TRAJECTORY TRACKING CONTROL OF NONHOLONOMIC DIFFERENTIAL DRIVE WHEELED MOBILE ROBOT FOR REHABILITATION PURPOSE

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To my beloved parents, thank you.

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ABSTRACT

The over ground gait rehabilitation is one of the popular rehabilitation devices to enhance rehabilitation outcome while reducing therapist's workload. However, in practice, it is a challenging task to design a system that is easily affected by uncertainties and external disturbances from the wheeled mobile robot (WMR). Thus, it is hard to maintain its stability and robustness when dealing with patients who are disabled to walk. It is very risky to let off this concern. The strategies of trajectory tracking control of the WMR can provide better motion and steer ability while assisting patients through gait treatment to improve rehabilitation outcomes. Therefore, a suitable controller is designed to ensure stability in human-robot interactions. In this work, a new control law has been proposed by improving the switching law of the sliding mode controller (SMC) to eliminate the chattering effect in the control system called Terminal Super Twisting Sliding Mode Control (TSTSMC). The enhanced TSTSMC uses sliding mode control techniques to achieve high-precision tracking of a reference signal with Cuckoo optimisation. The proposed TSTSMC algorithm enhances control law for the trajectory tracking control while reducing the chattering effect in the control system. The TSTSMC was tested for external disturbance and uncertainties to evaluate the chattering suppression of the controllers. The TSTSMC was benchmarked with SMC (SMC), Terminal SMC (TSMC) and super twisting SMC (STSMC), and terminal Super Twisting SMC (TSTSMC) without optimisation. A simulation study shows that the TSTSMC algorithm improves the chattering and steady error by up to 35% and 25%, respectively. The translational velocity from the data sampling that has been used in the control law simulation gives results within an average normal gait speed. The average speed performed by the WMR is 1.25ms^{-1} which is lesser than the normal speed. The proposed controller algorithm has been proven to provide trajectory robustness and stability for WMR and can be extended for future improvement for gait assistive devices.

ABSTRAK

Pemulihan berjalan di atas tanah adalah salah satu alat pemulihan yang popular untuk meningkatkan hasil pemulihan sambil mengurangkan beban kerja ahli terapi. Walau bagaimanapun, secara praktikalnya, merekabentuk system adalah satu tugas yang sangat mencabar kerana mudah dipengaruhi oleh gangguan luaran daripada robot mudah alih beroda (WMR). Oleh itu, untuk mengekalkan kestabilan dan keteguhan pesakit yang kurang upaya untuk berjalan adalah sangat berisiko. Isu ini adalah sukar untuk diabaikan. Strategi kawalan penjejakan trajektori WMR boleh memberikan pergerakan yang lebih baik dan keupayaan mengemudi sambil membantu pesakit melalui rawatan berjalan untuk meningkatkan hasil pemulihan. Oleh itu, pengawal yang sesuai direka untuk memastikan kestabilan terhadap interaksi robot-manusia. Dalam kerja ini, undang-undang kawalan baharu telah dicadangkan dengan menambahbaik undang-undang pensuisan Kawalan Ragam Lincir (SMC) untuk menghapuskan kesan berbual dalam sistem kawalan yang dipanggil Terminal Super Twisting Sliding Mode Control (TSTSMC). TSTSMC yang dipertingkatkan menggunakan teknik kawalan ragam lincir untuk mencapai penjejakan berketepatan tinggi bagi isyarat rujukan dengan pengoptimuman Cuckoo. Algoritma TSTSMC yang dicadangkan meningkatkan undang-undang kawalan untuk kawalan penjejakan trajektori sambil mengurangkan kesan penggelatukkan dalam sistem kawalan. TSTSMC telah diuji untuk gangguan luaran dan ketidakpastian untuk menilai penggelatukkan yang telah dimansuhkan. TSTSMC telah ditanda aras dengan SMC (SMC), Terminal SMC (TSMC) dan Super Twisting SMC (STSMC) dan Terminal Super Twisting SMC (TSTSMC) tanpa pengoptimuman. Kajian simulasi menunjukkan bahawa algoritma TSTSMC meningkatkan ralat penggelatukkan dan keadaan mantap masing-masing sehingga 35% dan 25%. Halaju translasi daripada pensampelan data yang telah digunakan dalam simulasi undang-undang kawalan memberikan keputusan dalam purata kelajuan berjalan normal. Kelajuan purata yang dilakukan oleh WMR ialah 1.25ms^{-1} yang lebih rendah daripada kelajuan biasa.

