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Modelling and Control of a Reconfigurable Multipurpose Wheelchair for Elderly/Disabled Mobility

A thesis submitted to the University of Sheffield for the degree of Doctor of Philosophy

By

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Abstract

This research is embarking on development of modelling and designing control strategies for a multipurpose wheelchair as a mobile transporter for elderly and disabled people to move in confined and domestic environments independently. The research is aimed at helping people who have physical weakness/disabilities in their upper and lower extremities to move on their own without human intervention. In this work, a novel reconfiguration which allows multi-task operations using the same wheelchair system with compact and simple mechanism is developed for use in confined domestic environment. It can perform manoeuvrability on flat surfaces, stairs climbing (ascending and descending), standing in the upright position on two wheels and transforms back to standard four wheels with reduced initial torque and reduced tilt angle.

The wheelchair model is designed in Visual Nastran 4D (VN4D) software with standard specifications of stairs dimension and size. A humanoid model with approximate weight of 71kg is also developed in solid works and incorporated in VN4D to represent a disabled/elderly person. The wheelchair mechanism is based on the link/cluster rotation by lifting the other pair of wheels at the vertical upright position like an inverted pendulum. The completed model in VN4D is then integrated with Matlab/Simulink for control design and performance evaluation. The challenge resides in an appropriate design and implementation of robust controller for the system to guarantee stability of the overall wheelchair while performing multi-function tasks without falling over.

A modular fuzzy logic control mechanism with integrated phases is introduced in this work for the two-wheeled stabilization as the main principle of the overall tasks. It is implemented in the stabilizing/landing for stair climbing and sit-to-stand/stand-to-sit transformation control system. Yaw and linear motions are considered in the stair climbing while seat height extension and suspension mechanism are incorporated during standing/sitting control. Moreover, systematic optimization approach is used for the fuzzy input output scaling parameters using

spiral dynamic algorithm for performance comparison purposes with heuristic values. Unique rule bases are implemented in all fuzzy modules and controlled independently. The developed control approaches are evaluated through intensive visual simulation and quantitative assessment to verify the proposed control design.

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Nomenclatures

The following are the variables being used in this work.

τ_{FL} , τ_{FR}	Front left and front right wheels motor
τ_{RL} , τ_{RR}	Rear left and rear right wheels motor
v_{ℓ}	Link/cluster motor
θ_{ℓ}	Link/cluster angle
θ_{s}	Overall seat angle
τ_{s}	Overall seat motor
w	Width of stair
h	Height of stair
d	Depth of stair
v_{h}	Height of linear actuator
v_{α}	Seat motor
v_{β}	Back seat motor
x_1	Front wheel position
x_2	Rear wheel position
ψ	Yaw angle
h	Position of seat
θ_{α}	Bottom seat angle
θ_{β}	Back seat angle

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Chapter 1

1 Introduction

1.1 Introduction and motivation

Mobility dominance has always been highly valued but is sometimes over sighted in case of people with disability and the elderly. The number of disabled persons across the world has kept on increasing. For example in Great Britain, there are a total of 11.2 million disabled persons, of whom 0.8 million are children, 5.2 million are working adults and the same goes to pension people according to 2010/2011 disability prevalence estimation data (Disability factsheet, 2011). This has caused high demand on some form of transport mechanism and thus wheelchairs continue to play a vital role. The wheelchair designs range from traditional to electric-powered types with their associated advantages and limitations. However, most of the manual wheelchair designs are not capable of performing multiple tasks within the same wheelchair system. Thus, there is a significant gap between the able bodied and paraplegic people in utilizing the facility especially in case of different operations with compact and simple mechanism for use in confined domestic environments. The main goal of this work revolves around provision of assistance with electric-powered wheelchairs (EPWs) to help disabled/elderly people with lower and upper extremity impairments so as to increase their functional mobility to perform multipurpose tasks independently. The wheelchair system allows manoeuvrability on flat surfaces, stairs climbing (ascending and descending), standing in the upright position on two wheels and transforming back to standard four wheels. Various mobility assistive techniques are highlighted in this thesis and recent advances in wheelchair mechanism are described.

1.2 Multi-functions wheelchair

EPWs allow functional mobility for people with spinal cord injury (SCI) and paraplegics with paralysis in both upper and lower limbs. It becomes increasingly prominent as more wheelchair users have changed to powered machine due to the ability to move within their homes and communities independently especially for people with high level of impairment. This chapter highlights current work for multipurpose wheelchair including stability control wheelchair, stair climbing wheelchair and sit-to-stand/ stand-to-sit manoeuvring using two wheeled wheelchair.

