UNIVERSITI TEKNOLOGI MARA

EFFECTIVE FLEXIBLE PAVEMENT DEFECT DETECTION VIA DETECTION TRANSFORMER WITH ENHANCED QUERY SELECTION EMBEDDINGS AND HESSIAN-FREE ADAMW TRUST-REGION OPTIMIZATION

MOHD IKMAL FITRI BIN MARUZUKI

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

Faculty of Electrical Engineering

August 2026

ABSTRACT

Automated detection of flexible pavement defects is critical for proactive road maintenance, enhancing transportation safety and reducing long-term infrastructure costs. While current DEtection TRansformer (DETR)-based solutions show significant promise for this task, their practical effectiveness is often constrained primarily by three interconnected challenges. The first limitation is the existing bottleneck within the Query Selection (QS) mechanisms of DETR. Current QS mechanisms heavily rely on non-differentiable and deterministic Top-*k* selection. This simplistic, hard-selection process prevents the model from learning an optimal selection policy. Second, the feature extractors used to guide the QS process are often inadequate. Existing modules typically rely on shallow convolutional layers that severely restrict the model's representational capacity, creating a suboptimal base for identifying important regions. The third outstanding issue pertains to the optimization strategies utilized during training. Current standard optimization methods struggle to efficiently navigate the highly non-convex loss landscapes characteristic of advanced DETRs. To address these identified gaps, the primary objective of this research focuses on developing a novel, high-performing framework to alleviate the limitations of current DETR solutions in flexible pavement defect detection. To achieve the primary objective, the proposed framework features three main contributions. First, a learnable and probabilistic Adaptive Query Indexing with Stochastic Alignment (AQISHA) selection mechanism was introduced to replace the deterministic Top-*k* methods. Second, a lightweight yet semantically rich MobileNetV3 feature extractor was integrated into the module. Together, the AQISHA and MobileNetV3 components formed the novel Query Selection Embedding (QS-Embedding) module for DETR. Third, a novel Hessian-Free AdamW Trust-Region (Adam-HFTR) optimizer was developed to improve training performance by approximating the Hessian matrix. Evaluation of the overall system on the benchmark Road Damage Detection Dataset 2020 (RDD2020) dataset validated its efficacy. The proposed framework achieved a mean Average Precision at 0.50 IoU (mAP@.50) of 0.6460, outperforming the current state-of-the-art SEAF-DETR performance of 0.6190. Extensive ablation studies further corroborated the significant individual efficacy of both the QS-Embedding module and the Adam-HFTR optimizer. In conclusion, the proposed framework establishes a highly effective system for flexible pavement defect detection, advancing the state-of-the-art in intelligent flexible pavement monitoring while directly supporting the United Nations (UN)' Sustainable Development Goal 11 (SDG11) by promoting safe, resilient, and sustainable transportation networks.

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful.

All praise is due to Allah SWT. This thesis is a miracle of His grace. I am eternally grateful to Him, in the name of Al-Waliy, Ar-Razzaq and Al-Wadud: for the strength to endure, the courage to forgive, and the light that guided me through the hard seasons of this journey. To look back from this moment is to see that every trial was a lesson, and every moment of hardship was held in His hands.

I would like to express my deepest gratitude to my supervisory committee for their unwavering belief in this work. To my main supervisor, Associate Professor Dr. Khusairi Osman (Faculty of Electrical Engineering); and to my co-supervisory team Dr. Anas Ibrahim (Faculty of Civil Engineering), Associate Professor Ir. Ts. Dr. Samsul Setumin (Faculty of Electrical Engineering). Thank you for the immense patience, for the technical brilliance, and for providing the academic pillars upon which this research stands.

To my close family, you are my heart's core. To my beloved wife, Sharifah Nadiah Binti Syed Adnan, who stayed by my side when the gradient was steepest, and your love was my constant. To my two precious daughters, Auni Qisha Arisa and Ayra Qisha Aqila: they are my "hidden" strength. Every smile they give me provided the spirit I needed to keep moving forward toward a better tomorrow. I would like to express my eternal gratitude to my siblings, whose motivation and financial support made this achievement possible.