Algoritma pengawal yang dicadangkan telah terbukti memberikan keteguhan dan kestabilan trajektori untuk WMR dan boleh dilanjutkan untuk penambahbaikan masa depan untuk peranti bantuan berjalan.

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LIST OF SYMBOLS AND ABBREVIATIONS

M	–	inertial mass
V	–	centripetal /Coriolis
G	–	gravity
B	–	input matrix
τ	–	input vector
$\Lambda^T (q)$	–	kinematic constraints
λ	–	Lagrange multiplier

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Chronic diseases such as Spinal Cord Injury (SCI), stroke, and Parkinson's disease are neurological disorders that can cause a permanent handicap if not treated effectively. In Malaysia, stroke is among the most significant contributors to deadly diseases [1]. More worrisome is that this fatal disease, usually seen in older people, has started to spread to people as young as their 30s, and there has been a huge rise in this [1-2]. Patients are burdened with their health problems and medical expenditures for the treatment needed during the therapy [2-3].

Robotic devices are used as mobile devices that provide walking lessons to regain the patient’s walking ability. Gait-oriented training can enhance recovering the loss of ability to ambulate caused by neurological disorders, and the number is rising with the aid of robotic devices [4]. Robotic devices provide patients with various functions that improve rehabilitation outcomes while reducing therapist workload. With the advent of robot-aided rehabilitation techniques, this process will become smoother, potentially covering a broad scope of therapy, ultimately making it even more effective [5-7].

Rehabilitation robotics has widely evolved over the last few decades, since the early 1960s. One of the most essential studies among researchers is robotics-aided gait neurorehabilitation. Overground gait neurorehabilitation is a rehabilitation therapy for individuals with movement disorders caused by neurological conditions such as stroke, spinal cord injury, or traumatic brain injury. The pioneer researchers regarding robotic devices have proven more effective, and the degree of ailments can be reduced simultaneously with patients' positive development [8]. There is growing evidence that chronic stroke patients can improve their motor skills with the help of good robotic gait education [4], [6-9].

The discipline of mobile robots in gait re-education is concerned with the stability and robustness aspects. Various rehabilitation robots may vary based on the degree of disability of an individual. From exoskeletons to overground gait-oriented rehabilitation robots, the aim is to increase the incentive of walking independently for inability people back into the workforce. Both treadmill and overground machines give a different experience to the patient. To boost their confidence in walking, the overground gait devices may greatly help them. Several robotic devices cater to gait problems, such as Ekso Bionics Exoskeleton, ReWalk, Indego Exoskeleton, HAL (Hybrid Assistive Limb), Andago, and Lokomat. Figure 1.1. shows a Wheeled Mobile Robot (WMR) that can assist patients in walking and provide support during the gait treatment.

Figure 1.1: Andago [10]

With this robotic-assisted device, gait therapy will be much easier, and walking ability can be gained in a shorter period. Andago is designed to help patients with gait impairment regain their walking power [11]. Unlike traditional approaches, robotic devices can offer intensive gait re-education that supersedes the conventional rehabilitation method. Gait training helps to improve balance, motor control, weightbearing ability, and the re-creation of a natural gait [4]. Patients can reach the highest levels of physical function through rehabilitation.

