Faculty of Electrical Engineering

PATH TRACKING CONTROL OF MECANUM−WHEELED ROBOT WITH OUTPUT−SCHEDULED FRACTIONAL−ORDER PROPORTIONAL−INTEGRAL CONTROLLER

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PATH TRACKING CONTROL OF MECANUM−WHEELED ROBOT WITH OUTPUT−SCHEDULED FRACTIONAL−ORDER PROPORTIONAL−INTEGRAL CONTROLLER

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DECLARATION

I declare that this thesis entitled "Path Tracking Control of Mecanum-wheeled Robot with Output-scheduled Fractional-order Proportional-integral Controller" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	………………………………
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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:	……………………………………
Supervisor Name	:	Dr. Loh Ser Lee
Date	:	……………………………………

DEDICATION

To my supervisors, beloved family and girlfriend

ABSTRACT

Mecanum-wheeled robot (MWR) has always been the limelight of mobile robot engineering and industrial applications due to its capability to manoeuvre from one position to another, achieving prominences of being time-saving and space-saving. However, as Mecanum wheel is made up of rollers, the MWR suffers from uncertainties arose from slippage, dynamic wheel radius and centre of mass, nonlinear actuation and et cetera. These factors complicate the control of the MWR. Merely kinematic and dynamic modellings are often inadequate to develop a path-trackable MWR control system. In other words, modelling and quantifying the uncertainties are often compulsory as shown in the literatures, but these further increase the complexity of the control system. Therefore, in this research, an Output-scheduled Fractional-order Proportional-integral (OS FOPI) controller is proposed as a simpler approach, with achievement of various complex path tracking as end result. First of all, the MWR in this research has two computer ball mice as positioning sensors to realize a 3-DOF localization, and four brushed DC geared motors rated at 19 RPM as actuators for Ø60 mm Mecanum wheels. The nonlinearities of the actuators are linearized based on open-loop step responses and are estimated by using polynomial regression. However, the nonlinearities are not completely eradicated and are significant especially during low RPM operation. Therefore, the OS FOPI controller which has fractional integral nonlinear properties is implemented. A conditional integral-reset anti-windup is supplemented to overcome controller saturation caused by the slow RPM actuations. Next, unlike conventional control method for MWR, the proposed control system does not require modellings of kinematics, dynamics and uncertainties in order to achieve path tracking. This is due to the output-scheduling method, which involves mathematical operation that linearly maps the summation of two angles – robot's immediate heading angle and angle between positions, into gains that control each Mecanum wheel. In addition, the output-scheduling method is directly a displacement-controlled approach and thus requires no unit conversion from velocity to displacement. Overall, the proposed control system is more intuitive and straightforward. The effectiveness of the OS FOPI controller is evaluated with OS P controller and OS PI controller. The experiment results show that all three output-scheduling controllers successfully achieve trackings of complex-shaped paths. However, the OS FOPI controller exhibits better tracking performance than the others with overall 28 % and 40 % of improvements on integrals of absolute error (IAE) and squared error (ISE), respectively. In addition, among the OS PI and OS FOPI controllers, OS FOPI controller outperforms the former with 17 % lesser path tracking vibration. In conclusion, successful trackings of various complex-shaped paths are experimentally demonstrated with a simpler control system.

