

# Simulation and control of multipurpose wheelchair for disabled/elderly mobility

N.M. Abdul Ghani<sup>a,\*</sup> and M.O. Tokhi<sup>b</sup>

<sup>a</sup>*Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang, Pekan, Malaysia*

<sup>b</sup>*Department of Automatic Control and Systems Engineering, The University of Sheffield, Sheffield, UK*

**Abstract.** This paper presents investigations into the development of modelling and control strategies for a multipurpose wheelchair as mobile transporter for elderly and disabled people. The research is aimed at helping people with physical weakness/disabilities in their upper and lower extremities to move independently without human intervention. A novel reconfiguration which allows multi-task operations in the same wheelchair system with improved design is modelled in Visual Nastran 4D (VN4D) software. A modular fuzzy logic control mechanism with integrated phases is introduced for the overall operations and two-wheeled stabilization of the wheelchair. It is shown that the proposed modular fuzzy control approach is able to ensure system stability while performing multipurpose tasks such as manoeuvrability on flat surfaces, stairs climbing (ascending and descending), standing in the upright position on two wheels and transformation back to standard four wheels with up to 50% less initial torque in comparison to previous designs.

Keywords: Multipurpose wheelchair, stair climbing, sit-to-stand, stand-to-sit, modular fuzzy logic control

## 1. Introduction

The current worldwide trend in increased disabled and elderly population has challenged extensive designs and advancements in mobility transport as essential needs. This includes mobility devices such as wheelchairs, which vary in designs depending on their functionalities, from use in sports for Paralympics or other sportspersons to individual use for outdoor and indoor environments. It is vital to an individual who uses the wheelchair as the main self-mobility transport to move from one place to another independently. Currently, standard four-wheeled wheelchair designs have some limitations and cannot perform standard routine tasks, such as stair climbing, sit-to-stand and stand-to-sit operations.

A stair climbing wheelchair will allow the user to utilise the same assistive mobility equipment to ma-

noeuvre on stairs as well as on flat surfaces. There will be no need for an elevator or an assistant to perform stair climbing, and this will allow the wheelchair user to exercise independence. A significant amount of work has been reported in the literature on the development and control of stair-climbing wheelchairs. These include crawler type [25,27,39,41,42], wheeled type [24,33,37] and legged type [29] wheelchairs.

The crawler type wheelchair works well on an uneven terrain and provides a high terrain adaptivity. The first commercial wheelchair models were based on a single-section track mechanism capable of climbing up and down staircases [39,42]. The design of the overall stair climber mechanism needed more refinement so as to reduce its total weight. Moreover, crawler mechanisms have some drawbacks when stepping on the edge of the first step; the entire track is forced to rotate during climbing down a staircase [27].

Nakajima proposed a step-up gait called RT-Mover [29], which comprised a four-wheel-type mobile robot for upward step like a legged robot with simple leg mechanism. The robot can move like a wheeled robot on normal terrain and transform to legged mechanism

\*Corresponding author: N.M. Abdul Ghani, Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang, 26600 Pekan, Malaysia. Tel.: +60 609 4246087; Fax: +60 609 4246111; E-mail: normaniha@ump.edu.my

during climbing a step. The wheel is lifted like a leg while supporting the body on at least three points in order to remain level on a supporting polygon. However, due to limitation in the robot's leg height it can perform step climbing tasks only on step dimensions with stair riser heights of 0.1 m and long stair tread depths for each step. Moreover, this robot does not seem practical for use in places where there are more than two steps and if the stairs' slope is high.

A noteworthy commercialized iBOT wheelchair was introduced in the early 1990 s to perform balancing and mobility in two-wheeled configuration and in stair climbing tasks [21]. The system only relies on the changes of centre of gravity (COG) as input signal in order to move from one step to another. In order to achieve that, the user needs to tilt the back seat forward and backward while holding the stair handrail to perform ascending and descending on stairs respectively [12,13]. Thus, it requires strong hand muscle to hold the handrail and support the whole wheelchair system on the stairs. Moreover, it requires another person or assistance to tilt the back seat if the disabled/elderly person is unable to use her/his own hands.

Disabled people using wheelchairs are exposed to many health problems associated with being sedentary. These include physical and psychological effects due to prolonged seated posture [17]. Other effects include depression and loss of confidence, which often result from feelings of loss of control in certain situations. A study to examine how frequently healthy free-living adults perform sit-to-stand movement on daily basis has been conducted recently and the results show that the participants perform on average 60 ( $\pm$  22) movements each day [31].

Thus, there is a need for sit-to-stand mechanism so that the disabled users can boost their confidence level and gain the associated health benefits. For example, standing maintains leg muscles in reasonable physical condition, improves blood circulation, urinary health and bowel function, and reduces spasticity and pressure sores efficiently [30]. Many paraplegics utilise walker type and exoskeleton devices as assistive devices using robot technology. For example, braces and crutches have been widely used by people with spinal cord injury (SCI) to provide the opportunity to stand and move. A standing-up robotic supportive device has been used to raise the human from sitting to standing posture. The device is driven by an electrohydraulic servo system and supports the subject under the buttocks [23]. Authors in [20] integrated functional neu-

romuscular stimulation (FNS) with braces to activate sensory neurons in paralyzed muscles using electrical stimulation to control standing posture. However, the system needs an assistant to support the standing process and overall stability. Moreover, current designs of such devices have several limitations; they are bulky and hard to manoeuvre in narrow spaces, are heavy and require considerable user's physical effort, thus increasing fatigue [23,30].

A design enabling the wheelchair to transform from four wheeled to two wheeled mode in an upright position, lift the seat to a higher position, perform linear motion and allow transformation back from two-wheeled to four-wheeled mode has been reported in [4-7,21]. The two-wheeled wheelchair system uses the same concept as a double inverted pendulum, which is known to be unstable as it needs to take into account the whole weight of the system and the user [5,6]. Moreover, recently a novel two-wheeled configuration vehicle has been reported [8], which has shown promising stability features when balancing a payload with a movable payload actuator placed on the second pendulum link. The authors have used the two link inverted pendulum concept for lifting both the front wheels and stabilizing the overall wheelchair body on its rear wheels in the upright two-wheeled mode. However, the system does not have standing mode and associated motion capability. The humanoid that was used as load was rigidly attached to the seat throughout the operations without any changes to its dynamics. Moreover, the wheelchair produced initial high torque at the wheels and tilt motors (Link 1 and Link 2) to lift the overall mechanism to the two-wheeled upright position. This will produce large tilt angles at the beginning of the transformation process as the overall system will need to be tilted with such high power [4-7]. The comfort issue of the user is important in this case especially for a disabled/elderly person.

The current research focuses on development of a novel compact and light weight multipurpose wheelchair model and further on the implementation of modular fuzzy logic control (FLC) strategies to perform the corresponding multipurpose tasks. Intuitively, although all the classical control methods have shown promising results in performing two-wheeled stability function, there are nonlinearity and uncertainty issues that need to be considered. Although fuzzy logic has been used intensively in both single and double inverted pendulum systems [18,26,32,38,44,49,50], none has implemented the approach in stair climbing wheelchair with

the inverted pendulum concept. In order to cater for the inherent nonlinearity of the two wheeled system, an intelligent control approach based on fuzzy logic is investigated in this work [2,3,22,35,36,50–56]. This research embarks on the development of an automatic interchangeable phases control structure using a modular fuzzy logic (IPFL) approach to coordinate the overall operations and to ensure system stability and safety.

It is aimed to help people with disability/weakness in their lower extremities, so to enable them manoeuvre independently [41]. The wheelchair prototype presented in this work adopts a similar mechanism as the commercial iBOT and NOBOROT, and previous work [4–7] but with the addition of important properties such as capability to perform stair climbing (ascending and descending) and standing/sitting motions with reduced initial torque and reduced tilt angle within the same wheelchair system.

The rest of the paper is organized as follows: Section 2 introduces the wheelchair design in Visual Nastran software. Section 3 proposes the modular FLC strategy for multipurpose tasks. Section 4 presents simulation results on performance assessment of the proposed control algorithm. Section 5 concludes the paper.

## 2. Multipurpose wheelchair model

Mathematical modelling of the wheelchair configuration to achieve multi-tasking is quite complex. Several assumptions have to be made for purposes of simplicity when deriving the corresponding complex and nonlinear mathematical equations. Thus, some considerations and important features might be left out due to the linearization process of the mathematical model. A simplified version of mathematical model is not sufficient to investigate the whole system performance due to the complex nature of the multipurpose wheelchair system. Therefore, in order to preserve the nonlinear aspect, a new reconfigurable wheelchair and humanoid model are developed in Visual Nastran 4D (VN4D) environment which allows assembling 3D parts and combining all physical interactions in a computer aided design (CAD) model [28,45]. It gives performance characteristics close to that of the real system through finite element analysis (FEA); motion and collisions, vibration, friction and gravity effects. Moreover, it is equipped with controllable elements such as sensors and meters that can be linked to Simulink/Matlab for developing and evaluating designed controllers. The

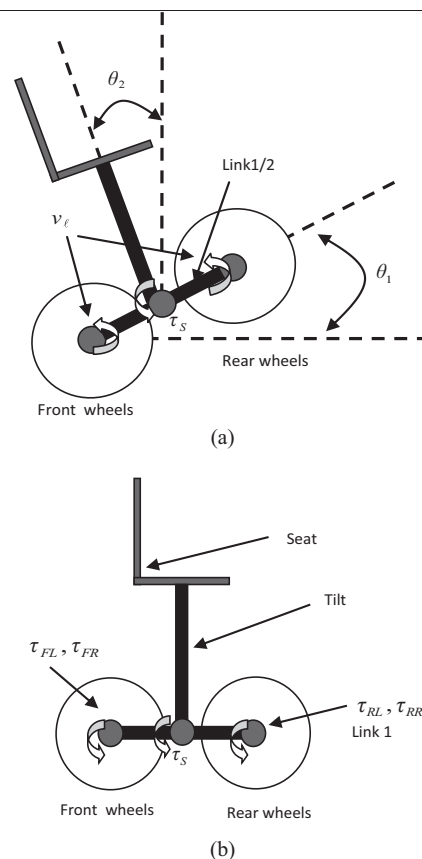


Fig. 1. Schematic diagram of a wheelchair in (a) standard mode (b) two-wheeled mode.

VN4D software is used as a simulation platform for testing the control action and the whole system simulation before it can be implemented in real hardware.