The over ground gait training device currently experiences progression as it offers practical and optimised recovery procedures for neuro patients. The robot’s behaviour is based on the kinematic criteria presented in the types of WMR. The nonholonomic WMR is easier to design and control but cannot render freely and is classified as an under-actuated robot. It appears to contradict the holonomic drive as it is said to be unconstrained [12]. The total number of freedoms may affect the robot's discipline, thereby making the robot perform as desired. However, the nonholonomic mechanism offers no longitudinal and lateral slipping during wheel motion. Figure 1.2 shows the nonholonomic WMR called Differential drive WMR (DDWMR).

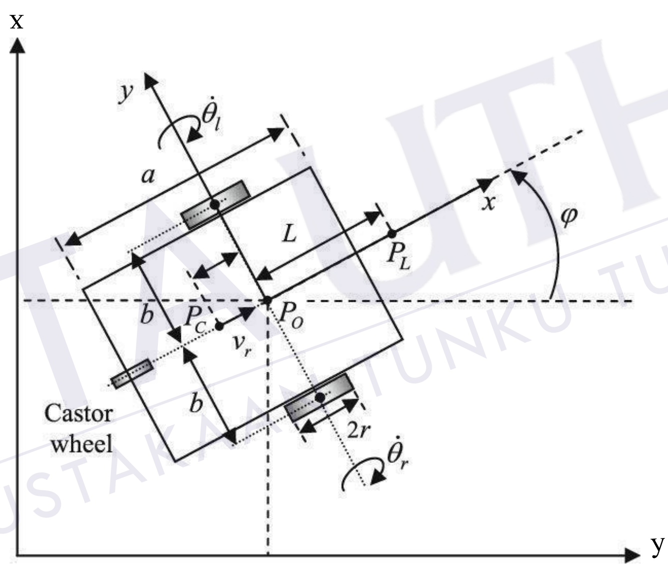

Figure 1.2: Differential drive WMR configuration [13]

Differential drive robots are equipped with two drive wheels, which are often powered by electric motors. These wheels are responsible for propelling the robot and enabling it to move. The term differential drive comes from the way these robots control their motion. They can move forward, backward, turn left, or turn right by independently varying the speed and direction of rotation of the two drive wheels. This differential motion control is achieved by providing different speeds or directions of rotation to the two wheels. To turn, a differential drive robot can execute two main types of turns. When one wheel spins faster than the other in the opposite direction, it will cause the robot to pivot in place. On the other hand, if one wheel spins faster than the other in the same direction, the robot will follow an arc-shaped path.

It is a challenging task to design trajectory tracking for the WMRs as the trajectory tracking will try to follow the reference trajectory of its desired path under nonholonomic constraints [14-16]. Changes in the terrain, unexpected obstacles, or variations in traction can affect the robot's ability to follow planned trajectory. Designing trajectories that are robust to these uncertainties is a challenge. Over the years, many different tracking controllers have been suggested to solve the problem of controlling the trajectory tracking of the nonholonomic WMR. Some of the control approaches from previous researchers are nonlinear, optimal, adaptive, and robust [17].

To ensure the WMR is designed with such a high degree of stability and robustness, it must be equipped with a controller that fulfils those criteria: trajectory tracking control algorithms that help maintain stability and robustness during movement. Sliding Mode Control (SMC) is an effective method for nonlinear systems that can deal with stability and robustness issues [18–19]. One of the SMC family is the Terminal SMC (TSMC) which is good at minimising the tracking error and maximising the convergence speed [20]-[23]. However, suffer from chattering issues that led to the integration of the Super Twisting SMC (STSMC), which can attenuate the chattering phenomenon [24-28].

1.2 Problem Statement

Robotics rehabilitation with over-ground walking is more advisable to upgrade gait performance and introduce standard gait patterns with actual foot contact [28–29]. However, designing a system that is easily affected by uncertainties and external disturbances, it is hard to maintain its stability and robustness [29-35]. It is quite dangerous to let this problem go when dealing with patients who are unable to walk. The WMR should follow the reference trajectory safely. Hence, the trajectory tracking control of the WMR is crucial when dealing with uncertainties and disturbance issues. It motivates the need for an enhanced controller to curb the drawbacks of the gait assistive device. It is crucial to properly derive the kinematic and dynamic modelling of WMR properly for trajectory tracking control. Inaccurate modelling leads to incorrect movements and positioning, unstabilised the robot, and reduces the effectiveness of the rehabilitation [36-40]. Therefore, a proper kinematic and dynamic modelling is crucial before designing the controller. By incorporating accurate modelling into the trajectory tracking design, rehabilitation robots can provide an effective and safe rehabilitation process [41-45].

