MODELLING OF PROPORTIONAL CONTROLLERS WITH COUNTER-SLIPPAGE MECHANISM FOR E-PATTERN OMNIWHEELED CELLULAR CONVEYOR

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

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DECLARATION

I declare that this thesis entitled “Modelling of Proportional Controllers with Counter-slippage Mechanism for E-pattern Omniwheeled Cellular Conveyor” 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 :

Name : KEEK JOE SIANG

Date : 10 June 2025

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 Doctor of Philosophy.

Signature :...

Supervisor Name : DR. LOH SER LEE

Date : 10 June 2025

DEDICATION

To my supervisors, beloved father, mother and wife.

ABSTRACT

Conveyor system is essential for many industries but can also become a potential chokepoint. It has direct impact on the efficiency of whole process flow. Downtime due to maintenance or reparation is unavoidable among conveyor system. Traditional conveyor such as belt or roller conveyor is prone to downtime due to wear and tear. Additionally, the traditional conveyor system is a single-input-single-output system that conveys object unidirectionally without capability of sorting and arranging. Traditional conveyor system also lacks flexibility and adaptivity to the surrounding environment. The traditional conveyor system has remained almost with the same design since decades ago, even though the world of technologies has gone through multiple revolutions. Therefore, in these recent years, modern conveyor system has risen to overcome the limitation of traditional conveyor. In this research, a modern conveyor system known as E-pattern omniwheeled cellular conveyor (EOCC) has been designed and proposed. EOCC is made up of cells and therefore, faulty cell can be replaced through plug-and-play without interrupting the industrial process flow. Each cell consists of omniwheels and capable of conveying object omnidirectionally. Therefore, while waiting faulty cell to be replaced, conveyance can be temporarily handled by neighbouring cells without stopping the whole conveyor. EOCC requires zero-downtime and ultimately solves the chokepoint issue. Besides that, due to omnidirectional capability, EOCC can support unlimited inputs-outputs, allowing it to handle multiple objects for tasks like sorting, arranging etc., thereby achieving unprecedented efficiency beyond the traditional conveyor. The modularity of EOCC also allows it to be highly adaptive and customizable based on environment. However, the existing modern conveyor literature often does not adequately address uncertain and nonlinear properties of modern conveyor system. Robustness and precision in tracking performance are also lacking. In this research, slippage (uncertainty) and nonlinear properties of the EOCC are first analyzed. It was found that omniwheels on both the X-axis and Y-axis are prone to slippage and nonlinear actuation, with the Y-axis omniwheel being more critical. It is impractical to mathematically model these properties and therefore, slippage detection (SD) and counter-slippage (CS) method are proposed. The final result shows that the proposed 4P-SDCS controller (four proportional gains with slippage detection and counter slippage) outperforms the benchmark controllers. In terms of X-axis and Y-axis trajectory tracking relative value distributions, the 4P-SDCS controller surpasses the benchmark controllers up to 70 % and 72.5 %, respectively. In term of Z-axis error mean and standard deviation, the 4P-SDCS controller outperforms the benchmark controllers up to 74.1 % and 14.4 %, respectively. Besides that, the 4P-SDCS controller scores zero catastrophic slippage throughout all trajectory tracking conducted. The EOCC and its control system are comprehensively validated across different trajectories, different box sizes and masses. Overall, the proposed EOCC and its control system have successfully achieved precision and robustness in trajectory tracking.

