern control approach for robotic wheelchair with inverse pendulum control," *Proceeding of 5th International Conference on Intelligent System Design and Application*, 2005, pp. 364-369, doi: 10.1109/ISDA.2005.67.
- [12] J. Vaščák, "Fuzzy control of a physical double inverted pendulum model," *Computational Intelligence*, pp. 482-494, 1999, doi: 10.5555/646225.683320.
- [13] R. J. Wai and L. J. Chang, "Stabilizing and tracking control of nonlinear dual-axis inverted pendulum system using fuzzy neural network," *IEEE Transactions on Fuzzy Systems*, vol. 14, no. 1, pp. 145-168, 2006, doi: 10.1109/TFUZZ.2005.859305.
- [14] A. M. Almeshal, K. M. Goher and M. O. Tokhi, "Dynamic modelling and stabilization of a new configuration of two-wheeled machines," *Robotics and Autonomous Systems*, vol. 61, no. 5, pp. 443-472, 2013, doi: 10.1016/j.robot.2013.01.006.
- [15] A. Aula, T. M. Altalmas, S. Ahmad, R. Akmeliawati, S. N. Sidek and M. O. Tokhi, "Integrated design, modelling and analysis of two-wheeled wheelchair for disabled," *Assistive technology: the official journal of RESNA*, vol. 28, no. 3, pp. 141-152, 2016, doi: 10.1142/9789814525534_0021.
- [16] N. M. A. Ghani and M. O. Tokhi, "A dwi-phase fuzzy control structure for an auto-mode stair climbing wheelchair," *Proceedings of the 2013 IEEE International Conference on Systems, Man and Cybernetics*, 2013, pp. 4694-4699, doi: 10.1109/ICSMC.2013.6736999.
- [17] N. M. A. Ghani et al., "Control of a stair climbing wheelchair," *International Journal of Robotics and Automation (IJRA)*, vol. 1, no. 4, pp. 203-213, 2012.
- [18] S. Ahmad, N. H. Siddique and M. O. Tokhi, "A modular fuzzy control approach for two wheeled wheelchair," *Journal of Intelligent and Robotic Systems*, vol. 64, no. 3-4, pp. 401-426, 2011, doi: 10.1007/s10846-011-9541-0.
- [19] S. Ahmad, M. O. Tokhi and N. H. Siddique, "Modular fuzzy control with input shaping technique for transformation of two-wheeled wheelchair to four-wheeled mode," *IEEE Symposium on Industrial Electronics and Applications (ISIEA 2010)*, 2010, pp. 562-566, doi: 10.1109/ISIEA.2010.5679402.