My deepest gratitude goes to first and foremost close members of Machine Learning Research Group (MLRG) and the colleagues of Faculty of Electrical Engineering, UiTM Cawangan Pulau Pinang. They are more than just an academic institution. I am profoundly thankful for the unwavering belief they had in me during my lowest points. Their support provided the bridge that allowed me to transition from a period of great difficulty, giving me a place to belong, and a reason to hope.

I also wish to extend my heartfelt thanks to PDMKM Hani and PMDUU Sheikh. Their encouragement and love had been a source of support. I am equally grateful to my colleagues: V Dharan, Yeap HC, Dr. SO Ayat, Dr. Boon KH, Dr. HUUH Abdellatef, Dr. Lee YH, Dr. A. Alamgir, and Dr. Jeevan. A very special mention to Dr. Liew SS, whose technical brilliance and motivational spirit were vital in the making of this thesis.

I would also like to acknowledge the many individuals who supported me directly and indirectly behind the scenes. Finally, this work is dedicated to my parents. To my father, Maruzuki Shaharudin, thank you for your enduring love. And to my late mother, , this is for *mak*. I hope you are looking down with a smile, knowing that family is the silent strength that carried me through the years.

TABLE OF CONTENTS

		Page
CONFIRMATION BY PANEL OF EXAMINERS		**ii**
AUTHOR'S DECLARATION		**iii**
ABSTRACT		**iv**
ACKNOWLEDGEMENT		**v**
TABLE OF CONTENTS		**vi**
LIST OF TABLES		**xi**
LIST OF FIGURES		**xiv**
LIST OF SYMBOLS		**xxiv**
LIST OF ABBREVIATIONS		**xxviii**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Research Background	1
1.2	Problem Statement	5
1.3	Research Objectives	9
1.4	Scope of Research	9
1.5	Thesis Outline	11
CHAPTER 2	**LITERATURE REVIEW**	**12**
2.1	Introduction	12
2.2	Pavement Systems	13
2.3	Taxonomy of Pavement Defects	16
	2.3.1 Cracking Defects	17
	2.3.2 Surface Deformation Defects	26
	2.3.3 Surface Texture and Edge Defects	33
2.4	Conventional Pavement Inspection Methodologies	45
	2.4.1 Manual Inspection	45
	2.4.2 Non-Destructive Testing (NDT) and Sensor-Based Systems	46
	2.4.3 Drawbacks of Conventional Pavement Inspection	50
2.5	Traditional Computer Vision and Machine Learning Approaches	52
	2.5.1 Past Works with Traditional Pavement Defect Detection	54

CHAPTER 1
INTRODUCTION

1.1 Research Background

Ensuring the integrity of flexible pavement infrastructure is critical for public safety and economic efficiency, serving as a primary catalyst for achieving the United Nations (UN)' Sustainable Development Goal 11 (SDG11) regarding sustainable and resilient urban transportation development (Almulhim et al., 2024; Barbhuiya et al., 2025; Beccarello & Di Foggia, 2022). The integrity of road infrastructure is a critical factor in ensuring public safety, economic efficiency, and sustainable urban development. Among the various components of road systems, flexible pavements are particularly susceptible to surface-level defects due to environmental stressors and traffic loads. In recent years, deep learning has emerged as a powerful tool for automating pavement defect detection, offering significant improvements over traditional manual inspection methods in terms of time and accuracy. This section provides the foundational context for this thesis by discussing key concepts related to pavement systems, defect detection methodologies, and the evolution of deep learning techniques particularly Deep Convolutional Neural Networks (DCNNs), DEtection TRansformers (DETRs), and the optimization strategies in modern deep learning.

Pavement is one of the critical components in transportation infrastructure. They are essential for the efficient movement of people and goods. Pavements play a pivotal role in ensuring safe and durable transportation networks, as they function as the surface on which vehicular traffic travels. A well-maintained pavement structure is crucial for withstanding the challenges posed by heavy traffic loads, diverse environmental conditions, and various factors that can impact its performance and service life (Santos et al., 2021).

The primary types of pavements include flexible pavement and rigid pavement. Flexible pavements are the most common type of pavement and are designed with a flexible and elastic surface course that distributes loads over a wider area. Rigid pavements, also known as concrete pavements, have a rigid surface layer made of Portland