The SMC-based method has been widely proposed for trajectory tracking issues [19], [46-51]. SMC is good at facing issues associated with external disturbances and uncertainties. It is well known as a robust controller in the uncertain WMR system [52–54]. Although SMC claims it is good at managing issues, the chattering phenomenon has become a significant drawback of this controller. Conventional SMC gives slow state convergence, requiring higher steady-state precision and greater control force [55-57]. To enhance the robustness of WMR, its needs to be integrated with an enhanced controller algorithm. The controller will help to generate smooth movement, help to reduce the risk of falls and improve the individual's gait. Therefore, designing a controller that can overcome perturbations due to plant uncertainties and external disturbances is highly desirable. If chattering occurs in overground gait in over ground gait neurorehabilitation, it can result in poor trajectory tracking performance, excessive control efforts, and potential damage to the rehabilitation robot or the patient [45], [58-59]. Chattering occurs when the control inputs oscillate rapidly, leading to instability and unpredictable behaviour. It can negatively impact the rehabilitation outcome and the patient's ability to perform the desired gait movement. [43-45]. It is important to design a control system that minimises or eliminates chattering to ensure a safe and effective rehabilitation process.

This thesis proposes an enhanced SMC model, the Terminal Super Twisting SMC (TSTSMC) algorithm based on a wheeled mobile robot to provide better trajectory tracking. The proposed algorithm takes advantage of the robustness and stability of the DDWMR platform for rehabilitation purposes. The Cuckoo Optimisation (CO) algorithms were then integrated into TSTSMC and the nonholonomic WMR, allowing a stable and robust system to be designed.

1.3 Research Objectives

The main goal of the work is to propose a SMC algorithm that provides better trajectory tracking of the nonholonomic WMR for over ground gait neurorehabilitation. To do so, the Terminal and Super Twisting SMC are integrated into the controller to achieve better performance. The Cuckoo Optimization is used to find the optimal solution for the gain of the proposed controller. To achieve the main goal of the work, the specific objectives of the research include the following:

i. To develop the kinematic and dynamic model of the nonholonomic differential drive.
ii. To design a robust controller TSTSMC for the DDWMR for trajectory tracking control.
iii. To verify the performance of the proposed controller algorithms using comparative study with other families of SMC strategies.

1.4 Research Scopes

The research scope will cover the area of gait rehabilitation, focusing on the mobile robot for over ground gait neurorehabilitation. The scopes are crucial for planning, executing, and communicating research effectively. The research development is within these mentioned scopes:

i. To apply the design of kinematics and dynamics of the nonholonomic WMR to the system.

   The nonholonomic WMR consists of a two-dimensional plane; the Cartesian plane is used in the proper research. For the differential drive WMR, it's assumed that it is rolling without slipping. The trajectory tracking for the standard kinematic model for differential drive nonholonomic WMR is formulated to follow the reference path at a specified velocity. The actual Andago parameters are then injected into the WMR model to resemble the gait device effectively. The Andago platform specification data is taken from Physiotherapy Unit, Rehabilitation Centre by the Social Security Organization of Malaysia (PERKESO), Melaka, Malaysia.

ii. Perturbation of the WMR system

   When the kinematics and dynamics of the robot are precisely determined, the controller is implemented to be compatible with behaving in line with its environment. However, the uncertainties and external disturbances will affect the controller's effectiveness. The actual mass of the WMR is supposed to be uniformly distributed all the time and to be time-varying with bounded uncertainty with known nominal mass. Due to time-varying mass, the moment of inertia becomes time-depending with bounded uncertainty.