PEMODELAN PENGAWAL KADARAN DENGAN MEKANISMA ANTI-GELINCIRAN BAGI PENGHANTAR BERCORAK-E BERSEL DAN BERODA-OMNI

ABSTRAK

Sistem penghantar penting untuk banyak industri dan boleh menjadi jalur penyumbatan yang kritikal. Ia mempunyai impak terhadap kecekapan aliran proses keseluruhan. Masa hentian disebabkan oleh penyelenggaraan atau pembaikan tidak dapat dielakkan. Penghantar tradisional seperti penghantar tali sawat atau roller terdedah kepada masa hentian akibat kehausan dan kerosakan. Selain itu, sistem penghantar tradisional adalah sistem satu-masukkan-satu-keluaran yang mengangkut objek secara sehala tanpa keupayaan untuk menyusun, mengatur dan sebagainya. Sistem penghantar tradisional juga kekurangan fleksibiliti dan adaptasi terhadap persekitaran. Sistem penghantar tradisional kekal hampir dengan reka bentuk yang sama sejak beberapa dekad yang lalu, walaupun dunia teknologi telah melalui pelbagai revolusi. Oleh itu, dalam beberapa tahun kebelakangan ini, sistem penghantar moden telah muncul untuk mengatasi keterbatasan sistem penghantar tradisional. Dalam kajian ini, satu sistem penghantar moden yang dikenali sebagai penghantar bercorak E bersel dan beroda omni (EOCC) telah direka dan dicadangkan. EOCC terdiri daripada sel-sel dan oleh itu, sel yang rosak boleh diganti melalui sistem pasang-dan-pakai tanpa mengganggu aliran proses industri. Setiap sel terdiri daripada roda omni dan mampu mengangkut objek dalam semua arah. Oleh itu, semasa menunggu sel yang rosak diganti, penghantaran boleh dikendalikan sementara oleh sel-sel bersebelahan tanpa masa hentian. EOCC tidak memerlukan masa hentian justeru menyelesaikan isu jalur penyumbatan. Disebabkan berroda omni, EOCC boleh menyokong bilangan masukkan-keluaran tanpa had, membolehkannya mengendalikan pelbagai objek untuk tugas seperti menyusun, mengatur dan sebagainya, sekali gus mencapai kecekapan yang luar biasa berbanding penghantar tradisional. EOCC yang bersel juga membolehkannya menjadi adaptif dan diubahsuai berdasarkan persekitaran. Literatur mengenai penghantar moden yang sedia ada selalunya tidak menangani ketidakpastian dan sifat tidak linear dengan secukupnya. Keteguhan dan ketepatan juga berkurangan. Dalam kajian ini, gelinciran (ketidakpastian) dan sifat tidak linear di EOCC telah dianalis. Roda omni di paksi X dan Y bersifat gelincir and tidak linear, terutamanya di paksi Y. Permodelan secara matematik adalah kurang berpraktikal, justeru, kaedah pengesanan gelinciran (SD) dan kaedah menentang gelinciran dicadangkan. Hasil menunjukkan bahawa pengawal 4P-SDCS yang dicadangkan mengatasi pengawal asas. Dari segi pengedaran nilai relatif penjejakan trajektori pada paksi X dan Y, pengawal 4P-SDCS mengatasi pengawal aras sebanyak 70% dan 72.5% masing-masing. Dari segi purata ralat paksi Z dan sisihan piawai, pengawal 4P-SDCS mengatasi pengawal aras sebanyak 74.1% dan 14.4% masing-masing. Selain itu, pengawal 4P-SDCS tidak mengalami gelinciran bencana di semua penjejakan trajektori. EOCC dan sistem kawalannya telah disah secara menyeluruh dengan trajektori, saiz kotak dan jisim yang berbeza. Secara keseluruhannya, EOCC dan sistem kawalannya telah berjaya mencapai ketepatan dan keteguhan dalam penjejakan trajektori.

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To myself, life has been really tough on you, but you’ve fought hard every time. You may not have started with favorable circumstances most of the time, but look how far you’ve come, it’s all because you never give up. Keep going, soon you will shine.

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LIST OF ABBREVIATIONS

EOCC	-	E-pattern Omniwheeled Cellular Conveyor
PLC	-	Programmable Logic Controller
FEM	-	Finite Element Method
AI	-	Artificial Intelligence
PID	-	Proportional-Derivative-Integral
KARIS	-	Karlsruhe Autonomous Robotic Interactive System
SCM	-	Small-Scaled Conveyor Modules
LSO	-	Large Size and Small Size of Omniwheels
F-ODT	-	Fast-Omnidirectional Treadmill
4P-SDCS	-	P-P-P-P Controller with slippage detection and counter-slippage
DCS	-	Decentralized Control System
CCS	-	Centralized Control System
RFID	-	Radio Frequency Identification
IoT	-	Internet of Things
CMS	-	Centralized Model System
CAN	-	Controller Area Network
R-CNN	-	Region-based Convolution Neural Network
VSC	-	Variable Structure Controller
SMC	-	Sliding Mode Control
VCS	-	Variable Structure Controller
IAE	-	Integral of Error
ISE	-	Integral of Squared Error
FSTC	-	Fuzzy Sliding-Mode Tracking Control

ML	-	Machine Learning
CAD	-	Computer Aided Design
V-REP	-	Virtual Robot Experimentation Platform
API	-	Application Programming Interface
OpenCV	-	Open Source Computer Vision
RPM	-	Rotation per Minute
SI	-	System of Units
DOE	-	Design of Experiment
HT	-	Horizontal-Top
HM	-	Horizontal-Middle
HB	-	Horizontal-Bottom
VL	-	Vertical-Left
VM	-	Vertical-Middle
VR	-	Vertical-Right
SD	-	Slippage Detection
CS	-	Counter-Slippage

