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LOOSE PALM FRUITLETS HARVESTING SYSTEM USING IMAGE SEGMENTATION AND RECURRENT NEURAL NETWORK-BASED INVERSE KINEMATICS FOR 6-DOF ROBOTIC ARM

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ABSTRACT

Palm oil is a vital commodity in global food and energy markets, with Malaysia contributing RM 36.19 billion to its GDP from the palm oil sector in 2023. However, due to a critical labor shortage, large quantities of palm oil fruitlets especially loose fruitlets, which contain the highest oil concentration were left uncollected. This research addresses this inefficiency by developing an AI-driven robotic system that automates the collection of loose fruitlets using a 6-degree-of-freedom (6-DOF) robotic arm integrated with a YOLO-based vision model. The YOLOv11 segmentation model was trained using two datasets: a clean dataset (fruitlets only) and a mixed dataset (fruitlets with background objects). When trained on the mixed dataset, the model achieved precision and recall of 0.999 and 1.000, respectively, and mean average precision (mAP@0.5:0.95) of 0.981, significantly outperforming the clean dataset model, which achieved precision of 0.544 and mAP@0.5:0.95 of 0.767. The model was evaluated in both PyTorch and TensorFlow Lite (TFLite) formats, with accuracy maintained across both. PyTorch delivered a faster inference speed of 84.7 ms, while TFLite required 195.4 ms per frame. For motion control, 4,000 inverse kinematics (IK) data points were generated using the Levenberg–Marquardt algorithm. These were used to train six Recurrent Neural Network (RNN) models. Among them, the Bidirectional Gated Recurrent Unit (BiGRU) model achieved the best results, with a mean squared error (MSE) of 0.506, root mean squared error (RMSE) of 0.712, and an R^2 score of 0.997. In testing, the robotic system completed five full pick-and-place cycles in under 30 seconds, with an average of 10 seconds for image segmentation and 15 seconds for mechanical actuation. After gripper modification, the pick-and-place success rate increased from 40% to 90%. In conclusion, the combination of YOLOv11 segmentation, BiGRU-based inverse kinematics, and robotic actuation demonstrates a robust and efficient solution for automating loose fruitlet collection. The system effectively addresses labor shortages while improving accuracy and operational speed, offering a an alternative solution, for the advancement of smart agriculture in Malaysia's palm oil industry.

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CHAPTER 1
INTRODUCTION

1.1 Research Background

The palm oil industry is crucial in Malaysia. In a vast perspective, Malaysia is the second largest of palm oil producer, right behind Indonesia [1]. In 2022, the palm oil industry contributed RM 36.1 billion to the Malaysian gross domestic product (GDP). Since the total GDP of Malaysia in 2022 was RM 1514.1 billion [2], this meant that in 2022, the palm oil industry contributed around 2.4 percent to the national GDP. However, in 2023, the total GDP is RM 1,568 billion. From this total value, the palm oil industry contributed RM 36.18 billion [3]. This meant that in 2023, the palm oil industry contributed around 2.3 percent to the total GDP. This is one of the reasons why the palm oil industry is a crucial sector of Malaysia's economy. The palm oil industry is also responsible for employment within Malaysia, especially for employment in rural areas far from cities. Although the exact number of employees isn't shared, based on [4], in 2020, the number of palm oil workers was 505,972 workers. Another figure shared in [5], stated that as of April 2020, the total of palm oil workers in Malaysia is around 420,000 workers with 80% of that being migrant workers mostly coming from Indonesia. This implies that the palm oil industry is highly dependent on manual labor, especially migrant workers. Since palm oils are more commonly found in rural areas, this means that palm oil provides the potential to increase economic yields and create job opportunities in rural areas [6]. This would also reduce poverty and narrow down the income gap between city and rural areas thus allowing access to private goods such as piping and many more [7].

Although the high number of employment would look good to increase individual income, this meant that the palm oil sector is highly dependent on manual labor [8]. Historically, this has brought problems for the palm oil industry in Malaysia. Due to labor shortages caused by the closing of international borders [9] and migrant workers returning home [5] due to COVID-19, an estimated shortage of 75,000 workers in the palm oil industry happened [10]. This has disrupted palm oil harvesting and its