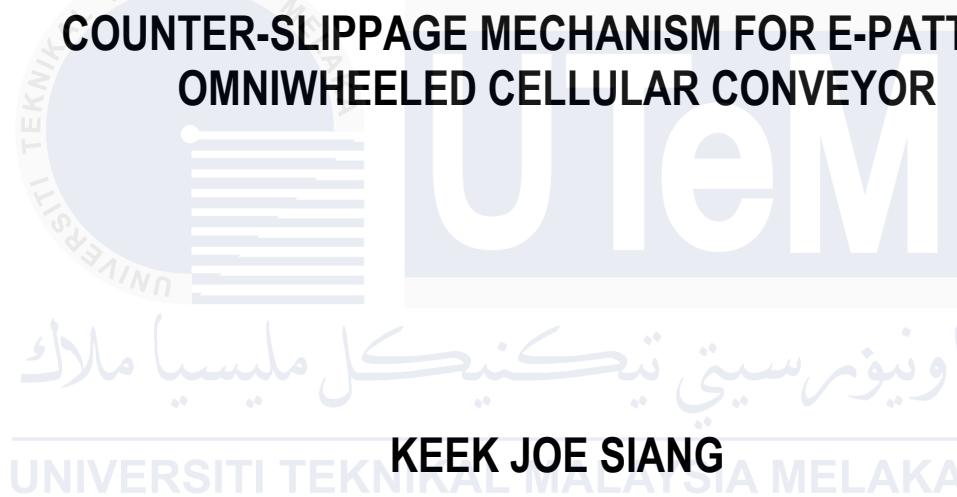




**MODELLING OF PROPORTIONAL CONTROLLERS WITH
COUNTER-SLIPPAGE MECHANISM FOR E-PATTERN
OMNIWHEELED CELLULAR CONVEYOR**



KEEK JOE SIANG

DOCTOR OF PHILOSOPHY

2025



Faculty of Electrical Technology and Engineering

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Faculty of Electrical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

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.



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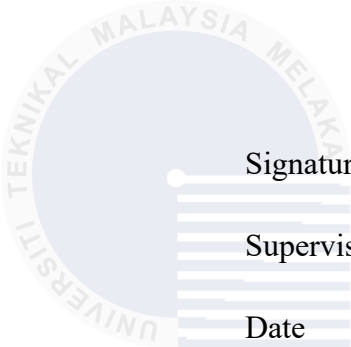
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APPROVAL

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 Doctor of Philosophy.

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	Date	: 10 June 2025

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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 BERSSEL 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 sehalu 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 beroda 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 dianalisis. 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.

ACKNOWLEDGEMENT

Firstly, I would like to express utmost gratitude to my supervisor, Dr. Loh Ser Lee, co-supervisor, Dr. Ainain Nur Binti Hanafi and former co-supervisor, Dr. Chong Shin Horng. Their support, guidance and kindness for me had helped me to complete this research.

I would like to acknowledge Fundamental Research Grant Scheme by Ministry of Higher Education of Malaysia, grant number FRGS/2018/FKE-CERIA/F00352 for funding the first and second year of this research. I would like to also acknowledge Motion Control Research Laboratory, Centre for Robotics and Industrial Automation, Faculty of Electrical Technology and Engineering and of course my beloved university, Universiti Teknikal Malaysia Melaka, a place where I spent a decade of bittersweet memories with.