iii. Case study to gait re-education

Collaboration with the Rehabilitation Centre by the Social Security Organization of Malaysia (PERKESO), Melaka, Malaysia will be a highlight in this research study as a case study will be another contribution to validate the whole work by running a case study based on the proposed gait re- education concept. A medical perspective is critical in designing a device for human function that partially restores their condition. The velocity and the root mean square (RMS) acceleration will be generated concerning the human body's comfort.

iv. Software development

Matlab is used for the software development for the TSTSMC algorithm. Matlab offers simulation capabilities for various domains. It allows to build the mathematical model of the differential drive WMR, simulate the system behaviour, and analyze the simulation result of the proposed controller.

1.5 Research Contribution

This research is proposed to produce an improved SMC algorithm as its optimisation method for trajectory tracking of nonholonomic WMR. The contributions of this research can be referred as below:

i. The kinematics and dynamics of Andago

The derive kinematics and dynamics of DDWMR for rehabilitation purposes are based on the Andago platform.

ii. The enhanced control law for the trajectory tracking control

To remove the chattering effect in the control system, a new control law has been proposed to improve the switching law of the SMC controller. The aim is to ensure that the tracking error will gradually converge into the boundary layer while the control torques amplitudes outside the boundary layer remain larger. When this result is achieved, the chattering is successfully reduced. The control law of the TSTSMC is proposed for this research to achieve robustness and stability provided by the WMR platform for rehabilitation purposes.

iii. A new design and application of TSTSMC in rehabilitation

This can be achieved after the proposed controller is applied to the modelling of the over ground gait rehabilitation. The modelling can give a better trajectory while patients are having therapy using this device. The robustness and stability issues can be improved with the trajectories' accuracy being composed by the TSTSMC. Hence, gait therapy can be done safely and smoothly.

1.6 Thesis Outline

This thesis comprises five chapters. This report begins with Chapter 1, which includes the background of the research study. The problem statement represents the current situation as it contributes to some downsides of the work. The objectives are to highlight the aim, specifically for the discussed issues. The final subchapter is the research scope, where the idea of the academic work is briefly discussed.

Chapter 2 is attained by compressing the literature work that has been done previously. Starting from the rehabilitation perspective, the mobile robot's behaviour subsequently takes on two different behaviours, which are holonomic and nonholonomic. The holonomic refers to the differential drive, while the nonholonomic alludes to the omnidirectional movement. Then, the application of the mobile rehabilitation robot invented so far is also presented as the reference while pursuing this research. The previous study on trajectory tracking control and SMC families is also discussed.

The modelling of nonholonomic WMR in Chapter 3 describes the project implementation and modelling of the nonlinear system of over ground gait neurorehabilitation. A brief outline is devoted to illustrating the flow of the study in achieving the aim of designing a better gait assistive device for human needs.

Next, Chapter 4 briefly demonstrated the design of the trajectory tracking controller. The control law of the proposed controller is discussed in this chapter. The controllers within the SMC families are then put into a comparative study for controller performance.

Chapter 5 describes the results and analysis of the proposed controller. The selected controllers are compared with the proposed nonlinear controller. The study of the mentioned issue analyses the proposed work to align with the simulated design's

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APPENDIX A

LIST OF PUBLICATIONS

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APPENDIX B

VITA

The author was born in January 1987, in Perak, Malaysia. She went to Sekolah Menengah Kebangsaan Temenggong Ibrahim, Batu Pahat, Johor, Malaysia for her secondary school. In 2007, she pursued her study in Mechatronic Engineering at Politeknik Johor Bahru. She then enrolled her degree at the Universiti Tun Hussein Onn Malaysia and graduated with the B.Eng. (Hons) in Electronic Engineering in 2011. She is then pursued her Master of Electrical Engineering at Universiti Tun Hussein Onn Malaysia. Now, she is the candidate for the Doctor of Philosophy in Electrical Engineering in Universiti Tun Hussein Onn Malaysia