ABSTRAK

Robot beroda Mecanum (MWR) selalu menarik perhatian kejuruteraan robot bermudah-alih dan aplikasi berindustri disebabkan keupayaannya untuk manuver dari satu kedudukan ke kedudukan yang lain dan mencapai kecemerlangan seperti penjimatan masa dan minimum ruang untuk beroperasi. Walaubagaimanapun, disebabkan roda Mecanum terdiri daripada penggelek, MWR berdepan dengan ketidakpastian yang timbul daripada tergelinciran, jejari roda Mecanum dan pusat jisim robot yang berdinamik, pergerakan yang tidak lurus dan lain-lain. Faktor-faktor ini merumitkan pengawalan MWR. Selalunya, semata-mata permodelan kinematik dan dinamik adalah tidak mencukupi untuk mencapai penjejakan laluan; permodelan dan pengiraan ketidakpastian adalah diwajibkan seperti yang ditunjukkan dalam literatur. Tetapi, permodelan dan pengiraan tersebut menambah kerumitan terhadap sistem kawalan MWR. Justeru, dalam penyelidikan ini, pengawal kamiran-berkadar susunan berpecahan keluaran berjadual (OS FOPI) dicadangkan sebagai pendekatan yang lebih mudah untuk mencapai penjejakan laluan berkomplikasi tinggi. Mula-mulanya, MWR dilengkapi dengan dua tetikus komputer jenis berbola untuk merealisasikan lokalisasi bertiga-darjah-kebebasan, dan empat DC motor berberus, bergear dan bernilai 19 RPM digunakan untuk menggerakkan Ø60 mm roda Mecanum. Ketidaklurusan yang timbul pada motor diluruskan melalui tindakbalas MWR dalam keadaan gelung terbuka dan dianggari dengan menggunakan regresi berpolinomial. Walaubagaimanapun, ketidaklurusan tersebut tidak dapat dihapuskan sepenuhnya dan menjadi ketara terutamanya pada operasi berRPM rendah. Oleh itu, pengawal OS FOPI yang mempunyai susunan berpecahan digunakan. Sebuah anti-penggulungan bersyarat bertujuan menetapkan semula integrasi digunakan bagi mengatasi masalah ketepuan yang disebabkan oleh keperlahanan motor tersebut. Seterusnya, tidak seperti cara pengawalan berkonvensional, sistem kawalan yang dicadangkan tidak memerlukan permodelan-permodelan kinematik, dinamik dan ketidakpastian untuk mencapai penjejakan laluan. Hal ini disebabkan penggunaan cara keluaran berjadual, di mana cara ini melibatkan operasi matematik yang memetakan jumlah dua sudut – sudut orientasi MWR dan sudut antara dua posisi secara lurus, ke nilai untuk mengawal roda Mecanum. Tambahan pula, cara ini mengawal posisi secara langsung dan tidak memerlukan penukaran unit. Secara keseluruhannya, sistem kawalan yang dicadangkan adalah lebih intuitif dan berterus terang. Keberkesanan pengawal OS FOPI disahkan dan dibandingkan dengan pengawal OS P dan pengawal OS PI. Hasil ujikaji menunjukkan bahawa ketiga-tiga pengawal berkeluaran berjadual berjaya mencapai penjejakan bagi laluan yang berkomplikasi tinggi. Tetapi, pengawal OS FOPI menunjukkan penjejakan yang lebih unggul dengan masing-masing mengurangkan ralat penjejakan sebanyak 28 % dan 40 % bagi integrasi ralat bermutlak dan berkuasa dua. Tambahan pula, pengawal OS FOPI mencapai 17 % kurang getaran berbanding dengan pengawal OS PI. Secara kesimpulannya, penjejakan laluan telah berjaya dicapai dengan menggunakan sistem kawalan yang lebih mudah.

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LIST OF ABBREVIATIONS

2-DOF	-	Two-degree-of-freedom
3-DOF	-	Three-degree-of-freedom
ABC	-	Artificial bee colony
ACO	-	Ant colony optimization
COV	-	Coefficient of variation
DC	-	Direct current
DWR	-	Differential-wheeled robot
FA-RBFNN	-	Firefly algorithm optimized radial basis function neural network
FLC	-	Fuzzy logic control
FOPI	-	Fractional-order Proportional-integral
FOPID	-	Fractional-order proportional-integral-derivative
FWNN	-	Fuzzy wavelet neural networks
GA	-	Genetic algorithm
IAE	-	Integral of absolute error
ISCO	-	Integral of squared controller output
ISE	-	Integral of squared error
ITSE	-	Integral of time-weighted squared error
LA-G	-	Linear angle-to-gain
LQR	-	Linear quadratic regulator