LIST OF SYMBOLS

k	-	Timestep
θ_c	-	Orientation of box
x_c	-	X-axis coordinate of box
y_c	-	Y-axis coordinate of box
x_r	-	X-axis coordinate of reference point
y_r	-	Y-axis coordinate of reference point
x_{diff}	-	Distance between box and reference point in X-axis
y_{diff}	-	Distance difference between box and reference point in Y-axis
Δ	-	Difference
R	-	Reference input of control system
A	-	Actual output of control system
e	-	Difference between reference input and actual output of control system
$\pm$	-	Plus-minus
$K_P^{x,S}$	-	Proportional gain of small omniwheel in X-axis control
$K_D^{x,S}$	-	Derivative gain of small omniwheel in X-axis control
$K_P^{y,L}$	-	Proportional gain of large omniwheel in Y-axis control
$K_D^{y,L}$	-	Derivative gain of large omniwheel in Y-axis control
$K_P^{z,S}$	-	Proportional gain of small omniwheel in Z-axis control
$K_P^{z,L}$	-	Proportional gain of large omniwheel in Z-axis control
$C_{\text{PD}}(z)$	-	PD controller in discrete time domain
T_s	-	Sampling time
K_U	-	Ultimate gain
T_U	-	Period when controller gain equals to ultimate gain
$\alpha(n)$	-	Exponential decaying factor

n	-	Index of an element in a sample sampled from a population
$E_{\max}$	-	Duration of trajectory generation
r_{HT}^{x}	-	HT trajectory reference value in X-axis
r_{HT}^{y}	-	HT trajectory reference value in Y-axis
Σ	-	Summation
$\lvert e(k) \rvert$	-	Modulus of error at timestep k

LIST OF APPENDICES

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

1. J. S. Keek, S. L. Loh, A. N. Hanafi and T. H. Cheong, 2024. Pre-slippage detection and counter-slippage for e-pattern omniwheeled cellular conveyor. *Bulletin of Electrical Engineering and Informatics*, 13(4), pp. 2298–2309. (*Published. Scopus Q3*)

2. J. S. Keek, S. L. Loh, and S. H. Chong, 2021. Design and Control System Setup of an E-Pattern Omniwheeled Cellular Conveyor. *Machines*, 9(2), pp. 1–32. (*Published WoS / Scopus Q2*)

CHAPTER 1

INTRODUCTION

1.1 Background

The origin of conveyor system can be traced back all the way to the first industrial revolution in the late 18th century. Conveyor system was primarily used to convey or transport raw materials such as coal, grain and rock. Back then, when motorized rotor is still in bud stage, people are willing to develop a hand-operated conveyor system to assist their operations. As one can expect, once advanced actuator such as coal-powered and electric-powered actuators were invented, conveyor system became the limelight of automation. Conveyor technology achieved a significant breakthrough when Henry Ford introduced conveyor-based assembly line into automobile industry in early 19th century, successfully boosting the productivity. It then became a stepping stone or a launching pad that popularized the conveyor system. Conveyor technology then became a de facto for many industries.

It is remarkable that conveyor technology has persisted since the first industrial revolution, which has been almost two centuries ago. Unlike other machinery from the same era, such as the telegraph and steam engine, which have become obsolete due to rapid technological advancement, the importance of conveyor technology has continued to remain relevant and without any sign of obsolescence in near future. In many industrials nowadays, one of the bottlenecks of a process flow is located at the logistics section and conveyor system is a part of it. In other words, improving the efficiency of conveyor system can directly improve the productivity, which will impact the revenue of the company.

The demand for conveyor system has been growing exponentially and without any sign of slowing down. It is fascinating to see conveyor system from conveying raw material in 18th century to now 20th century in new industries such as e-commerce, airports and many more. Despite growing demand, conveyor technology has not been through significant changes or advancement. Belt and roller conveyors have remained the primary conveyor for centuries. Without advancement, reliance on belt and roller conveyor means stagnant in efficiency improvement. Moreover, traditional conveyor such as belt and roller conveyor are highly prone to physical wear and tear, which require never-ending hectic maintenance and sustaining. Therefore, it is crucial for researchers and engineers from the field of conveyor technology to innovate beyond the traditional conveyor systems, pursuing greater efficiency to quickly catch-up with the fast-growing demand.

1.2 Problem Statement

Traditional conveyor system is simple and straightforward, but it has several critical limitations that create bottlenecks in productivity and efficiency. Traditional conveyor system can only convey objects in one direction, with only one inbound and one outbound available. No sorting, no orientation control and no precise positioning available by default. It is common to add linear actuator to the traditional conveyor to enable a few additional degrees of freedom. However, this requires additional design and development but yet after all these efforts, the traditional conveyor only achieves a slight improvement in efficiency.