In this work, a cluster/link rotation mechanism is utilized with separate motors for the wheels and cluster/link control to perform multi-tasking work including stair climbing and sit-to-stand/stand-to-sit motions. Moreover, it allows for more degrees of freedom for the wheelchair system so that the wheels motors can be used to control the position, while the cluster/link motor to control the link rotation for the climbing operation.

### 2.1. Stair climbing

A detailed schematic diagram of the wheelchair mechanism is shown in Fig. 1 in two dimensions in standard four-wheeled mode. Note that each wheel is driven by a motor;  $\tau_{FL}, \tau_{FR}$  represent the torques due to left and right front wheel motors, and  $\tau_{RL}, \tau_{RR}$  are torques due to the left and right rear wheel motors

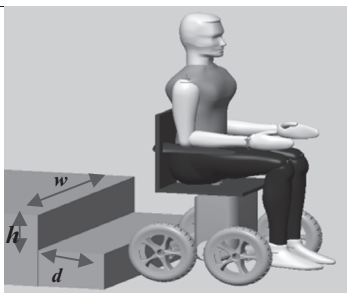


Fig. 2. Standard mode.

210 respectively. The climbing mechanism involves two  
 211 links, Link1 and Link 2, placed at the right and left  
 212 side of the wheelchair axle respectively. In order to  
 213 perform a climbing task, both links need to be rotated  
 214 by the link/cluster motor,  $v_\ell$ , using the link rotation  
 215 mechanism. The link/cluster motor,  $v_\ell$  is placed at both  
 216 left and right links for the link/cluster rotation, angle  
 217  $\theta_1$ , to perform the two-wheeled stabilization and  
 218 climbing tasks. In this research, a human model with  
 219 1.75 m height and 71 kg weight as an adult average  
 220 height/weight is used. However, the tolerance level of  
 221 the human's weight is  $\pm 10$  kg for the system around  
 222 the designed weight, and so the system will be able  
 223 to perform in a stable manner for up to 81 kg human  
 224 weight. The height and sex of the user would not cause  
 225 a problem as long as the weight is within the given  
 226 range. During this operation, the seat which carries a  
 227 humanoid with a weight of 71 kg might oscillate forward  
 228 and backward due to the cluster rotation of the  
 229 wheelchair. Thus, it is important that the seat is in the  
 230 upright position,  $\theta_2$  at all times with the seat torque,  $\tau_s$ .  
 231 In this design, the seat is attached to a revolute motor  
 232 for the control actuation.

233 The wheelchair parameters were taken from stan-  
 234 dard wheelchair dimensions [5,6], and the wheels di-  
 235 mensions were adopted from the iBOT mobility sys-  
 236 tem which conforms to the applicable requirements of  
 237 the ISO 7176-19: 2008 standard [46].

238 Figure 2 shows a straight stairway that was tested in  
 239 VN4D simulation where each flight of stairs continues  
 240 in the same direction as the previous flight. According  
 241 to codes of practice and standards, the recommended  
 242 range for a stair slope is from  $30^\circ$  to  $35^\circ$  due to its  
 243 preference by people. However, the maximum range is  
 244  $20^\circ$ – $50^\circ$ . A straight stairway which follows the Cana-  
 245 dian Centre for Occupational Safety and Health, 2010  
 246 recommendation [9] is tested in this work with a slope  
 247 of  $31.5^\circ$  and steps with height,  $h$  and width,  $w$  as illus-  
 248 trated in Fig. 2. The design adheres to standard dimen-  
 249 sions and structure to allow safe manoeuvrability and

Table 1

Dimension and specifications of the wheelchair and humanoid model

Item	Dimension (m)	Mass (kg)
Wheelchair body		
Wheel	$0.15 \times 0.07$	$1.50 \times 4$
Seat	$0.45 \times 0.43 \times 0.08$	0.20
Back rest	$0.02 \times 0.40 \times 0.45$	0.30
Front horizontal axis	$0.04 \times 0.55$	14.00
Back horizontal axis	$0.04 \times 0.55$	14.00
Base link	$0.38 \times 0.06 \times 0.04$	1.00
Left connecting rod	$0.34 \times 0.02 \times 0.01$	3.00
Right connecting rod	$0.34 \times 0.02 \times 0.01$	3.00
Left base joint	$0.05 \times 0.02$	1.00
Right base joint	$0.05 \times 0.02$	1.00
Vertical rod	$0.03 \times 0.45$	1.00
Battery	$0.38 \times 0.23 \times 0.32$	1.55

250 feasibility of the wheelchair system as it is inherently  
 251 hazardous. Two different tread sizes  $d$  were tested in  
 252 the simulations; 0.302 m and 0.407 m. These param-  
 253 eters were chosen because 0.302 m is the minimum stair  
 254 tread size that the wheelchair can climb as it is approxi-  
 255 mately equal to the wheel diameter. The stair tread size  
 256 of 0.402 m was tested for the purpose of comparison  
 257 with a different dimension following the ISO 7176-24:  
 258 2004 standard for requirements and test methods for  
 259 user-operated, stair-climbing devices [47]. There is no  
 260 maximum width,  $w$  of the stairs as the minimum is set  
 261 to 0.762 m to test the wheelchair in confined spaces.  
 262 The wheelchair is able to perform stair climbing with  
 263 the height,  $h$  of up to 0.302 m which is approximately  
 264 equal to the wheel diameter. The same limitation ap-  
 265 plies to the minimum stair's depth as studied in this  
 266 work. Details of masses of the wheelchair components  
 267 are given in Table 1. The humanoid was downloaded  
 268 from a web site in a Solidwork format [10] and recon-  
 269 figured in VN4D based on anthropometric data with  
 270 height,  $h_b$  and weight,  $w_b$  [48]. These segment prop-  
 271 erties serve as good approximations in the absence of  
 272 better data or directly measured data from the individ-  
 273 ual. Recent works using similar VN4D environment  
 274 for control system design purposes include [1,5,6].

## 2.2. Sit-to-stand and stand-to-sit

275  
 276 The wheelchair model in standing position is shown  
 277 in Fig. 3. This process requires a motor to provide rota-  
 278 tion to a certain angle and remain stable while the sys-  
 279 tem is in standing position (as used in previous task). A  
 280 linear actuator and two revolute motors are added and  
 281 introduced to fulfil the sit-to-stand transformation pro-  
 282 cess. The linear actuator allows the human's leg to be  
 283 placed on the leg rest while in the upright position, see  
 284 Fig. 4(c).

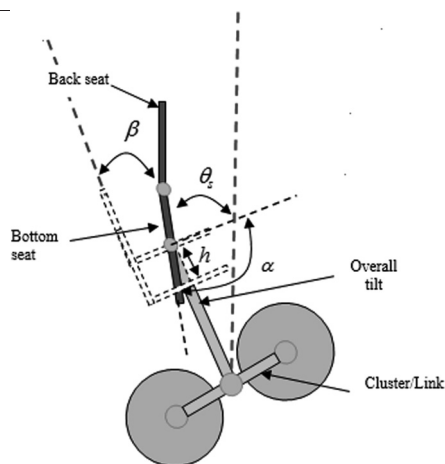


Fig. 3. Standing mechanism.

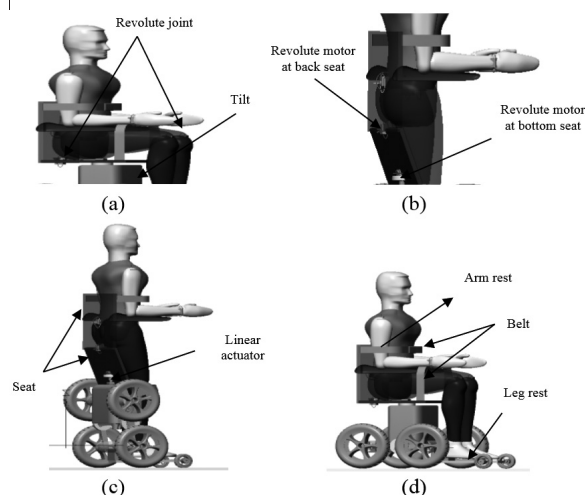


Fig. 4. Sit-to-stand and stand-to-sit.

Other revolute motors are added to the bottom seat and back seat of the wheelchair respectively as shown in Fig. 4(b). Revolute motors are placed at both bottom and back of the seat to allow the rotational operation to certain angles to realise the standing operation, in which case the back seat is kept at zero degree upright position.

In this work, the whole human body is not rigidly attached to the seat as it is made to be flexible to perform sit-to-stand and stand-to-sit motions. For this case, the lower part of human's body is connected to revolute joint that can rotate around the  $y$ -axis to allow the standing and sitting operations. The revolute joint is placed between trunk-thigh, and thigh-bottom leg for both left and right sides as shown in Fig. 4(a). This has increased the degree of freedom and the system

tends to be unstable while performing the sit-to-stand and stand-to-sit motions due to free movement at the bottom part of human's body.

However, the trunk is rigidly attached to the back seat in order to hold the whole body while the leg rest is provided to support the human's weight. The same rigid joint is applied to the rest of the human's body connection.

For purposes of safety, a belt and knee stop are inserted at the upper and lower back seat to hold the trunk and legs from collapsing forward during the transformation process. Both facilities provide straps around the abdomen and knee which can be clipped or unclipped by the user, see Fig. 4(d). An arm-support mechanism is attached to both sides of the back seat for full support of user's arm while performing a stand-up operation. Authors in [15] have suggested that applying strong arm-support may lead to better transition from sitting to standing and the transformation becomes more stable. A meter (sensor) is attached to the wheelchair seat in order to feed the measured signal back to the controller for the linear actuation motor. The reference height for the human to stand on the leg rest is approximately 0.51 m. The linear actuator is declared as the controller to produce the required control output to compensate for the height error. In this case, the control output signal is measured in velocity (m/s) and this will determine whether the actuator should increase or decrease its speed due to the input. The output of this linear actuator is seat height (m).

### 3. Interchangeable phase modular fuzzy logic control structure

Linear controllers such as PID or linear quadratic regulator (LQR) were not tested in this project as these have been considered in previous studies. The results have shown that fuzzy logic control outperforms PID and LQR in simulation [6] and hardware implementation [40]. A method of COG adjustment by the user input has previously been developed for stair climbing, in which the user or an assistant needs to adjust the COG of the wheelchair by leaning the wheelchair seat backward or forward depending on ascending or descending motion [12,13]. Moreover, in such a system, there is no stability assessment in ascending/descending stair operation as the user will need to hold the handrail/guardrail at all times or rely on an assistant to keep the wheelchair system on the stairs from slipping off. An automatic stair climbing opera-

tion for a wheelchair system provides extra advantages over such a method. In the current work, the transition from one step to another is done automatically using FLC. Therefore, an automatic mechanism using interchangeable phase modular fuzzy logic (IPFL) is designed to perform two tasks: ‘balancing and stabilizing’ and ‘front and rear’ wheels switching. A switching function is incorporated in the algorithm, which coordinates the switching between these two phases. Distance sensors are installed at both front and rear wheels to detect the required distance and this measurement is used for the switching.

