UNIVERSITI TEKNOLOGI MARA

AN ENHANCED MOTION PLANNING METHOD FOR INDUSTRIAL ROBOTS BASED ON THE DIGITAL TWIN CONCEPT

FAN RUI

Thesis submitted in fulfilment
of the requirements for the degree of
Doctor of Philosophy
(Electrical Engineering)

Faculty of Electrical Engineering

September 2025

ABSTRACT

With the rapid advancement of global digital transformation and smart manufacturing strategies, industrial robots and Digital Twin(DT) technologies have emerged as core drivers in promoting intelligent manufacturing upgrades, enhancing production efficiency, and optimizing workforce allocation. Motion planning for industrial robots based on DT technology helps improve trajectory accuracy, optimize operational efficiency, and reduce physical debugging risks. This study proposes a novel motion planning method for six-degree-of-freedom industrial robots based on DT technology. By integrating an improved Artificial potential field method, A* algorithm, and a synergistic approach combining 3-5-3 polynomial interpolation with particle swarm optimization, we effectively address the challenges of dynamic obstacle avoidance and trajectory optimization. The research establishes an accurate kinematic model using Denavit-Hartenberg parameters and develops an efficient simplified envelope collision detection method. Experimental validation was conducted on a DT verification system comprising MATLAB, PQFactory (a Chinese virtual debugging software), and a physical robot workstation. The experimental results demonstrate that the proposed method achieves an 85% success rate in obstacle avoidance while significantly reducing trajectory execution time by 44.52%. The system maintains high-precision synchronization between virtual and physical counterparts, with positioning errors constrained within 0.224% for the end-effector and 0.300% for joint angles. Compared to traditional virtual simulation techniques, the DT approach employed in this study, featuring real-time data interaction, multi-physics accurate modeling, and closed-loop feedback mechanisms, not only substantially improves motion planning accuracy and execution efficiency but also provides an innovative solution for developing highly adaptable, efficient, and reliable intelligent manufacturing robotic systems. These findings establish a solid technical foundation for industrial robot applications in complex environments.

ACKNOWLEDGEMENT

Firstly, I wish to thank God for giving me the opportunity to embark on my PhD and for completing this long and challenging journey successfully. My gratitude and thanks go to my supervisor Muhammad Azmi Ayub, Fazlina Ahmat Ruslan, Mohd Nor Azmi Ab Patar and Sukarnur Che Abdullaha.

My appreciation goes to the leaders and teachers of Hebei Institute of Mechanical and Electrical who provided the facilities and assistance during sampling and experiment. Special thanks to my colleagues and friends for helping me with this project.

Finally, this thesis is dedicated to my parents. Thanks to them for nurturing me and giving me strong support in completing my studies, this piece of victory is dedicated to both of you.

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CHAPTER 1
INTRODUCTION

1.1 Research Background

Against the backdrop of accelerated digital transformation in global manufacturing, industrial robots are being increasingly applied across various sectors, including automotive, electronics, food processing, and aerospace, significantly enhancing productivity, product quality, and competitiveness [1]. As a representation of a nation's high-level manufacturing capabilities, industrial robots have consistently been a focal point for research and development among leading industrial nations worldwide. Many leading industrialized nations have formulated strategic frameworks to advance their robotics industries. For example, Japan launched the "New Robot Strategy" as early as 2015, aiming to make Japan a world center for robotics innovation; The German Federal Ministry of Education and Research released the "High Tech Strategy 2025", which includes development projects for multiple robot systems [2]; The National Science Foundation of the United States released the "National Robotics Initiative 2.0" in 2019 to support the research and application of innovative robots [4]. The Chinese government has introduced the " Made in China 2025" to enhance its robotics industry by improving the development system, increasing core component production capacity, fostering technological innovation, and advancing application integration [5]. These strategic frameworks underscore the vital role of industrial robotics as a hallmark of advanced manufacturing.

According to the "2024 World Robotics Report" released by the International Federation of Robotics (IFR), the number of robots operating in factories worldwide reached 4281585 by the end of 2023. Compared to the previous year, it has increased by 10%. The annual installation volume has exceeded 500000 units for the third consecutive year, with a total of 541302 units installed in 2023, as shown in Figure 1.1 [6]. To address global economic competition, companies are increasingly adopting robotics to boost productivity, lower costs, and advance automation. This trend of rapid growth underscores the broadening and deepening application of industrial robots worldwide.