LSOGP	-	Localized sparse online gaussian process
MIMO	-	Multi-input multi-output
MWR	-	Mecanum-wheeled robot
NHV	-	Number of high velocities
NLA-G	-	Nonlinear angle-to-gain
OS	-	Output-scheduling
PD	-	Proportional-derivative
PID	-	Proportional-integral-derivative
PI	-	Proportional-integral
PWM	-	Pulse-width-modulation
RFWNN	-	Recurrent fuzzy wavelet neural networks
RL	-	Riemann-Liouville
RMSE	-	Root-mean-square error
RPM	-	Revolutions per minute
SD	-	Standard deviation
SMC	-	Sliding mode controller
SISO	-	Single-input single-output
SPI	-	Serial Peripheral Interface
TSK	-	Takagi-Sugeno-Kang
ZOH	-	Zero-order hold

LIST OF SYMBOLS

K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
λ	-	Fractional integral
μ	-	Fractional derivative
X_G	-	X-axis of global coordinate frame
Y_G	-	Y-axis of global coordinate frame
Z_G	-	Z-axis of global coordinate frame
X_m	-	X-axis of coordinate frame of computer ball mouse *m*
Y_m	-	Y-axis of coordinate frame of computer ball mouse *m*
Z_m	-	Z-axis of coordinate frame of computer ball mouse *m*
k	-	Time-step
$x_{G,\mathrm{MWR}}$	-	X-coordinate of MWR with respect to global coordinate frame
$y_{G,\mathrm{MWR}}$	-	Y-coordinate of MWR with respect to global coordinate frame
$\alpha_{G,\mathrm{MWR}}$	-	Heading of MWR with respect to global coordinate frame
x_m	-	X-coordinate of computer ball mouse *m* with respect to own coordinate frame
y_m	-	Y-coordinate of computer ball mouse *m* with respect to own coordinate frame

α_m	-	Heading of computer ball mouse *m* with respect to own coordinate frame
$\pm$	-	Plus-minus
$g_j(k)$	-	Gain for *j* pair of Mecanum wheel at time-step *k*
$\Gamma(.)$	-	Euler gamma function
$a_p(k)$	-	Actual position at time-step equals to *k*
$r_p(k)$	-	Reference position at time-step equals to *k*
$e_p(k)$	-	Positioning error at time-step equals to *k*
$\Delta t(k)$	-	Difference between two consecutive time-steps
$CO(k)$	-	Controller output
v_j	-	45°-angled velocity of actuation *j*
$y_{f,j}$	-	Final longitudinal displacement of actuation *j*
$x_{f,j}$	-	Final lateral displacement of actuation *j*
$t_{f,j}$	-	Final time of actuation *j*
$t_{s,j}$	-	Starting time of actuation *j*
σ	-	Standard deviation
$\overline{X}$	-	Mean

LIST OF PUBLICATIONS

Journal:

1. Joe Siang Keek, Ser Lee Loh, and Shin Horng Chong, 2019. Comprehensive Development and Control of a Path-trackable Mecanum-wheeled Robot. *IEEE Access,* 7(1), pp.18368–18381.
2. Joe Siang Keek, Ser Lee Loh, and Shin Horng Chong, 2018. Fractional-order Proportional-integral (FOPI) Controller for Mecanum-wheeled Robot (MWR) in Path-tracking Control. *International Journal of Mechanical Engineering and Technology*, 9 (11), pp.325–337.

Conference:

1. J. S. Keek, S. L. Loh, S. H. Chong, 2018. Path Tracking and Optimization for Mecanum-wheeled Robot via Linear Angle-to-Gain (LA-G) Method. In: *2018 6th International Conference on Robot Intelligence Technology and Applications (RiTA).* [Accepted]