1.2.1 Stability control wheelchair

Three or more points of contact on the ground are needed for a wheelchair to be stable, similar to modern vehicles approach. If a balance mechanism is used, two points of contact will be adequate, e.g. a rickshaw supporting a person as an external balance mechanism, bicycle and motorcycle in case of using an internal balance mechanism. The person in this case needs to control the vehicle's lateral motion in order to maintain the appropriate COG position for the bicycle and motorcycle. If a single point of contact with the ground is used, such as unicycle and wheelbarrow, then acquiring control and balance at both side to side and front to rear will be a complex task.

It is vital to ensure safety of a user during manoeuvring using a wheelchair to prevent any severe accidents such as tips and falls. Tipping stability occurs when one or more wheels of a wheelchair are lifted due to the loss of control of a driver. Cooper et al. (1998) indicated that leg rests play a significant role on the wheelchair stability and can increase the possibility of falling and tipping. Corfman et al. (2003) also suggested that proper leg rest position and the use of seatbelt might guarantee the stability of the wheelchair when traversing on any obstacles.

Torres et al. (2000) implemented a level sensor to detect the seat height and maintain level while the wheelchair traverse on untreated surfaces through

extension and retraction control mechanism. A commercialized iBOT wheelchair utilized the balance mode throughout the wheelchair operation which operates on two-wheeled mode using inverted pendulum principle. It controls the (COG) of the wheelchair system by bringing the rear wheels at the upright vertical position. It uses the on board sensors system; gyroscope and encoder to measure the tilt angle of the seat, angular velocity and base linear velocity to drive and balance the iBOT system through the motor voltage and current (Kamen et al., 2002). Cooper et al. (2006) conducted a study to report the various types of wheelchair activities at home and in the community. The tasks include performing eye-to-eye level discussion with people and reaching items at higher shelves at home and library.

Similar to iBOT design principle with the ability to transform from four wheeled to two wheeled mode with additional capabilities to lift the seat to a higher position has been introduced by Ahmad et al. (2011, 2014). They used the two-links inverted pendulum concept for lifting both the front wheels and stabilizing the overall wheelchair body on its rear wheels at the upright two wheeled position. However, the front wheels dimension, called caster wheels in this design were much smaller than the rear wheels which contribute to easy transformation processes. Moreover, the wheelchair produced initial high torque at the wheels and tilt motors (Link 1 and Link 2) to lift the overall mechanism to two-wheeled upright position. This will produce big tilt angle at the beginning of the transformation process as the overall system need to be tilted with such high power. The comfort issue of the user is important in this case especially for a disabled person and elderly.

1.2.2 Stair climbing wheelchair

Stair climbing wheelchair provides a facility to the user to utilize the same assistive mobility equipment to move on a flat surface and on the stairs. There is no reliance on the elevator or an assistance to perform stair climbing, thus leading to independent life. A number of stair-climbing wheelchair mechanisms have been developed and these include crawler type, leg type, hybrid type and wheeled type; as described below.

Chapter 1

1 Introduction

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Chapter 3

3 Modular Fuzzy Logic Control

3.1 Introduction

In this work, a reconfigurable wheelchair is developed based on the two-wheeled inverted pendulum concept and intended for use in narrow and confined domestic environments. The subtle operation involves a transformation from standard four-wheeled wheelchair to two-wheeled mode using a link rotation mechanism in order to lift the whole wheelchair system to the upright position, which is referred to as stabilizing on two-wheeled process. This mechanism also allows the wheelchair to perform stair climbing (ascending and descending), sit-to-stand and stand-to-sit operations using the stabilizing concept. Stabilizing a wheelchair in a two-wheeled mode is not an easy task as it needs to take into account the whole weight of the system and the user. The two-wheeled wheelchair system uses the same concept as an inverted pendulum which has surfaced over the years for balancing control and is known to be an unstable system. At the same time, the seat and the whole wheelchair mechanism have to stay stable at the upright vertical position to ensure that the system does not collapse or slip while carrying a human load of 71kg. Due to the configuration and complexity of the task, the system was incorporated with an intelligent control approach to accomplish the goal.

