UNIVERSITI TEKNOLOGI MARA

RECONFIGURABLE ROBOT AND DEEP LEARNING-BASED SYSTEM FOR SEWER PIPELINE INSPECTION

JIA CHAOYU

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

Faculty of Electrical Engineering

October 2025

ABSTRACT

The inspection of underground sewer pipelines presents significant challenges due to harsh environmental conditions and structural complexities. Conventional methods such as manual evaluations and CCTV-based assessments are often inefficient and lack adaptability to varied pipeline structures, while existing inspection robots suffer from limited manoeuvrability, power efficiency, and defect detection accuracy, especially in unstructured environments with sediment and water. To address these issues, this study proposes a reconfigurable pipeline robot with an adaptive locomotion mechanism designed for enhanced navigation and stability in complex sewer settings. The robot features a compact structure, underwater sealing, and a high-load transmission system, supported by a dynamic posture adjustment mechanism using yaw and pitch control to improve mobility across inclined and sediment-laden surfaces. Complementing the hardware, an enhanced deep learning model based on the IYOLOv8 architecture is introduced, incorporating RepGFPN and DynamicHead modules to improve multi-scale feature extraction and detection precision. Experimental results on a real-world sewer defect dataset show that the proposed system achieves a mean Average Precision (mAP) of 90.9%, with a detection speed of 61.5 FPS and robustness across various noisy conditions, outperforming the original YOLOv8 and other state-of-the-art models. These results confirm the system's effectiveness and reliability in sewer pipeline defect detection, providing a scalable solution for intelligent underground infrastructure monitoring.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisor, Wan Nurshazwani Wan Zakaria and Nor Azmi Bin Ab Patar, for their invaluable guidance, encouragement, and continuous support throughout my PhD journey. Their profound insights, rigorous academic standards, and unwavering patience have greatly shaped both my research and my personal growth. I am truly fortunate to have had the opportunity to learn from such an inspiring mentor.

I would like to acknowledge my institution for providing the resources, facilities, and funding necessary to conduct this research. Without this support, many aspects of this work would not have been possible.

Above all, I am profoundly thankful to my family for their unconditional love, patience, and encouragement. Their unwavering belief in me, even during the most challenging times, has been my greatest source of strength. I am especially grateful to my wife Yao Liuchi for her sacrifices and constant support throughout this long journey.

This journey has been filled with learning, growth, and unforgettable experiences. I will forever cherish the support I have received from everyone who has been part of this chapter in my life. Thank you all.

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

1.1 Research Background

As a vital component of urban infrastructure, the municipal underground sewer network serves not only to discharge rainwater and sewage but also plays a critical role in flood prevention, waste management, and enhancing the urban ecological environment. Its proper functioning is directly linked to the city's overall operational efficiency and the quality of life for its residents. However, with the rapid pace of urbanization, rising urban population density, and the growing frequency of extreme weather events driven by climate change, the significance of sewer networks has become increasingly evident (Abraham et al. 1998; Zeydalinejad et al. 2024). Meanwhile, the advancement of urbanization has led to the gradual expansion of the sewer network, but the accompanying problems have become increasingly severe (Mohandes et al. 2024). Due to prolonged construction periods, ageing materials, deteriorating pipeline structures, and the inadequate consideration of modern urban sewer demands during initial design phases, certain pipelines are unable to withstand heavy loads. In addition, due to the imperfect construction standards and inadequate maintenance and management work, the phenomenon of sedimentation, blockage, leakage, and even collapse in the pipeline network is not uncommon (Cheng, 2024). Especially during the flood season, the insufficient capacity of the sewer system often directly leads to urban waterlogging problems, causing road damage, breakage to public facilities, and even endangering life and property safety. This situation not only causes serious disruption to the daily lives of urban residents but also poses a huge challenge to the overall operational efficiency and environmental governance effectiveness of the city.

In this context, the demand for detecting sewer defects in sewer networks has rapidly increased, becoming a key area of concern in current urban construction and management (Fu et al. 2022; Tscheikner-Gratl et al. 2019). Regular frequency and comprehensive detection and evaluation of the operation status of the sewer pipeline network is important for maintenance and efficient management of the pipeline network This practice can reduce potential risks and hidden dangers and provide guarantee for