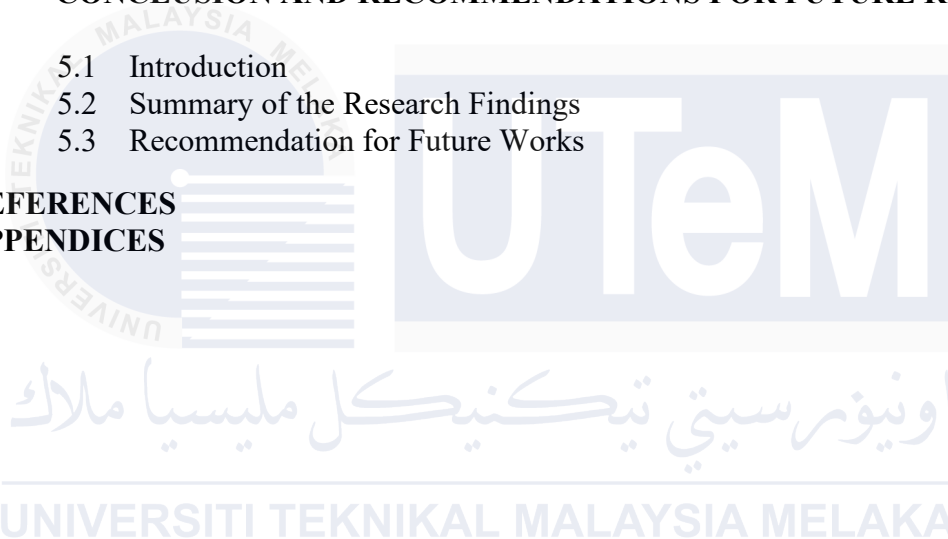
I would like to thank my beloved father, mother and brother for they have encouraged and shaped me into a person capable of pursuing highest level of education. To my beloved wife, I can't thank her enough for her unwavering support, patience and encouragement for me throughout this journey, through the thick and thin, from girlfriend to now as my wife. This achievement stands as a testament to their love and belief in me.

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.

TABLE OF CONTENTS

	PAGES
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	viii
LIST OF ABBREVIATIONS	xi
LIST OF SYMBOLS	xiii
LIST OF APPENDICES	xv
LIST OF PUBLICATIONS	xvi
 CHAPTER	
1. INTRODUCTION	17
1.1 Background	17
1.2 Problem Statement	18
1.3 Research Objective	21
1.4 Scope of Research	21
1.5 Research Contribution	22
1.6 Thesis Outline	23
 2. LITERATURE REVIEW	24
2.1 Introduction	24
2.2 Conveyor Technologies	25
2.3 Existing Traditional Conveyor Technologies	29
2.4 Existing Omnidirectionality and Modularity in Conveyor Technologies	39
2.5 Existing Control System	54
2.6 Existing Controller	65
2.7 Slippage and Dead Spot	75
2.8 Summary	82
 3. METHODOLOGY	84
3.1 Introduction	84
3.2 Environment Setup	84
3.3 Design of Control System	91
3.3.1 Design of 'Feedback' Block	92
3.3.2 Characterization of 'Process' Block	100
3.3.3 Design of 'Controller' Block	109
3.4 Design of Experiment	122
3.4.1 Design of Trajectory	123
3.4.2 Performance Indexes	126
3.5 Summary	128

4.	RESULT AND DISCUSSION	129
4.1	Introduction	129
4.2	Trajectory Tracking Performance Analysis	129
4.2.1	Horizontal-Top Trajectory	131
4.2.2	Horizontal-Middle Trajectory	149
4.2.3	Horizontal-Bottom Trajectory	168
4.2.4	Vertical-Left Trajectory	185
4.2.5	Vertical-Middle Trajectory	202
4.2.6	Vertical-Right Trajectory	218
4.3	Combined Analysis	235
4.4	Summary	239
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	240
5.1	Introduction	240
5.2	Summary of the Research Findings	240
5.3	Recommendation for Future Works	242
	REFERENCES	244
	APPENDICES	258



LIST OF TABLES

TABLE	TITLE	PAGE
Table 2.1	Summary of selected modern conveyors from the literature	83
Table 3.1	Parameters (controller gain) of each controller	117
Table 4.1	IAE of X-axis tracking error in HT trajectory	146
Table 4.2	ISE of X-axis tracking error in HT trajectory	146
Table 4.3	IAE of Y-axis tracking error in HT trajectory	147
Table 4.4	ISE of Y-axis tracking error in HT trajectory	147
Table 4.5	IAE of Z-axis tracking error in HT trajectory	148
Table 4.6	ISE of Z-axis tracking error in HT trajectory	148
Table 4.7	IAE of X-axis tracking error in HM trajectory	165
Table 4.8	ISE of X-axis tracking error in HM trajectory	165
Table 4.9	IAE of Y-axis tracking error in HM trajectory	166
Table 4.10	ISE of Y-axis tracking error in HM trajectory	166
Table 4.11	IAE of Z-axis tracking error in HM trajectory	167
Table 4.12	ISE of Z-axis tracking error in HM trajectory	167
Table 4.13	IAE of X-axis tracking error in HB trajectory	181
Table 4.14	ISE of X-axis tracking error in HB trajectory	181
Table 4.15	IAE of Y-axis tracking error in HB trajectory	182
Table 4.16	ISE of Y-axis tracking error in HB trajectory	182
Table 4.17	IAE of Z-axis tracking error in HB trajectory	183
Table 4.18	ISE of Z-axis tracking error in HB trajectory	183
Table 4.19	IAE of X-axis tracking error in VL trajectory	198
Table 4.20	ISE of X-axis tracking error in VL trajectory	198