The flow chart of switching operation is illustrated in Fig. 5(a) while Fig. 5(b) shows the specific coordination of both front and rear wheels motor torques,  $\tau_F$  and  $\tau_R$ . This operation needs an integration between ‘front and rear’ link motors and ‘front and rear’ wheels motors which are highly interconnected to each other. In this case, IPFL is introduced which involves ‘stabilizing and landing’ phases and ‘front and rear’ wheels motor switching action. The stabilizing phase involves transformation from standard four wheeled to two wheeled mode in the vertical position. Once the system is in two wheeled mode, it is able to perform linear motion task according to the stairs tread dimension before landing. Several switches are used at the supervisory level to coordinate the decision making process for the climbing task. Accordingly, each switch shown in Fig. 5(b) will permit only one input at a time (either from point 1 or point 3) to pass through to the output. In this case, it acts as a coordinator selecting the required phase and wheel as input to the wheelchair system. The decision is based on a threshold condition located at point 2; if the threshold condition is met, the signal from point 1 is activated, otherwise the input signal from point 3 will be activated. The parameters ‘ $i1a$ ’ and ‘ $i1b$ ’ are the input signals to the fuzzy logic controller block, where FLC1a and FLC1b are for stabilizing and landing phases respectively, depending on state of switch1. The output of switch1 is link velocity,  $v_\ell$  and acts as the control input signal to the system while the control output signal, angular position of link, is fed back to the system and establishes the state of switch1 at point 2.

A similar structure is used for the front and rear wheels motor switching operation, which involves FLC2a and FLC2b for control of the front and rear wheels respectively. The inputs to the fuzzy module block are a constant value of front wheels position, ‘ $i2a$ ’, and rear wheels position, ‘ $i2b$ ’, while  $x_1$  and  $x_2$  are feedback signals of these positions. The condition

at point 2 is defined by the distance  $d$  between respective wheels and stairs. Figure 5(b) shows detailed illustration of the specific ‘front and rear’ wheels motor switching coordination. It shows that there is a coupling effect between the distance of the wheels and the stairs for the front and rear side. This condition in this case is monitored by a supervisor to authorize the decision making process at Switch2\_i, Switch2\_ii, Switch2\_iii and Switch2\_iv which involves tight interconnections for the front and rear wheels torque switching action. There is no switching coordination for the seat motor torque,  $\tau_S$ , as the wheelchair system remains stable at constant vertical position, ‘ $i3$ ’ at all times throughout the overall climbing operation with  $\theta_2$  as the feedback tilt angle.

The modular strategy is chosen to segregate complex tasks and to simplify the overall process while maintaining stability of the wheelchair system. In conventional FLCs, the number of rules increases exponentially as the number of system variables increases [34]. Modular FLCs (MFLC) can be used to reduce the number of rules by dividing a global task into sub-tasks independently and coordinating the sub-controllers to achieve the global objective. The modules are relatively autonomous and may interact with each other. The modular system is decomposed into N-subsystems, located at the lower level. Each subsystem executes its own control law and communicates relevant information to the coordinator at the upper level [43]. The approach is selected here due to its ability to perform tasks in parallel for both stabilizing the two-wheeled system and maintaining wheelchair position. The operation of each fuzzy module is discussed in detail in the subsections below.

In the FLC, the inputs  $e$  and  $\Delta e$  with their respective gains are mapped onto a fuzzy inference to give a control output. Each module is designed with PD-fuzzy Mamdani type and consists of five membership function (MF) levels; Positive Big (PB), Positive Small (PS), Zero (Z), Negative Big (NB) and Negative Small (NS). The inputs and outputs used result in  $5 \times 5 = 25$  rules for each fuzzy controller with 25% overlap between the MFs. They are normalized at universe of discourse within the range  $[-1, +1]$ . Gaussian Bell-shape MFs are used and this function is chosen to give smooth and steady response to the system.

A hybrid of proportional and derivative gain is integrated with fuzzy controllers to form PD-fuzzy control as shown in Fig. 6. This combination is chosen because the proportional and derivative terms can minimize the rise time and the steady state error respec-

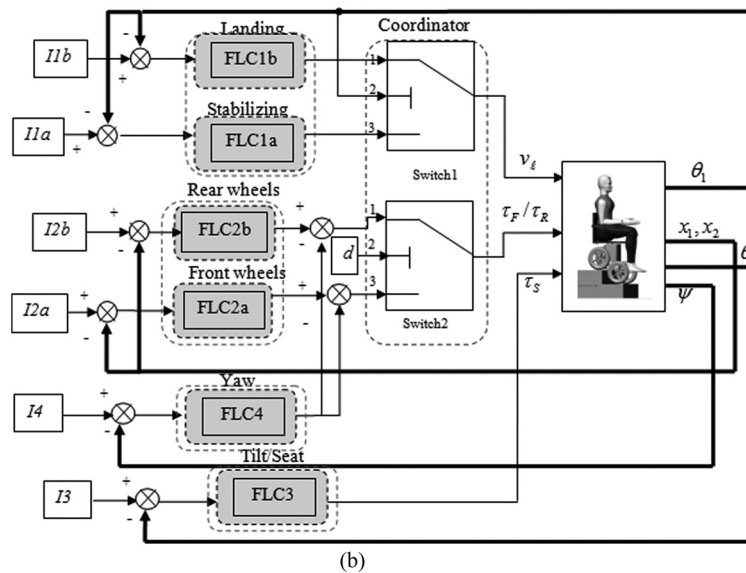
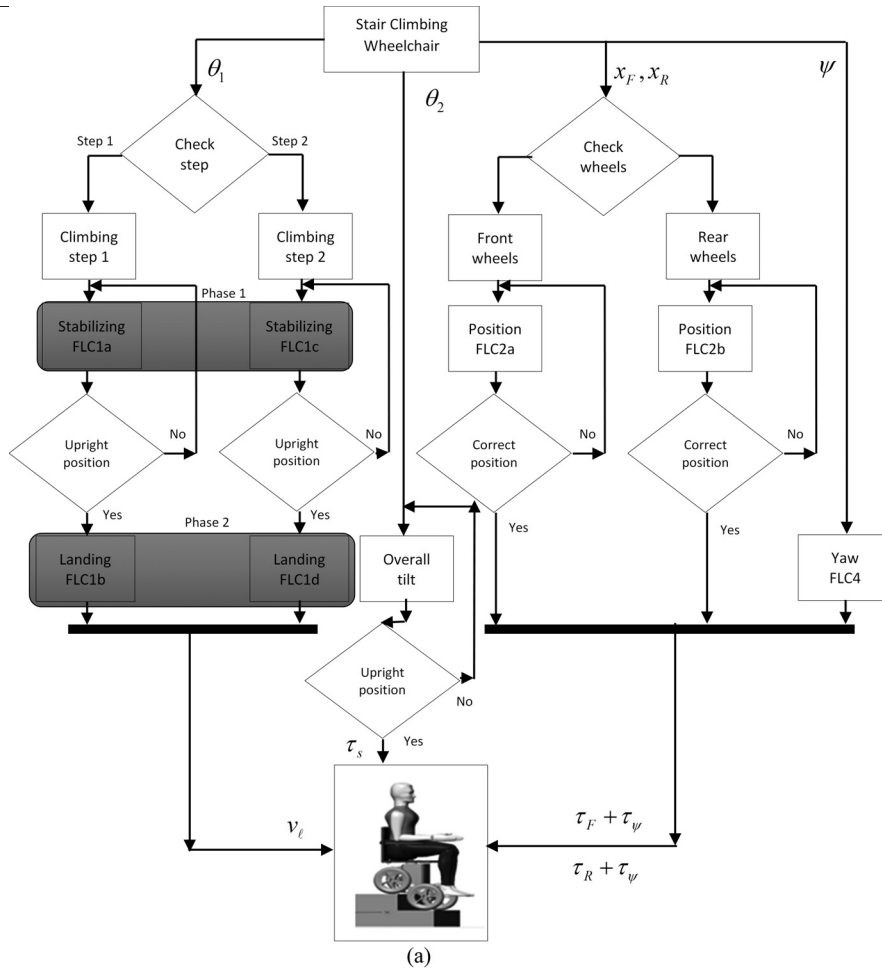


Fig. 5. Architecture of the modular fuzzy controller. (a) Flow chart of IPFL for  $\tau_F$  and  $\tau_R$ ; (b) Coordination of IPFL.

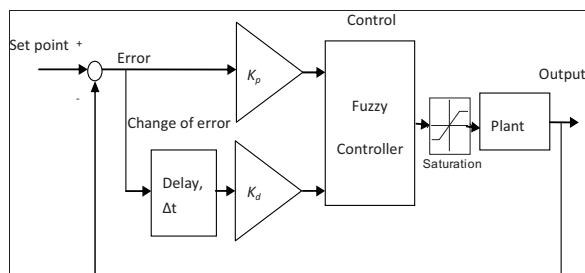


Fig. 6. Block diagram of a PD-fuzzy control system.

tively. A PD-Mamdani fuzzy controller is developed for this purpose to achieve steady and smooth system response. The main operation of the climbing process is initiated by lifting the link motor to the upright vertical (an inverted pendulum like) position while keeping the acting wheel motors at the same position as well as the tilt/seat stabilization to reach a certain angle,  $\theta$ . The control signals,  $\tau$  and  $v$  are defined as:

$$\tau_{or}v = k_p e + k_d \Delta e \quad (1)$$

where  $\tau$  or  $v$  represents the control output signal,  $k_p$  and  $k_d$  are the proportional and differential gains respectively for the fuzzy gain scaling factors,  $e$  is the input error and  $\Delta e$  is the change of input error. The scaling factor constraints are known as sensitivity factors to the controller. The scaling factors may be tuned with heuristic trial and error approach. However, such an approach is tedious and consumes significant time for achieving favourable, and yet not optimum, results. Thus to avoid such issues these parameters are tuned with spiral dynamic optimization algorithm (SDA) [16] in this work. SDA is a nature-inspired optimization algorithm, which uses a metaheuristic strategy [11] similar to those employed in computational intelligence optimization algorithms [19].