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mecanum wheel was born in the era when industrial revolution is vigorously rising, and industrial automation is heavily emphasized, which was during 1970s. Bengt Erland Ilon, who is commonly known as the 'father' of Mecanum wheel, had the ambition of producing manoeuvring omni-directional mobile robot. He then redesigned the conventional wheel into a wheel whose circumference is made up of rollers with all angled at a specific angle and as a result, manoeuvrability is realized (Ilon, 1975). This pioneering design is then named after a Swedish company that he was working with – the Mecanum AB company. Despite having more sophisticated physical design than conventional wheel, the Mecanum wheel is well-accepted and had expeditiously gained popularity since then. This is due to the superiorities of being time-saving and space-saving offered by the manoeuvring Mecanum wheel are highly desirable by many automation and robotic industries (Dickerson and Lapin, 1991). In addition, the wheel was reported in the past (Dillmann et al., 1993) and recent (Olimpiu et al., 2014) literatures for having high load capacity. Today, the application of Mecanum wheel has quickly escalated from industrial robotic manipulator (Hörmann et al., 1991) and automated guided vehicle (Dillmann et al., 1994) to non-industrial application such as humanoid manipulator for kitchen (Asfour et al., 2008), robotic waiter for restaurant (Cheong et al., 2016), rehabilitation (Phichitphon Chotikunnan et al., 2017), just to name a few. The contribution by the technology is undeniably evidently.

However, the heavy price of being manoeuvrable is, the Mecanum-wheeled robot (MWR) is highly prone to various uncertainties such as inconsistent wheel radius, shifting of centre of mass, dynamic wheel-floor friction, nonlinearity and so on. All these factors lead to an ultimate drawback i.e. slippage. The inconsistency within the wheel radius is originated from the gaps between consecutive rollers. Such phenomenon had been noticed in early years and is said to be unavoidable (Dickerson and Lapin, 1991). Whereas in recent years, the characteristic was visualized and studied through simulation and experiment (Villiers and Tlale, 2012). Such varying or oscillating properties of the Mecanum wheel may be relatively small and can be assumed as insignificance, but it certainly has the potential to cause instability (Han et al., 2009). While the shifting of centre of mass and dynamic wheel-floor friction are partially originated from the inconsistent wheel radius, physical factor such as mechanical limitation and floor properties are also the compelling factors of the uncertainties. In additional with the nonlinearity i.e. unique characteristic of each actuators (brushed DC geared motors in this research), occurrence of slippage is very common among the MWR especially during lateral motion (Nagatani et al., 2000; Rohrig et al., 2010). Therefore, under the presence of these uncertainties, the control of MWR in achieving complex path tracking is inevitably a challenging task.

Over the past decades, various types of control structure have emerged for path-trackable MWR. One of the earliest control method reported for the MWR was by using velocity profiles, in which the MWR was controlled with designated angular velocities so that it will stop at desired position (Dillmann et al., 1993). Other than that, Proportional-integral-derivative (PID) controller was more preferred during the 1990s (Wu et al., 1994; Bühler et al., 1995). Since PID controller is single-input single-output (SISO), more than one PID controllers are then needed in order to control all Mecanum wheels.

Therefore, during 2000s, a multi-input multi-output (MIMO) intelligent controller such as fuzzy logic control (FLC) stepped in as an alternative. Generally, modelling of the FLC is based on human intelligence or experience, thus making it flexible and robust towards uncertainties (Kumile and Tlale, 2005). Meanwhile, PID controller remains ubiquitous due to its simplicity, but with additional efforts such as position rectification and corrective methods needed to improve the existing control structure. (Viboonchaicheep et al., 2003; Shimada et al., 2005). Presently, in 2010s, both FLC and PID controller are remained but have incorporated with many advanced schemes such as heuristic online parameter tuning, gain-scheduling, nonlinear modelling and many more. Meanwhile, adaptive, robust and artificial intelligent controllers have started taking place significantly and display promising path tracking performance under the presence of the uncertainties.

Among the above-mentioned controllers, kinematic and dynamic modellings are frequently found in the MWR plant model and are represented as compulsory elements in the hierarchy of the MWR control system. While these modellings assume ideal situation, extra effort such as modelling of uncertainties or introduction of dynamic parameters is required, which is exactly the case of the modern controllers mentioned earlier. It is undeniable that these controllers successfully counteract the uncertainties and achieved decent path tracking performance, however, as more and more supplementary advanced scheme is added into the existing classical controller, the overall control system and modelling process become sophisticated and time-consuming. Eventually, or perhaps it is already happening now that the current trend gives an impression that complex control structure is mandatory in order to develop a robust path-trackable MWR. Straightforward and intuitive control system for the MWR may no longer be an anticipation or convincing approach in the future.