Table 4.21	IAE of Y-axis tracking error in VL trajectory	199
Table 4.22	ISE of Y-axis tracking error in VL trajectory	199
Table 4.23	IAE of Z-axis tracking error in VL trajectory	200
Table 4.24	ISE of Z-axis tracking error in VL trajectory	200
Table 4.25	IAE of X-axis tracking error in VM trajectory	215
Table 4.26	ISE of X-axis tracking error in VM trajectory	215
Table 4.27	IAE of Y-axis tracking error in VM trajectory	216
Table 4.28	ISE of Y-axis tracking error in VM trajectory	216
Table 4.29	IAE of Z-axis tracking error in VM trajectory	217
Table 4.30	ISE of Z-axis tracking error in VM trajectory	217
Table 4.31	IAE of X-axis tracking error in VR trajectory	232
Table 4.32	ISE of X-axis tracking error in VR trajectory	232
Table 4.33	IAE of Y-axis tracking error in VR trajectory	233
Table 4.34	ISE of Y-axis tracking error in VR trajectory	233
Table 4.35	IAE of Z-axis tracking error in VR trajectory	234
Table 4.36	ISE of Z-axis tracking error in VR trajectory	234

LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 2.1	Comparison of different material carriers	25
Figure 2.2	Comparison of two types of conveyor system	28
Figure 2.3	Physical appearance of reviewed modern conveyors	42
Figure 3.1	Physical appearance of one E-pattern omniwheeled cellular conveyor (EOCC) cell, which consists of large and small omniwheels	85
Figure 3.2	Modelling of omniwheel's wheel and roller by using joint and sphere in V-REP	88
Figure 3.3	A top view screenshot of the proposed E-pattern omniwheeled cellular conveyor (EOCC) platform in V-REP environment	90
Figure 3.4	General block diagram of a control system	92
Figure 3.5	Image acquisition and stages of image processing	93
Figure 3.6	Stages of image processing to extract absolute position and orientation of the box	96
Figure 3.7	(a) and (d) refers to images captured at time $k = 0$ ms, (b) and (e) at time $k = 660$ ms, and (c) and (f) at time $k = 8040$ ms in one of the trajectory tracking experiment	99
Figure 3.8	Open-loop step response in terms of starting position (128 px, 128 px) – (a), (c), (e), (g), (i) and starting position (102 px, 173 px) – (b), (e), (f), (h), (j)	102
Figure 3.9	Closed-loop step response of PD-PD controller with starting position (128 px, 128 px)	106
Figure 3.10	Closed-loop orientation control with PD-PD controller and with step reference input of 180 at different starting position	107
Figure 3.11	Control system block diagram of EOCC	110
Figure 3.12	Working principle of 'Rotation Direction Decider' block	112
Figure 3.13	Oscillatory response for ZN tuning method	116

Figure 3.14	Symmetrical triangular signal for counter-slippage mechanism	118
Figure 3.15	Trajectory tracking performance with and without slippage detection	121
Figure 3.16	Finalized control system block diagram for EOCC	122
Figure 3.17	S-shaped trajectories span horizontally	124
Figure 3.18	S-shaped trajectories span vertically	124
Figure 4.1	Different sizes of box with respect to the size of the EOCC platform	130
Figure 4.2	HT trajectory tracking performances on Cartesian plane	133
Figure 4.3	HT trajectory tracking performances in term of X-axis tracking error	136
Figure 4.4	HT trajectory tracking performances in term of Y-axis tracking error	139
Figure 4.5	HT trajectory tracking performances in term of Z-axis tracking error	143
Figure 4.6	HT trajectory tracking performances by using 0.333 kg 0.040 m ² box 144	
Figure 4.7	HM trajectory tracking performances on Cartesian plane	151
Figure 4.8	HM trajectory tracking performances in term of X-axis tracking error	155
Figure 4.9	HM trajectory tracking performances in term of Y-axis tracking error	158
Figure 4.10	HM trajectory tracking performances in term of Z-axis tracking error	162
Figure 4.11	HB trajectory tracking performances on Cartesian plane	169
Figure 4.12	HB trajectory tracking performances in term of X-axis tracking error	173
Figure 4.13	HB trajectory tracking performances in term of Y-axis tracking error	176
Figure 4.14	HB trajectory tracking performances in term of Z-axis tracking error	180