For each FLC block, the error,  $e$  and change of error,  $\Delta e$  with corresponding gains are mapped to fuzzy inference to provide a control output, as defined by the fuzzy relational formulation:

$$\tau_{or}v = ((e \wedge \Delta e)) \circ R \quad (2)$$

Numerous methods can be acquired through fuzzy relations with the fuzziness mapping represented by  $R$ . Expert knowledge is used to develop fuzzy rules to minimize the angular position error for Link and tilt, and position of front and rear wheels.

In this work, Mamdani inference is the best option to be utilised as information about the system is limited.

Table 2  
Fuzzy Rules for link,  $v_L$ , wheels,  $\tau_{F/R}$  and seat motors,  $\tau_S$ 

$\Delta E$	NB	NS	Z	PS	PB
E	Group 2				Group 3
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
	Group 4				Group 1
	Group 5				

Sugeno type may be used if there is extensive system data and information available [14].

Mamdani type is thus utilized in all fuzzy controllers for the wheelchair in this work. Moreover, it is easy to understand by human expert and the rules are simple to formulate. The form of Mamdani type inference used is as follows:

If  $x$  is  $A$  and  $y$  is  $B$  then  $z$  is  $C$

The inputs are determined by  $A$  and  $B$  and the output for each linguistic variable set is indicated by  $C$ . Fuzzy values are obtained through fuzzification of the crisp values, and a defuzzification phase is realized for the fuzzy control output to achieve crisp control signal for application to the plant.

The fuzzy rules are developed based on expert knowledge to minimise the error and change of error of each input variable. All modules use the same fuzzy rule base and the fuzzy rules are shown in Table 2 [31]. There is a specific way to develop fuzzy rules set according to the system behaviour and desired performance. At first, the rules are viewed based on the most extreme situation as can be seen in Table 2. In general, if the error and the change of error are both positive big (PB), the control action must produce negative big (NB) signal in order to bring the output back to the reference set point as in Group 1. Similarly, the same amount of negative control action should be applied for the region within Group 1. On the contrary, if both the error and change of error are negative big (NB), positive big (PB) signal should be generated by the controller to ensure that the output is close to the set point. The same positive signal is produced for the



516 region in Group 2. For the other two extreme points, if  
 517 the error is positive big (PB) and the change of error is  
 518 negative big (NB) or vice versa, zero (Z) control signal  
 519 should be applied to the system because the system has  
 520 reached a steady-state condition. The same amount of  
 521 control signal is applied within the region in Group 3.  
 522 Group 4 and Group 5 show that small amount of con-  
 523 trol action is needed to compensate for the errors. As  
 524 the system performance varies, and this is problem de-  
 525 pendent, the control signal is not necessarily fixed as  
 526 discussed here. However, most control problems fol-  
 527 low the standard rules and similar pattern as shown in  
 528 Table 2 for the wheelchair system in this work.

529 The inputs used for the respective controllers are de-  
 530 fined as follows: FLC1a and FLC1b take two inputs,  
 531 which are angular position error of link,  $e_{\theta_1}$  and change  
 532 in angular position error of link/cluster  $\Delta e_{\theta_1}$  respec-  
 533 tively. The output is link velocity,  $v_\ell$  within the uni-  
 534 verse of discourse. Similarly, FLC2a and FLC2b have  
 535 input and output fuzzy relationship but in terms of po-  
 536 sition error and change in position error of front and  
 537 rear wheels,  $e_{x_1/x_2}$  and  $\Delta e_{x_1/x_2}$  while the fuzzy output  
 538 is front and rear wheel torques,  $\tau_F$  and  $\tau_R$ . Error in an-  
 539 gular position of tilt  $e_{\theta_2}$  and change in angular position  
 540 error of tilt,  $\Delta e_{\theta_2}$  are the fuzzy input for FLC3 for the  
 541 seat torque,  $\tau_S$ . The yaw error,  $e_\psi$  and change of yaw  
 542 error,  $\Delta e_\psi$  are the fuzzy inputs to FLC4 for yaw torque  
 543 compensation,  $\tau_\psi$ .

### 544 3.1. Stair ascending

545 In order to perform stair climbing operation, link  
 546 motor,  $v_\ell$  will rotate a link to the upright vertical po-  
 547 sition while the front wheel torque,  $\tau_F$  keeps the left  
 548 and right wheels in the same position. This is called  
 549 stabilization phase where the link is stabilised at the  
 550 upright position before continuing to the landing phase  
 551 depending on the stair tread depth. This stabilization  
 552 phase is designed to allow the wheelchair transforma-  
 553 tion from climbing mode to linear mode on the stairs.  
 554 This will permit testing of variations of stairs' tread  
 555 size for the climbing task and will allow the wheelchair  
 556 to move in two-wheeled mode on the stairs. Once the  
 557 rear wheels have landed on the next step, the rear  
 558 wheel's torque,  $\tau_R$  is activated and the front wheel's  
 559 torque,  $\tau_F$  is deactivated to ensure that the rear wheels  
 560 are maintained at the same position on the stairs to  
 561 prevent slipping. The link will repeat the stabilization  
 562 phase and landing phase again and so forth for climb-  
 563 ing operation to subsequent steps. It is found that both  
 564 controllers (FLC1 and FLC2) need more specific tasks

565 especially when switching from 'front to rear wheels  
 566 torque' phases and from 'stabilizing to landing' phases  
 567 and vice versa to perform stair climbing operation.  
 568 This is due to the fact that all torques have specific  
 569 tasks to ensure the stability of the system while uphold-  
 570 ing large payload mass (approximately 100 kg includ-  
 571 ing human and wheelchair mass) on the stairs. This  
 572 task is repeated automatically with the other motor,  
 573  $\tau_F$  or  $\tau_R$ , to climb the next step and this process is  
 574 characterized as a phase interchangeable mechanism:  
 575 'front and rear wheel' phases and 'stabilization and  
 576 landing' phases. The two phases are interconnected to  
 577 each other and require a complex control structure to  
 578 supervise and coordinate the whole process.

579 A fuzzy controller block is added with sub mod-  
 580 ules, FLC1a and FLC1b to each stabilizing and land-  
 581 ing phase module. Similar control structure is used for  
 582 executing the front and rear wheel's torque but with  
 583 additional task of linear motion and yaw angle con-  
 584 trol capability. The only difference is that the switching  
 585 condition is based on the distance  $d$  between wheels  
 586 and stairs, and yaw control is added with the front or  
 587 rear wheel's torque via FLC4 block. The front and rear  
 588 wheel's torque allows the wheelchair to perform a lin-  
 589 ear motion in its two wheeled mode without any yaw  
 590 movement on the stairs. Once it has reached the second  
 591 step, the landing phase is activated in order to place  
 592 the other pair of wheels on the stairs. The torque is  
 593 switched accordingly and the set point inputs are rep-  
 594 resented by 'I2a' and 'I2b' for the front wheels phase  
 595 and rear wheels phase respectively.

596 The stabilization of the whole system is realised  
 597 with tilt/seat torque,  $\tau_S$ . The whole wheelchair sys-  
 598 tem including humanoid is stabilized through FLC3  
 599 module via a constant I3 throughout the stair climb-  
 600 ing operation. The FLC3 controls the wheelchair seat  
 601 to be levelled and is always active without the involv-  
 602 ment of any switching action. The IPFL control struc-  
 603 ture has been designed and implemented for different  
 604 situations. The main advantage of this design is that  
 605 each module uses the same fuzzy rule to perform dif-  
 606 ferent control actions. Hence, only one FLC was de-  
 607 signed and applied to achieve three different objec-  
 608 tives, climbing, controlling the wheels position and the  
 609 tilt angle.

### 610 3.2. Safety precaution

611 It is vital that the control structure is added with  
 612 safety elements so as to account for the case of con-  
 613 trol failure due to any uncertainties or hard disturbance

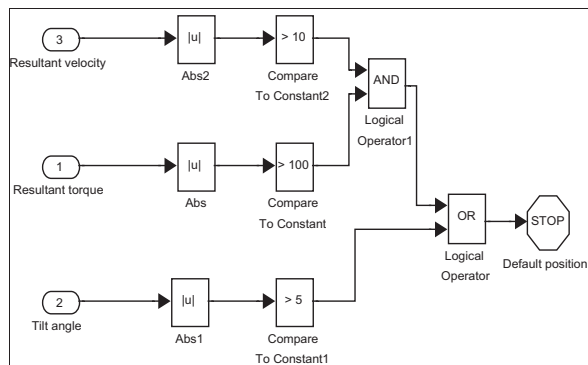


Fig. 7. Additional element for system safety.

force applied to the wheelchair system. It has been determined through tests that the system will become unstable if the torque and velocity are more than  $\pm 100$  Nm and  $\pm 10$  deg/s respectively. The tilt angle of the system must be within  $\pm 5$  deg to make sure that the user stays within safe and stable region, almost upright position at all times. If the control signals are higher than certain amount of limits, the wheelchair system will stop automatically and transform to the default four-wheeled mode. The safety mechanism is shown in Fig. 7.

### 3.3. Stair descending

It is known that performing a descending operation is more challenging than ascending operation because there is no block/step at the front of the wheelchair to prevent the system from collapsing. Due to this situation, the wheels tend to roll forward and may slip off the stairs causing instability and thus making the system harder to control. In order to adapt to different system dynamics and descending motion, different set points and angular positions,  $\theta_1$  are used. The main control structure for climbing down the stairs is similar to the climbing up task in automatic mode as mentioned earlier in the ascending task.

### 3.4. Sit-to-stand and stand-to-sit

A block diagram of the modular design is shown in Fig. 8 with integration between Simulink and VN4D and coordinated by switching elements. There are five modules to operate both sit-to-stand and stand-to-sit tasks, namely link/cluster lifting, height extension, back seat rotation, bottom seat rotation and overall tilt. A hybrid PD-Mamdani fuzzy controller is developed to perform smooth standing and sitting opera-

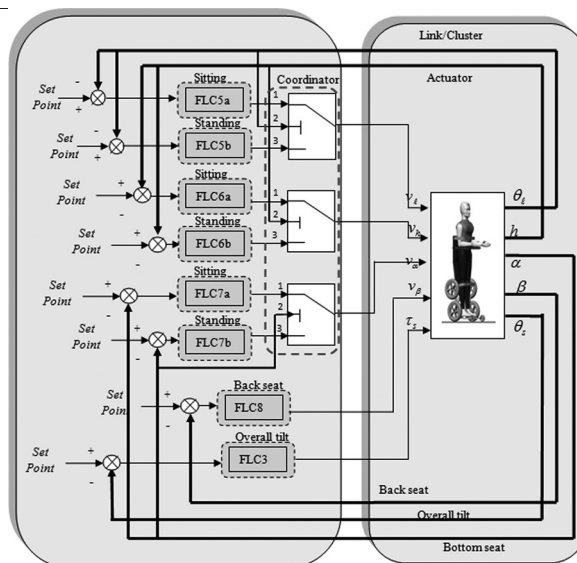


Fig. 8. Simulink/Matlab and VN4D integration.