- [20] S. Ahmad, M. O. Tokhi and S. F. Toha, "Genetic algorithm optimisation for fuzzy control of wheelchair lifting and balancing," *Third UKSim European Symposium on Computer Modelling and Simulation*, 2009, pp. 97-100, doi: 10.1109/EMS.2009.115.
- [21] S. Ahmad, M. O. Tokhi and Z. Hussein, "Rejection of yaw disturbance in a two-wheeled wheelchair system," *Third Asia International Conference on Modelling and Simulation*, 2009, pp. 454-459, doi: 10.1109/AMS.2009.65.
- [22] S. Ahmad and M. O. Tokhi, "Forward and backward motion control of wheelchair on two wheels," *Industrial Electronics & Applications, ICIEA Third IEEE Conference*, 2008, pp. 461-466, doi: 10.1109/ICIEA.2008.4582558.
- [23] J. S. Lekshmi and J. L. Nandagopal, "Control for transformation of a four wheeled to two wheeled mobile robot," *International Conference on Processing of Materials, Minerals and Energy*, 2016, pp. 1-7.
- [24] Q. W. Qian, J. F. Wu and Z. Wang, "A novel configuration of two-wheeled self balancing robot," *Tehnicki Vjesnik*, vol. 24, no. 2, pp. 459-464, 2015, doi: 10.17559/TV-20160608105436.
- [25] A. M. Almeshal, K. M. Goher, M. O. Tokhi and S. A. Agouri, "A new configuration of a two wheeled double inverted pendulum-like robotic vehicle with movable payload on an inclined plane," *2012 First International Conference on Innovative Engineering Systems (ICIES)*, 2012, pp. 97-102, doi: 10.1109/ICIES.2012.6530852.
- [26] C. C. Lee, "Fuzzy logic in control systems: fuzzy logic controller – part I," *IEEE Transactions on Systems, Man and Cybernetics*, vol. 20, no. 2, pp. 404-418, 1990, doi: 10.1109/21.52551.
- [27] S. Ahmad and M. O. Tokhi, "Linear quadratic regulator (LQR) approach for lifting and stabilizing of two-wheeled wheelchair," *2011 4th International Conference on Mechatronics (ICOM)*, 2011, doi: 10.1109/ICOM.2011.5937119.
- [28] D. Pratama, E. H. Binugroho and F. Ardilla, "Movement control of two wheels balancing robot using cascaded PID controller," *2015 International Electronics Symposium (IES)*, 2015, pp. 100-105, doi: 10.1109/ELECSYM.2015.7380821.
- [29] P. Chotikunann and B. Panomruttanarug, "The application of fuzzy logic control to balance a wheelchair," *Control Engineering and Applied Informatics*, vol. 18, no. 3, pp. 41-51, 2016.
- [30] B. Panomruttanarug and P. Chotikunann, "Self-balancing iBOT-like wheelchair based on type-1 and interval type-2 fuzzy control," *ECTI-CON 2014*, 2014.
- [31] Q. Zhou, H. Li, C. Wu, L. Wang and C. K. Ahn, "Adaptive fuzzy control of nonlinear systems with unmodeled dynamics and input saturation using small-gain approach," *IEEE Transactions on Systems, Man and Cybernetics: Systems*, vol. 47, no. 8, pp. 1979-1989, Aug. 2017, doi: 10.1109/TSMC.2016.2586108.
- [32] N.A. Sofianos and Y.S. Boutalis, "Stable indirect adaptive switching control for fuzzy dynamical systems based on T-S multiple models," *International Journal of Systems Science*, vol. 44, no. 8, pp. 1546-1565, 2013, doi: 10.1080/00207721.2012.659697.
- [33] N.A. Sofianos and Y.S. Boutalis, "Robust adaptive multiple models based fuzzy control of nonlinear systems," *Neurocomputing*, vol. 173, no. 3, pp. 1733-1742, 15 January 2016, doi: 10.1016/j.neucom.2015.09.047.
- [34] N. F. Jamin, N. M. Ghani, Z. Ibrahim, M. Masrom, N. A. Razali and A. M. Almeshal, "Two-wheeled wheelchair stabilization using interval type-2 fuzzy logic controller," *International Journal of Simulation: Systems, Science & Technology*, vol. 19, no. 3, pp. 3.1-3.7, June 2018, doi: 10.5013/IJSSST.A.19.03.03.
- [35] J. Huang, M. H. Ri, D. Wu and S. Ri, "Interval type-2 fuzzylogic modeling and control of a mobile wo-wheeled inverted pendulum", *IEEE Transactions on Fuzzy Systems*, vol. 26, no. 4, pp. 1-9, 2017, doi: 10.1109/TFUZZ.2017.2760283.
- [36] N. F. Jamin, N. M. A. Ghani and Z. Ibrahim, "Movable payload on various conditions of two-wheeled double links wheelchair stability control using enhanced interval type-2 fuzzy logic," in *IEEE Access*, vol. 8, pp. 87676-87694, 2020, doi: 10.1109/ACCESS.2020.2991433.
- [37] C. Yang, "Using an imaginary planar rack cutter to create a sphericalgear pair with continue involute teeth," *Arabian J. Sci. Eng.*, vol. 42, no. 11, pp. 4725-4735, Nov. 2017, doi: 10.1007/s13369-017-2630-z.
- [38] K. Tamural and K. Yasuda, "Primary study of spiral dynamics inspired optimisation," *IEEE Transactions on Electrical and Electronic Engineering*, vol. 6, no. 1, pp. 98-100, 2011, doi: 10.1002/tee.20628.
- [39] M. R. Hashim and M. O. Tokhi, "Greedy spiral dynamic algorithm with application to controller design," *2016 IEEE Conference on Systems, Process and Control*, 2016, pp. 29-132, doi: 10.1109/SPC.2016.7920698.
- [40] N. M. A. Ghani, A. N. K. Nasir and M. O. Tokhi, "Optimization of fuzzy logic scaling parameters with spiral dynamic algorithm in controlling a stair climbing wheelchair: Ascending task," *19th International Conference on Methods and Models in Automation and Robotics*, 2014, pp. 776-781, doi: 10.1109/MMAR.2014.6957454.
- [41] N. A. A. Razali, N. M. Abdul Ghani, N. F. Jamin and M. F. Masrom, "Stability control of wheelchair system using interval type-2 fuzzy logic control," *2018 9th IEEE Control and System Graduate Research Colloquium (ICSGRC2018)*, 2018, doi: 10.1109/ICSGRC.2018.8657514.
- [42] O. Castillo, P. Melin, J. Kacprzyk and W. Pedrycz "Type-2 fuzzy logic: theory and applications," *IEEE International Conference on Granular Computing*, 2007, pp. 145-150, doi: 10.1109/GrC.2007.118.
- [43] M. H. Ri, J. Huang, S. Ri, H. Yun and C. Kim "Design of interval type-2 fuzzy logic controller for mobile wheeled inverted pendulum," *2016 12th World Congress on Intelligent Control and Automation (WCICA)*, 2016, pp. 535-540, doi: 10.1109/WCICA.2016.7578403.
- [44] H. A. Hagra, "A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots," in *IEEE Transactions on Fuzzy Systems*, vol. 12, no. 4, pp. 524-539, Aug. 2004, doi: 10.1109/TFUZZ.2004.832538.

- [45] J. Mendel, "Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions," *Upper Saddle River, NJ: Prentice-Hall*, 2001.

BIOGRAPHIES OF AUTHORS



N. A. A. Razali is currently a postgraduate student at Universiti Malaysia Pahang. She pursues study in Master of Science at Faculty of Electrical Engineering Technology and specialize in control engineering system field. Currently she is working on control system using fuzzy logic type-2 and optimization of fuzzy logic for two wheeled wheelchair system.



N. M. Abdul Ghani is an Associate Professor and currently serving at College of Engineering, Universiti Malaysia Pahang. She received her B.Eng. in 2003 and M.Eng. in 2006 from Universiti Teknologi Malaysia, and Ph.D. in 2015 from The University of Sheffield, United Kingdom. Her current research interests include Model and System Control, Control Parameter Optimization, Balancing Stability Control, Intelligent and Fuzzy Logic Control.



Bifta Sama Bari received her M.Sc. from Faculty of Electrical and Electronics Engineering Technology at the University Malaysia Pahang, Malaysia in 2020. She obtained her B.Sc. in Electrical and Electronic Engineering from Pabna University of Science and Technology, Bangladesh in 2016 by securing Top Merit Position (1st Position among 42 students). Her research interests include Brain-Computer Interface, Biomedical Signal Processing, Machine Learning, Microwave Imaging, and Wireless Communications. She is the recipient of a Graduate Research Scheme Scholarship from the University Malaysia Pahang, Malaysia.