Figure 4.15	VL trajectory tracking performances on Cartesian plane	186
Figure 4.16	VL trajectory tracking performances in term of X-axis tracking error	190
Figure 4.17	VL trajectory tracking performances in term of Y-axis tracking error	193
Figure 4.18	VL trajectory tracking performances in term of Z-axis tracking error	197
Figure 4.19	VM trajectory tracking performances on Cartesian plane	203
Figure 4.20	VM trajectory tracking performances in term of X-axis tracking error	207
Figure 4.21	VM trajectory tracking performances in term of Y-axis tracking error	210
Figure 4.22	VM trajectory tracking performances in term of Z-axis tracking error	213
Figure 4.23	VR trajectory tracking performances on Cartesian plane	220
Figure 4.24	VR trajectory tracking performances in term of X-axis tracking error	224
Figure 4.25	VR trajectory tracking performances in term of Y-axis tracking error	227
Figure 4.26	VR trajectory tracking performances in term of Z-axis tracking error	230
Figure 4.27	Collection of all X-axis relative value of each controller	236
Figure 4.28	Collection of all Y-axis relative value of each controller	237
Figure 4.29	Collection of all Z-axis tracking error of each controller	238

LIST OF ABBREVIATIONS

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

<i>ML</i>	-	Machine Learning
<i>CAD</i>	-	Computer Aided Design
<i>V-REP</i>	-	Virtual Robot Experimentation Platform
<i>API</i>	-	Application Programming Interface
<i>OpenCV</i>	-	Open Source Computer Vision
<i>RPM</i>	-	Rotation per Minute
<i>SI</i>	-	System of Units
<i>DOE</i>	-	Design of Experiment
<i>HT</i>	-	Horizontal-Top
<i>HM</i>	-	Horizontal-Middle
<i>HB</i>	-	Horizontal-Bottom
<i>VL</i>	-	Vertical-Left
<i>VM</i>	-	Vertical-Middle
<i>VR</i>	-	Vertical-Right
<i>SD</i>	-	Slippage Detection
<i>CS</i>	-	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
$C_{PD}(z)$	-	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
$ e(k) $	-	Modulus of error at timestep k



LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Open-loop Step Response Analysis	258



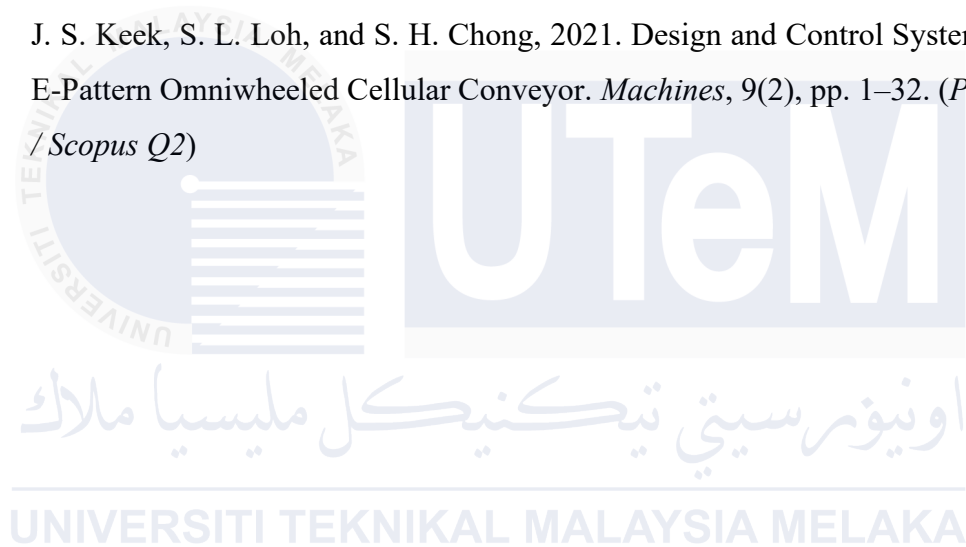
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LIST OF PUBLICATIONS

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.