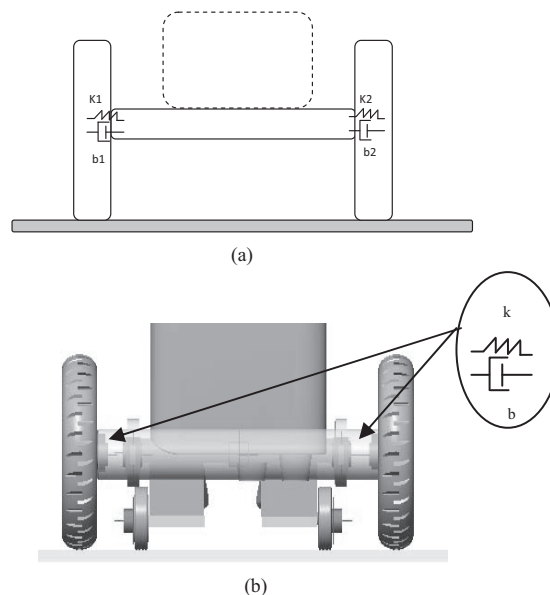


Fig. 9. Spring/Damping elements.

tions. The input for each modules is given in terms of set points. The set points for link/cluster lifting, height extension, back seat rotation, bottom seat rotation and overall tilt modules are  $\theta_l$ ,  $h$ ,  $\beta$ ,  $\alpha$  and  $\theta_s$  respectively. These modules use fuzzy operation as indicated in the blocks; FLC5a, FLC6a and FLC7a for sit-to-stand task while blocks FLC5b, FLC 6b and FLC7b for stand-to-sit operation. Both tasks use the same FLC3 and FLC8 modules for back seat and overall tilt stabilization.

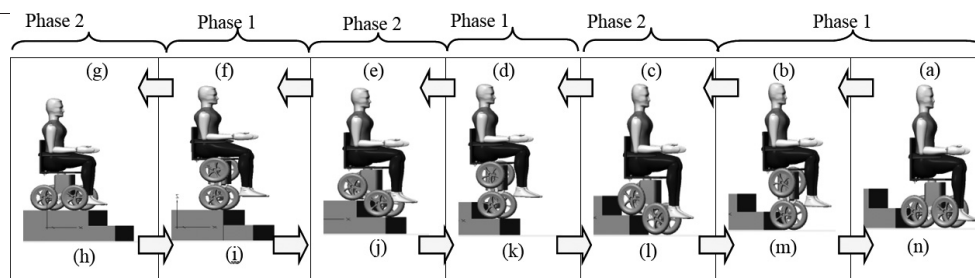


Fig. 10. Ascending and descending stairs motion.

Wheelchair with active suspension control can prevent traumatic shocks and vibration to the rider caused due to prolonged driving on rough outdoor surfaces, bumps and curbs. The rider can experience mental fatigue caused by the trauma which can worsen their health condition. By installing a suspension system, these problems can be alleviated and a highly comfortable ride achieved.

In this work, it is crucial to ensure smooth and good floor contact while performing stand-to-sit operation, referred to as back transformation. This is due to the system needing to support heavy load of the user and the mass of both rear wheels. The respective wheels may hit the ground with large impact in the absence of an appropriate mechanism. For this reason, all four wheels of the wheelchair system are independently mounted with revolute spring/damping element. This makes it easier to negotiate high impact and smoothen the back transformation process while maintaining good floor contact with the wheels. Figure 9 shows the location of revolute spring/damper as seen from the front view. The values of spring and damper constants used were  $k_1 = k_2 = 0.01$  Nm/deg and  $b_1 = b_2 = 0.000914$  Nms/deg respectively [4]. The damping elements are placed at both left and right side of the wheels with the same coefficient values.

## 4. Simulation and performance analysis

### 4.1. Stair climbing

The climbing operation was tested with two different stair depths,  $d = 0.302$  m and  $d = 0.407$  m. Figure 10 shows visual images of the wheelchair performance while ascending Figs 10(a)–(g) and descending Figs 10(h)–(n) in VN4D. Both phases are repeated to ensure the stair climbing operation is done in sequence. The third, fourth and n-th steps will copy the same procedure as climbing the second step (not shown). Note

that the wheelchair system climbs backwards up the stairs, with the user facing downstairs, and descends forward down the stairs with the user also facing downstairs as described in the ISO 7176-24: 2004 standard [9].

#### 4.1.1. Stair ascending

Figures 11(a) and (b) illustrate simulation of the stair climbing performance according to the motion in Fig. 10 for both stair depths. It is noted that it took approximately 1.7 s and up to 4.5 s to complete the first and second steps respectively for the wheelchair to perform the stair climbing task for stair depth  $d = 0.302$  m. The final step was completed in less than 3 s, and thus it took the wheelchair approximately 7.3 s to reach the upper flat surface, as in Fig. 10(g). During climbing the first step, both the front motor torques are active while the rear are not active and vice versa as illustrated in Fig. 11(b). Note that the tilt/seat angle was able to stay at the upright position at all the times with seat motor torque  $\tau_s$ . For  $d = 0.407$  m, the system performed slower as there was a linear motion (red region) of the wheelchair on the second step as seen for both links during 2<sup>nd</sup> step in Fig. 11(a). Both links remained at the same position while performing this linear task for almost 1 s, from 3.8 s to 4.8 s. The front and rear wheels (acting wheels) showed a travelled distance,  $T_d$  of approximately 0.3 m during the linear motion (red region) process. The corresponding control efforts are shown in Fig. 11(b).

It is worth mentioning that the tilt angle was larger in previous work [5,6] at the initial stage; this was  $-25^\circ$  at Link 2, as compared to this new wheelchair configuration with only  $-3^\circ$  for the initial tilt angular position. Moreover, the initial energies consumed by the cluster and tilt motors were much lower than previous wheelchair design [5,6], and this has reduced by approximately 82% (from 110 Nm to 20 Nm) for the wheel's torque and 69% (from  $-160$  Nm to  $-50$  Nm) for the tilt motor torque in order to bring the wheelchair mechanism to the upright position.

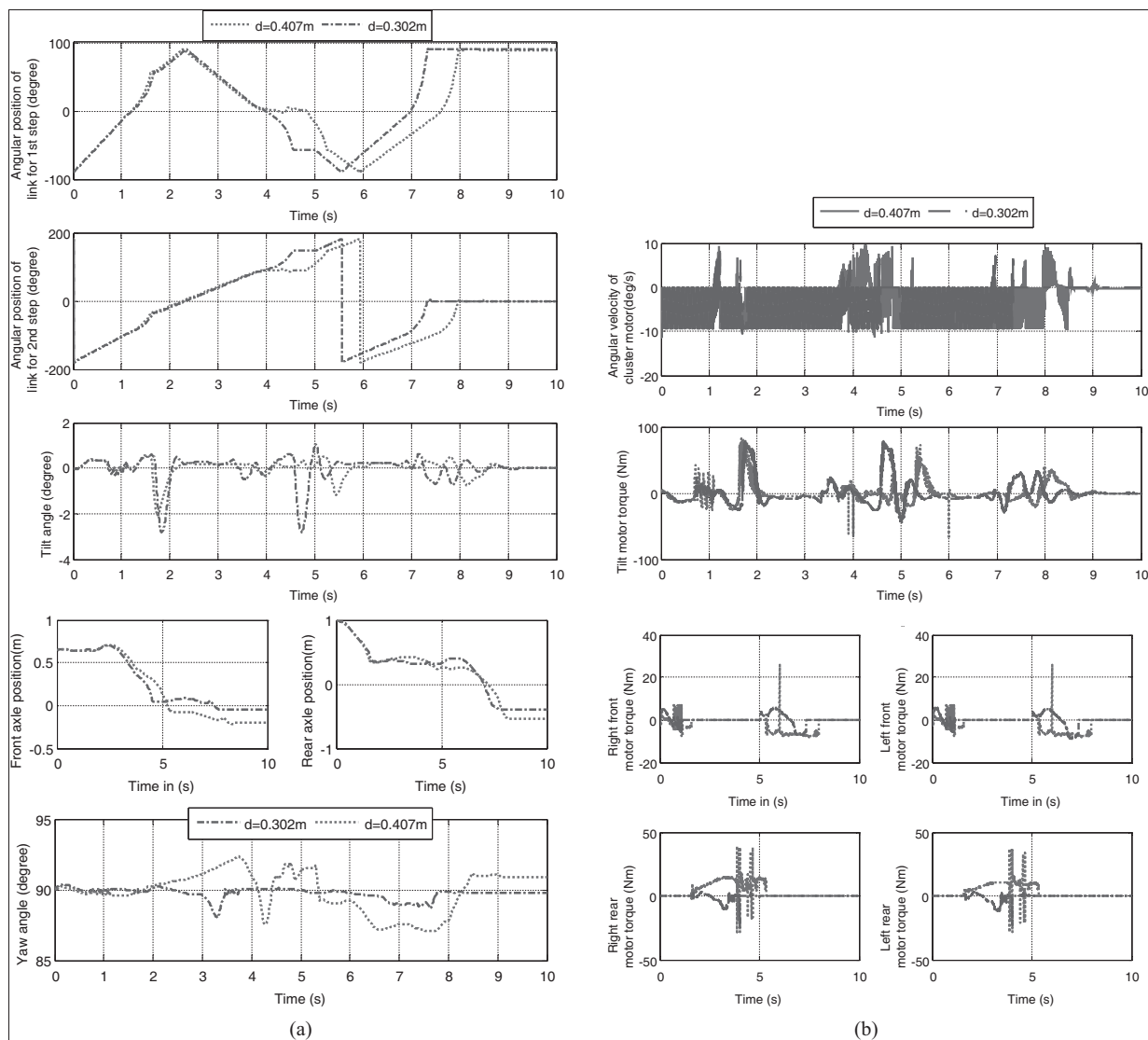


Fig. 11. (a) System performance for  $d = 0.302$  m; (b) Control input signals for  $d = 0.302$  m.