Tremendous successes have been reported through the implementation of natural and biological intelligence, resulting in ‘Intelligence System’. The intelligent algorithm form part of the field of ‘Artificial Intelligence’ in broad research disciplines, for example, computer science, physiology, philosophy, sociology and biology. Figure 3.1 shows paradigm of computational intelligence (Engelbrecth, 2007).

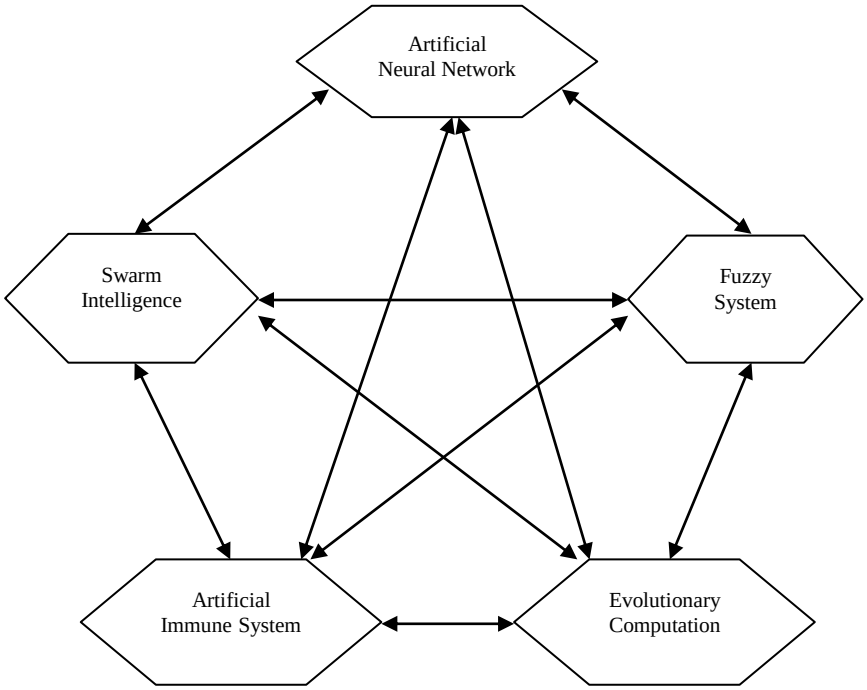

Figure 3.1: Computational Intelligence Paradigm (Engelbrecth, 2007)

Artificial Neural Network (ANN) is originated from nerve cells called neurons which are represented as artificial neurons, ANN and acting like data training machine where as Swarm Intelligence (SI) is adopted from swarm and colonies social organisms such as bird flocks and ant colony behaviours which prompted the design of efficient optimization and clustering algorithms. Natural behaviour and genetic were the main contributing factors to create evolutionary algorithm as one of the approach to evolve behaviour model. Meanwhile, Artificial Immune System (AIS) modelled human immune system to interact with foreign cells known as antigen which enters the body to be able to adapt and memorize the structure of these antigens for faster future response.

Fuzzy logic is with inherent property incorporating uncertainties and nonlinearities of a system (Engelbrecth, 2007). In this sense, fuzzy logic plays a vital role in executing rational decision making process in an uncertainty and imprecision environment by human (Zadeh, 1988). Fuzzy logic has significant advantages because it is one of the computational intelligence approaches which are

close to human reasoning and decision making. Fuzzy logic has found greatest successful in most fields and systems ranging from engineering to social studies due to its ability to construct rule of knowledge which is similar to human expression and thinking. Moreover, fuzzy logic is easy to implement in terms of interpreting the behaviour of environments and real systems. Fuzzy logic control (FLC) has become more favourable due to its significant superiority compared to conventional methods in terms of theory and practicality (Wang, 1993). The stability of fuzzy logic, considered as its disadvantage, is hard to establish and there is no standard approach to analyse its stability. However, the following attributes strongly motivate the adoption of a fuzzy logic approach in this work:

- Suitable for a system which is difficult to model and obtain the mathematical description and need linguistic vague information from human experts.

- The fuzzy control itself does not require mathematical equations as in most conventional controllers, just rely on the rule of knowledge based on the systems' requirement.

- Can be implemented to nonlinear systems due to the nonlinear elements in the fuzzy control in order to perform nonlinear control actions.

- Easy to understand by those who are not control specialists because it emulates human control strategy.

- Simple to implement in both software and hardware and inexpensive to develop.

A basic diagram for fuzzy logic approach is shown in Figure 3.2 which consists of fuzzification, inference mechanism based on the rule construction and defuzzification. Each element is described in detail in next section.