#### 4.1.2. Stair descending

Contrary to ascending task, the transformation process involves stabilization in two wheeled mode via backward motion while forward stabilization is used in the descending operation as in Fig. 10(h)–(n). This is because the user/human needs to be at the same position as in ascending the stairs. Next, the system executes a landing phase to place the rear wheels to the next step from vertical position. Once the rear wheels are placed on the next step and the required distance is achieved, the operation is switched to the rear wheels motor control through ‘front and rear wheel’ switching phase.

For the descending task, similar test was conducted

on different stair tread depths,  $d = 0.302$  m and  $d = 0.407$  m as in the ascending task. The switching phases from Phase 1 (Stabilizing) to Phase 2 (Landing) can be seen clearly in this simulation and the performances are shown in Fig. 12. The performance is assessed with yaw and without yaw control on the respective wheels motor, due to the turning motion of wheels while in the descending operation. The steering motion will affect the system not to perform the descending task in straight-line manner and cause the wheels to turn either right or left, and this may cause the system to slip off the staircase and collapse.

As can be noticed in Fig. 12, the system was able to perform the descending task smoothly in a stable man-

732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745

746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759

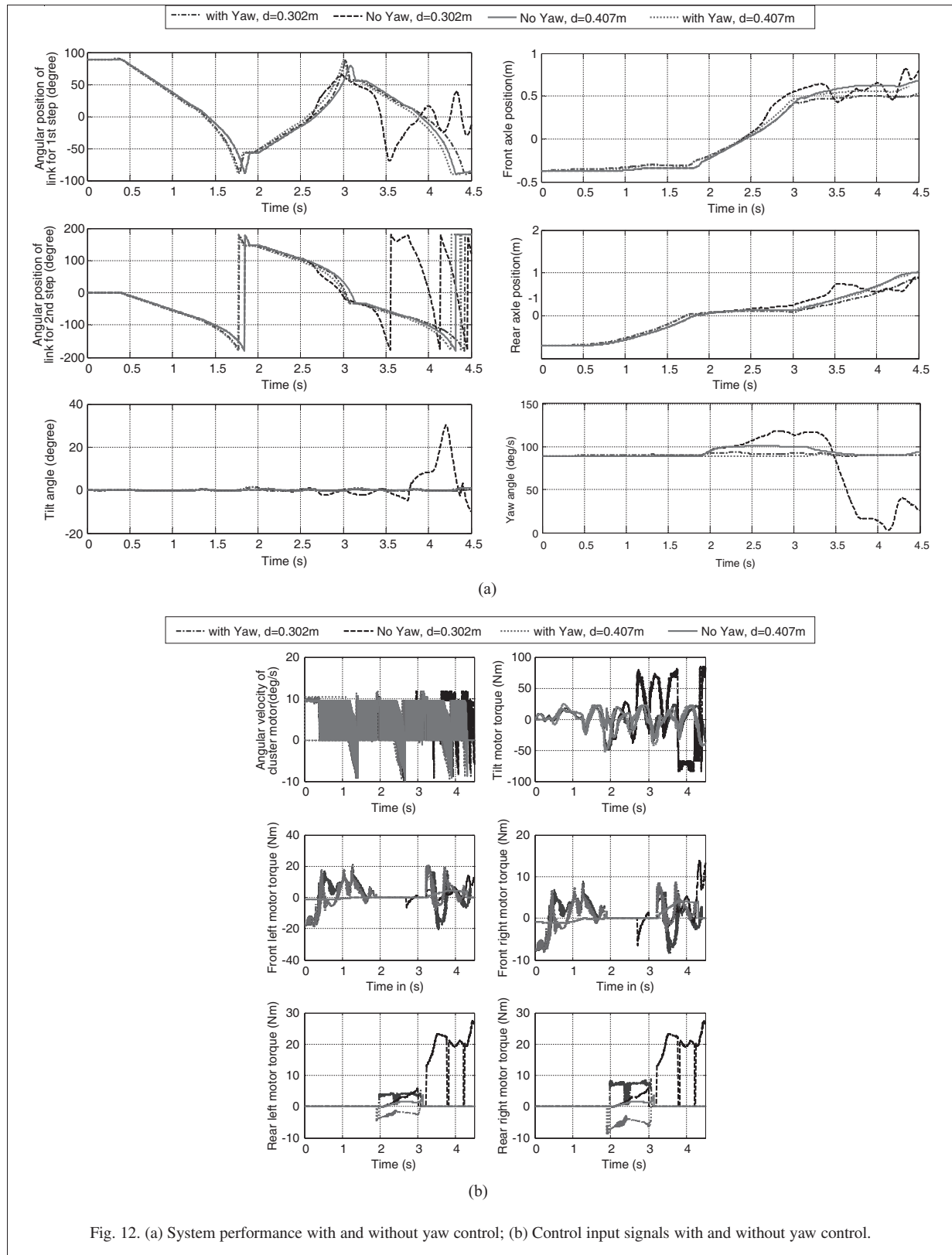


Fig. 12. (a) System performance with and without yaw control; (b) Control input signals with and without yaw control.

ner with yaw control for both stair-tread depths. It is noted that the system performed better and was able to maintain the wheelchair straight without slipping and collapsing. The wheelchair on stair-tread depth,  $d = 0.407$  m also performed in similar manner in terms of the links angular position, tilt angle, respective wheels positions and yaw motion. As noted both wheels stayed on the stair during corresponding tasks as they moved within acceptable displacement while yaw and tilt angle resulted significant changes when climbing the second step but still in a stable manner.

It is obvious that the wheelchair system collapsed and became unstable after 3 s when tested with the stair-tread depth of  $d = 0.302$  m without yaw control. This is due to the limited step space for the respective wheels to move and support the whole wheelchair system to perform the descending motion. It is also noticed that from two to three seconds, the yaw error was high for the system without yaw angle control on stairs tread depth of 0.407 m with approximately  $10^\circ$  difference. The rear wheels motor was activated during this period to compensate for the error, thus producing negative motor torques to the rear wheels motor. As a result, the tilt angle for the seat was smaller for the system without yaw control as compared to the system with yaw control,  $\pm 0.5^\circ$  and  $\pm 1.5^\circ$  respectively. It is noted that it took the wheelchair approximately 1.8 s and up to 3 s to complete the first and second step manoeuvres respectively. The final step manoeuvre was completed in less than 1.5 s, which was up to 4.3 s to reach on the lower flat surface according to Fig. 10(n). Both yaw and tilt angles exhibited large changes while the front and rear wheels were less affected when climbing the second and final steps for stair-tread size  $d = 0.302$  m.

#### 4.2. Sit-to-stand and stand-to-sit

A displacement point of 4 m was tested to complete the linear motion task once the human was in fully standing mode in the upright position. The performance was assessed with two approaches; with spring/damper and without spring/damper mechanism. Note that the wheelchair started to travel in linear forward motion to 4 m once it had reached vertical standing position at approximately 2 s after performing sit-to-stand operation. It took less than 4 s to travel to the set point and stayed until 7 s. It is also noted that both back seat and overall tilt angles were kept at zero degrees although the tilt angle produced was slightly higher in magnitude. This is due to the fact that the

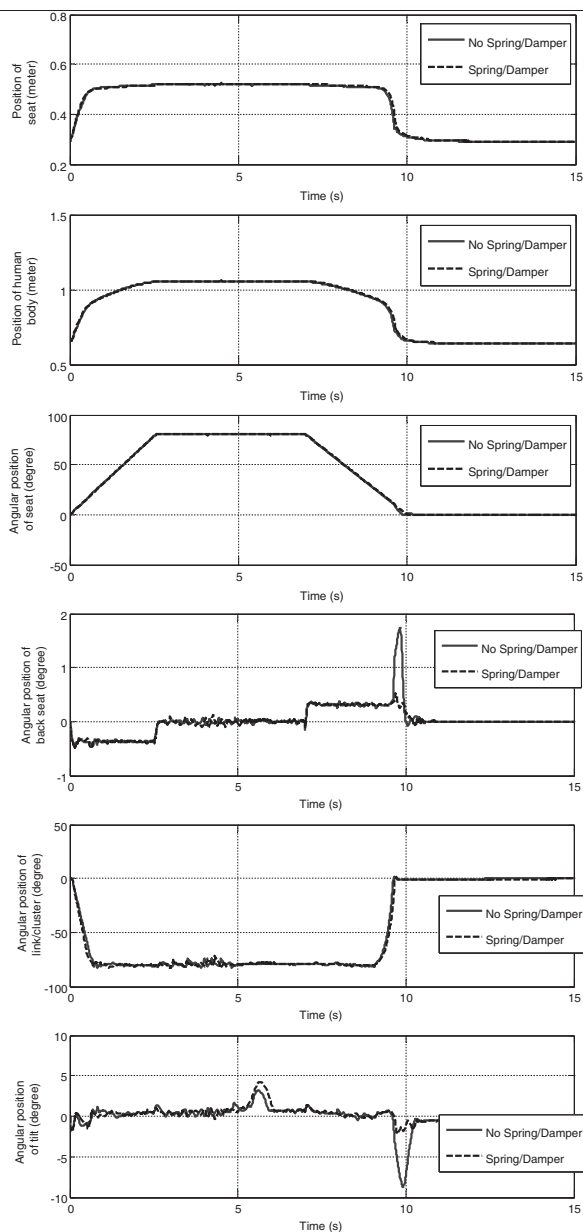


Fig. 13. System performances.

wheelchair was about to stop at 4 m and counteracted the forward motion by giving opposite torque to the wheels.

For sit-to-stand, both approaches showed similar performances. It is noted that it took less than 1 s for the cluster/link to lift the wheelchair to the upright position,  $-80^\circ$  and approximately 2.5 s to complete the transformation process and reach the standing position. The seat angle was fully unfolded at  $80^\circ$  and lifted to 0.51 m height. During these operations, the tilt/seat an-

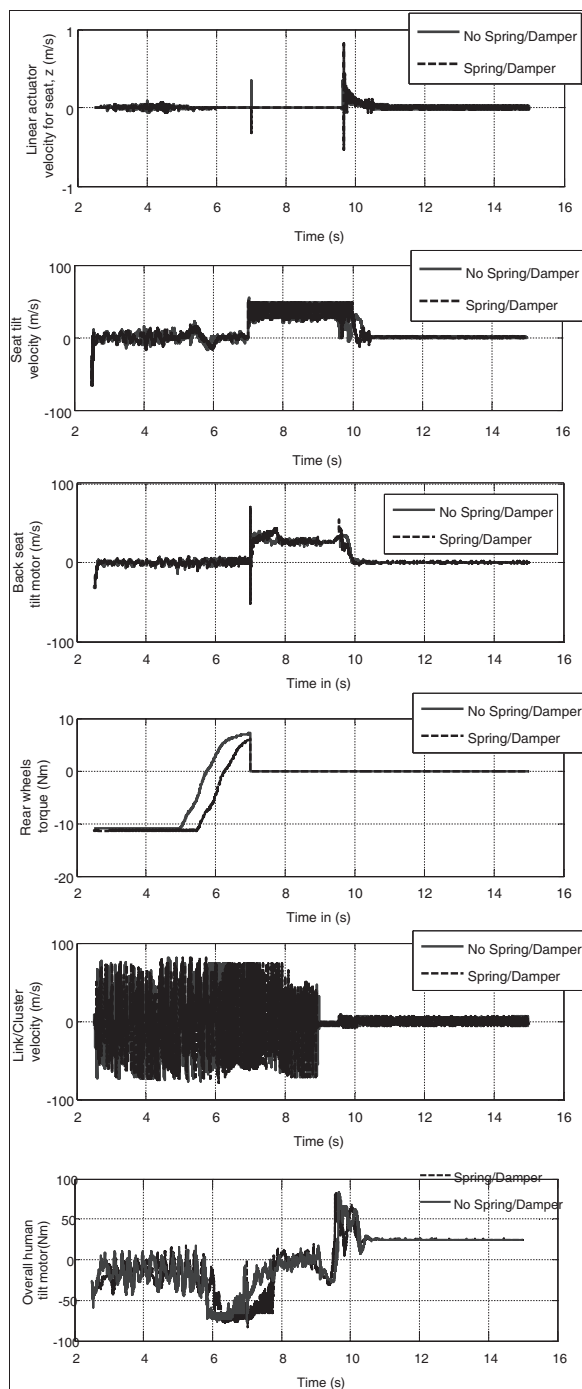


Fig. 14. Control efforts.

was activated and transformed the wheelchair from two-wheeled to four-wheeled mode (as shown in the graph).

The stand-to-sit operation took 3 s to bring the respective wheels on the ground in a stable manner even though there was a big change in the tilt angular position during the landing process. Similar performance was noted with the back seat motion; reached up to  $1^\circ$  for the system without spring/damper mechanism. However, both tilt and back seat angles were significantly reduced by more than 50% as compared to the system without spring/damper mechanism. The corresponding control velocity and torque are shown in Fig. 14. Note that there was an impulse as indicated at 7 s at which the back transformation process occurred.

It is noted that both angular position of back seat and tilt were quite high without spring/damper mechanism due to fast landing operation. However, the force exerted by the pair of spring/damper mechanisms characterized by  $k1$ ,  $b1$  and  $k2$ ,  $b2$  were reduced. The passive control approach used for the transformation process showed the significant ability of the approach to suppress high ground impact and ensure user's comfort. The results presented have shown that the developed wheelchair model is able to perform multiple tasks: stair climbing (ascending/descending) and sit-to-stand/stand-to-sit operations with a humanoid model of 71 kg weight in a stable manner with reduced initial torque and reduced tilt angle.

## 5. Conclusion

A new reconfigurable wheelchair using link/cluster rotation with compact design has been developed in VN4D environment. The introduced system is intended for use in small and confined indoor spaces for disabled and elderly mobility to enable them perform daily life activities independently. An interchangeable phase modular fuzzy logic control mechanism has been proposed and successfully implemented with the wheelchair system to perform two tasks: 'balancing and stabilizing' and 'front and rear' wheels switching. The same wheelchair system is also able to perform stair climbing and sit-to-stand/stand-to-sit tasks. The stabilizing mechanism in a two-wheeled position has been utilised for the sit-to-stand transformation for saving space. A chair height extension mechanism and several revolute motors have been added to accomplish the standing motion in vertical straight position. A passive suspension system has been developed and incor-

819 gle stayed at the upright position at all times with only  
820  $-0.5^\circ$  in magnitude for the maximum seat's tilt angle  
821 as shown in Fig. 13. After 5 s, the wheelchair performed  
822 the back transformation task which started to fold the seat  
823 at  $0^\circ$ . Once it reached  $25^\circ$ , the link/cluster

872 porated into the wheelchair by adding spring/damping  
873 element at each wheel to provide a comfortable ride  
874 to the user especially during landing in the stand-to-  
875 sit process. It has been demonstrated that the system  
876 performs well with damping mechanism; more than  
877 70% and 38% reduction for the 4 m and 5 m travel  
878 distances respectively in tilt and back seat angles have  
879 been achieved. It has been demonstrated that, the cur-  
880 rent wheelchair configuration produces low initial tilt  
881 angle and low overall tilt torque; approximately more  
882 than 50% reduction as compared to previous design,  
883 for transformation to the upright two-wheeled mode.

884 This work has carried out a first phase of the project  
885 study in simulations on modelling and control of a  
886 multipurpose wheelchair for disabled/elderly with re-  
887 duced initial torque and reduced tilt angle. A range  
888 of standard daily life activities have been tested using  
889 the wheelchair system to validate the developed con-  
890 trol approach. The results achieved are convincing and  
891 thus suitable for real hardware implementation. Further  
892 work will look at robustness of the control mechanism  
893 with humans of greater weight, and realisation of the  
894 proposed design and control approach.

## 895 References

- 896 [1] S.C. Abdulla, O. Sayidmarie and M.O. Tokhi, Functional  
897 electrical stimulation-based cycling assisted by flywheel and  
898 electrical clutch mechanism: A feasibility simulation study,  
899 *Robotics and Autonomous Systems* **61** (2013), 443–472.
- 900 [2] H. Adeli and S.L. Hung, *Machine Learning – Neural Net-*  
901 *works, Genetic Algorithms and Fuzzy Systems*, John Wiley  
902 and Sons, New York, 1995.
- 903 [3] H. Adeli and K. Sarma, *Cost Optimization of Structures –*  
904 *Fuzzy Logic, Genetic Algorithms and Parallel Computing*,  
905 John Wiley and Sons, West Sussex, United Kingdom, 2006.
- 906 [4] S. Ahmad, M.O. Tokhi and N.H. Siddique, Modular fuzzy  
907 control with input shaping technique for transformation of  
908 two-wheeled wheelchair to four-wheeled mode, *Proceeding*  
909 *of IEEE Industrial Electronics and Applications (ISIEA)*,  
910 (2010), 562–566.
- 911 [5] S. Ahmad, N.H. Siddique and M.O. Tokhi, A modular fuzzy  
912 control approach for two-wheeled wheelchair, *Journal of In-*  
913 *telligent Robotic System* (2011), 401–426.
- 914 [6] S. Ahmad, N.H. Siddique and M.O. Tokhi, Modelling  
915 and simulation of double-link scenario in a two-wheeled  
916 wheelchair, *Integrated Computer Aided Engineering* **21**  
917 (2014), 119–132.
- 918 [7] S. Ahmad and M.O. Tokhi, Forward and backward motion  
919 control of wheelchair on two wheels, *Proceeding of IEEE*  
920 *Conference on Industrial and Applications*, (ICIEA), (2008),  
921 461–466.
- 922 [8] A.M. Almeshal, K.M. Goher and M.O. Tokhi, Dynamic mod-  
923 elling and stabilization of a new configuration of two-wheeled  
924 machines, *Robotics and Autonomous Systems* **61**(5) (2013),  
925 443–472.
- 926 [9] Canadian Centre for Occupational Safety and Health, 2010,  
927 (28<sup>th</sup> Nov 2012), [Available from], [http://www.ccohs.ca/osh-](http://www.ccohs.ca/oshanswers/safety_haz/stairs_fallprevention.html)  
928 [answers/safety\\_haz/stairs\\_fallprevention.html](http://www.ccohs.ca/oshanswers/safety_haz/stairs_fallprevention.html).
- 929 [10] C. Cardero, Articulated human body, 2012, [https://grabcad.](https://grabcad.com/library/articulated-human-body-2)  
930 [com/library/articulated-human-body-2](https://grabcad.com/library/articulated-human-body-2).
- 931 [11] L.F.S. Coletta, E.R. Hruschka, A. Acharya and J. Ghosh, Us-  
932 ing metaheuristics to optimize the combination of classifier  
933 and cluster ensembles, *Integrated Computer-Aided Engineer-*  
934 *ing* **22**(3) (2015), 229–242.
- 935 [12] R.A. Cooper, M.L. Boninger, R. Cooper and A. Kelleher, Use  
936 of the independence 3000 IBOT transporter at home and in  
937 the community: A case report, *Disability and Rehabilitation: Assistive Technology* **1–2** (2006), 111–117.
- 938 [13] D. Ding and R.A. Cooper, Electric powered wheelchairs, a re-  
939 view of current technology and insight into future directions,  
940 *IEEE Control Systems Magazine* **25** (2005), 22–34.
- 941 [14] A.P. Engelbrecht, *Computational intelligence: An introduc-*  
942 *tion*, Chichester, England, John Wiley and Sons, 2007.
- 943 [15] B. Fariba, R. Robert, J.M. Parviz and S. Gunther, Biomechan-  
944 ical analysis of sit-to-stand transfer in healthy and paraplegic  
945 subjects, *Clinical Biomechanics* **15** (2000), 123–133.
- 946 [16] N.M.A. Ghani, A.N.K. Nasir and M.O. Tokhi, Optimization  
947 of fuzzy logic scaling parameters with spiral dynamic algo-  
948 rithm in controlling a stair climbing wheelchair: Ascending  
949 task, *Proceeding of 19<sup>th</sup> International Conference on Meth-*  
950 *ods and Models in Automation and Robotics (MMAR)* (2014),  
951 776–781.
- 952 [17] K.M. Goher, Modelling and simulation of a reconfigurable  
953 wheelchair with sit-to-stand facility for a disabled child, *Pro-*  
954 *ceeding of IEEE 18<sup>th</sup> International Conference on Methods*  
955 *and Models in Automation and Robotics, (MMAR)*, (2013),  
956 430–434.
- 957 [18] J. Huang, F. Ding, T. Fukuda and T. Matsuno, Modelling and  
958 velocity control of a novel narrow vehicle based on mobile in-  
959 verted pendulum, *IEEE Trans on Control Systems Technology*  
960 **21**(5) (2013), 1607–1617.
- 961 [19] J. Chen and T. Wu, A computational intelligence optimiza-  
962 tion algorithm: Cloud drops algorithm, *Integrated Computer-*  
963 *Aided Engineering* **21**(2) (2014), 177–188.
- 964 [20] J. James and J.C. Abbas, Gillaette, using electrical stimulation  
965 to control standing posture, *IEEE Control System Magazines*  
966 (2001), 80–90.
- 967 [21] Johnson and Johnson Company, Independence iBOT mobil-  
968 ity system, (1<sup>st</sup> Jun 2012), [Available from], [http://www.ibot-](http://www.ibotnow.com/index.html)  
969 [now.com/index.html](http://www.ibotnow.com/index.html).
- 970 [22] F.M. Juan-Antonio, G. Cipriano and G. Javier, Assistive nav-  
971 igation of a robotic wheelchair using a multi hierarchical  
972 model of the environment, *Integrated Computer Aided Engi-*  
973 *neering* **11**(4) (2004), 309–322.
- 974 [23] R. Kamnik and T. Bajd, Standing-up robot: An assistive reha-  
975 bilitative device for training and assessment, *Journal of Med-*  
976 *ical Engineering and Technology* **28**(2) (2004), 74–80.
- 977 [24] M. Lawn and T. Takeda, Design of a robotic-hybrid  
978 wheelchair for operation in barrier present environments, *Pro-*  
979 *ceeding of IEEE International Conference on Medicine and*  
980 *Biology Society* (1998), 2678–2681.
- 981 [25] M.J. Lawn, T. Sakai, M. Kuroiwa and T. Ishimatsu, Develop-  
982 ment and practical application of a stair climbing wheelchair  
983 in nagasaki, *Journal of HWRS-ERC* **2** (2001), 33–39.
- 984 [26] Z. Li, C. Yang, C. Su and W. Ye, Adaptive fuzzy-based motion  
985 generation and control of mobile, *Engineering Applications*  
986 *of Artificial Intelligence* **30** (2014), 86–95.
- 987 [27] R. Morales, V. Felio and A. González, Optimized obstacle  
988 avoidance trajectory generation for a reconfigurable staircase  
989



- 990 climbing wheelchair, *Robotics and Autonomous Systems* **58** 1039  
 991 (2010), 97–114. 1040
- 992 [28] MSC software simulating reality, delivering certainty, MSC 1041  
 993 nastran multidisplinary structure analysis, <http://www.msc-> 1042  
 994 [software.com/product/msc-nastran](http://www.msc-software.com/product/msc-nastran). 1043
- 995 [29] S. Nakajima, Proposal for step-up gait of RT-mover, a four- 1044  
 996 wheel-type mobile robot for rough terrain with simple leg 1045  
 997 mechanism, *Proceeding of IEEE International Conference on* 1046  
 998 *Robotics and Biomimetics* (2010), 351–356. 1047
- 999 [30] I. Oden and E. Knutsson, Evaluation of the effects of muscle 1048  
 1000 stretch and weight load in patients with spastic paraplegia, 1049  
 1001 *Scan J Rehabil Med* **13**(4) (1981), 117–121. 1050
- 1002 [31] M.D. Philippa and K. Andrew, Frequency of the sit to stand 1051  
 1003 task: An observational study of free-living adults, *Applied Er-* 1052  
 1004 *gonomics* **41** (2010), 58–61. 1053
- 1005 [32] R. Ping, M. Chan, K.A. Stol and C.R. Halkyard, Review of 1054  
 1006 modelling and control of two-wheeled robots, *Annual Reviews* 1055  
 1007 *in Control* **37**(1) (2013), 89–103. 1056
- 1008 [33] G. Quaglia, W. Franco and R. Oderio, Wheelchair, q, a me- 1057  
 1009 chanical concept for a stair climbing wheelchair, *Proceeding* 1058  
 1010 *of IEEE International Conference on Robotics and Biomimet-* 1059  
 1011 *ics*, Guilin, China, (2009), 800–805. 1060
- 1012 [34] G. Raju, J. Zhou and R.A. Kisner, Hierarchical fuzzy control, 1061  
 1013 *International Journal of Control* **54**(5) (1991), 1201–1216. 1062
- 1014 [35] G.G. Rigatos, Adaptive fuzzy control for differentially flat 1063  
 1015 MIMO nonlinear dynamical systems, *Integrated Computer* 1064  
 1016 *Aided Engineering* **20**(2) (2013), 111–126. 1065
- 1017 [36] N. Siddique and H. Adeli, Computational intelligence – syner- 1066  
 1018 gies of fuzzy logic, *Neural Networks and Evolutionary Com-* 1067  
 1019 *puting*, Wiley, West Sussex, United Kingdom, 2013. 1068
- 1020 [37] Y. Sugahara, N. Yonezawa and K. Kosuge, A novel stair- 1069  
 1021 climbing wheelchair with transformable wheeled four-bar 1070  
 1022 linkages, *Proceeding of IEEE/RSJ International Conference* 1071  
 1023 *on Intelligent Robots and Systems* (2010), 3333–3339. 1072
- 1024 [38] Z. Sun, N. Wang and Y. Bi, Type-1/Type-2 fuzzy logic sys- 1073  
 1025 tems optimization with RNA genetic algorithm for double in- 1074  
 1026 verted pendulum, *Appl Math Modell* **39**(1) (2014), 70–85. 1075
- 1027 [39] Sunwa Co. Ltd (2006). (1<sup>st</sup> Apr 2012), [Available from], [http:](http://www.sunwa-jp.co.jp/en/accessibility/) 1076  
 1028 [//www.sunwa-jp.co.jp/en/accessibility/](http://www.sunwa-jp.co.jp/en/accessibility/). 1077
- 1029 [40] M.K.A. Tareq, Design and development of a new stabilization 1078  
 1030 mechanism for two-wheeled wheelchair, *Master's Thesis*, In- 1079  
 1031 ternational Islamic University of Malaysia, 2015. 1080
- 1032 [41] Y. Teng, T. Wang, C. Yao and X. Li, The research of tension 1081  
 1033 optimal estimation and stair-climbing ability of transforma- 1082  
 1034 tion wheelchair robot, *Proceeding of 29<sup>th</sup> Chinese Control* 1083  
 1035 *Conference* (2010), 3716–3721. 1084
- 1036 [42] Top Chair, (2003). The first stair-climbing powered wheel- 1085  
 1037 chair, (1<sup>st</sup> Apr 2012), [Available from], [http://www.topchair.](http://www.topchair.fr/) 1086  
 1038 [fr/](http://www.topchair.fr/). 1087  
 1088
- [43] J. Vascak, Fuzzy control of a physical double inverted pendu- 1039  
 lum, computational intelligence, *Lecture Notes in Computer* 1040  
*Science* (1625) (1999), 482–494. 1041
- [44] L. Vermeiren, A. Dequidt and T.M. Guerra, Modeling, con- 1042  
 trol and experimental verification on a two-wheeled vehicle 1043  
 with free inclination: An urban transportation system, *Control* 1044  
*Engineering Practice* **19** (2011), 744–756. 1045
- [45] S.L. Wang, Motion simulation with working model 2D and 1046  
 MSC, visual nastran 4D, *J Comput Soft Engin* **1**(2) (2001), 1047  
 193–196. 1048
- [46] Wheelchair-part 19: Wheeled mobility devices for use as seats 1049  
 in motor vehicles, ISO 7176-19, 2008. [http://www.iso.org/iso/](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=40993) 1050  
[home/store/catalogue\\_ics/catalogue\\_detail\\_ics.htm?csnum-](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=40993) 1051  
[ber=40993](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=40993). 1052
- [47] Wheelchair-part 24: Requirements and test methods for user- 1053  
 operated stair-climbing devices, ISO 7176-24, 2004. [http://](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=45653) 1054  
[www.iso.org/iso/home/store/catalogue\\_ics/catalogue\\_detail\\_](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=45653) 1055  
[ics.htm?csnumber=45653](http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=45653). 1056
- [48] D.A. Winter, Biomechanics and motor control of human 1057  
 movement, Wiley-Interscience, New York, 1990. 1058
- [49] J. Xu, Z. Guo and T. Heng, Synthesized design of a fuzzy 1059  
 logic controller for an underactuated unicycle, *Fuzzy Sets and* 1060  
*Systems* **207** (2012), 77–93. 1061
- [50] W.Y. Hsu, Assembling a multi-feature EEG classifier for left- 1062  
 right motor data using wavelet-based fuzzy approximate en- 1063  
 tropy for improved accuracy, *International Journal of Neural* 1064  
*Systems* **25**(8) (2015). 1065
- [51] L. Forero Mendoza, M. Vellasco and K. Figueiredo, Intelli- 1066  
 gent multiagent coordination based on reinforcement hierar- 1067  
 chical neuro-fuzzy models, *International Journal of Neural* 1068  
*Systems* **24**(8) (2014), 1450031. 1069
- [52] C. Chai and Y.D. Wong, Fuzzy cellular automata models for 1070  
 signalized intersections, *Computer-Aided Civil and Infra-* 1071  
*structure Engineering* **30**(12) (2015), 951–964. 1072
- [53] J.L. Ponz-Tienda, E. Pellicer, J. Benlloch-Marco and C. 1073  
 Andrés-Romano, Fuzzy project scheduling problem with 1074  
 minimal generalized relations, *Computer-Aided Civil and In-* 1075  
*frastructure Engineering* **30**(11) (2015), 872–891. 1076
- [54] W. Zhang, K. Sun, C. Lei, Y. Zhang, H. Li and B.F. Spencer, 1077  
 Jr., Fuzzy analytic hierarchy process synthetic evaluation 1078  
 models for the health monitoring of shield tunnels, *Computer-* 1079  
*Aided Civil and Infrastructure Engineering* **29**(9) (2014), 1080  
 676–688. 1081
- [55] H. Adeli and S.L. Hung, A fuzzy neural network learning 1082  
 model for image recognition, *Integrated Computer-Aided En-* 1083  
*gineering* **1**(1) (1993), 43–55. 1084
- [56] X. Jiang and H. Adeli, Fuzzy clustering approach for accu- 1085  
 rate embedding dimension identification in chaotic time se- 1086  
 ries, *Integrated Computer-Aided Engineering* **10**(3) (2003), 1087  
 287–302. 1088