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A PRELIMINARY EVALUATION OF A RADIO-CONTROLLED HYDROSTATIC TRANSMISSION MOWER FOR OIL PALM PLANTATION

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ABSTRACT

Maintaining effective weed control is essential for oil palm fields. To address sustainability concerns and the increasing cost of chemicals, a cutting-edge mechanical mower has been recommended as an alternative solution. Integrating mechanical, fluid mechanics and electronic systems in a mower is a solution to enhance manoeuvrability in the field. The development and testing of an integrated hydrostatic transmission (iHST) mower with a teleoperation system to improve operational efficiency were discussed. The time-motion study on a 3 ha plot showed that the prototype could achieve an effective field capacity of 0.44 ha/hr at RM255.50/ha, an annual cost for path and palm circle mowing operation in the test area of flat terrain, mild weed infestation and in a dry condition. A 5.8 GHz FPV camera enabled the machine's teleoperation, which provides real-time feedback for improved control during operations. Although its productivity was inferior to the current mechanised spraying approach, the machine could be a sustainable alternative with benefits such as attracting skilled local workforces in plantation operations and environmental friendliness.

Keywords: mechanisation, teleoperation, weed management.

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INTRODUCTION

Palm oil plays a critical role in global food and other industries. Malaysia alone has a total planted area of 5.67 million hectares with an average fresh fruit bunch (FFB) yield of 15.49 t/ha in 2022 (Parveez et al., 2023). Productivity and planted areas experienced fluctuations due to various factors, including environmental impacts, operational practices, and other influences. The availability of workers is one of the primary determinants of productivity. Unfortunately, a situation such as the COVID-19 pandemic has further strained the availability of workers for tasks such as FFB harvesting and other fieldwork. To address this issue, there is a growing need to modernise field practices to minimise reliance on foreign workers and attract local participation within the industry.

Maintaining field conditions in oil palm plantations is crucial for smooth operation, particularly in fruit evacuation and loose fruit collection. Herbicides such as glyphosate, metsulfuron-methyl and triclopyr are commonly used for weed control in oil palm plantations (Rusli et al., 2014). However, their application comes with environmental implications. In this respect, mechanical mowing could be an alternative to minimise environmental impact (Darras et al., 2019). Due to its cost-effectiveness, mechanical mowing technology, such as zero turn and push-over mower, is not widely practised in matured palm oil. Besides, the operator's onboard mechanical drive is unsuitable for palm circle mowing. Thus, integrating a mechatronic system on a mower could alleviate the situation through autonomous or teleoperation navigation.

In autonomous function, various sensors, actuators, processors and system interfaces must be configured to work seamlessly through specific algorithms. Autonomous agriculture vehicles have faced challenges in heterogeneous field conditions, with systems such as RTK-GNSS and vision-based

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obstacle avoidance showing limitations in accuracy and complexity (Villemazet, et al., 2022). Fusion of sensors in autonomous vehicles is challenging due to the unpredictable nature of agricultural fields, especially in crop-type agriculture.

Among the appealing methods to increase automation for machinery navigation in the field is the teleoperation system. Teleoperation uses human interaction as the central controller with machines as executors, known as the Human-Machine Interaction (HMI) method (Vasconez et al., 2019). Three teleoperation modes have been identified and described in *Table 1* (Al-Razgan et al., 2016; Murakami et al., 2008).

Figure 1 shows the basic configuration of the teleoperation system. Feedback varied depending on the selection of the principle. However, a field of view (FOV) system is commonly utilised in direct control mode (Saputra & Mirdanies, 2015), with feedback for decision-making sent through visualisation.

Most of the innovations in radio control mowers available in the market are based on battery-powered systems. The battery could only last for a specific time, even with a rechargeable system (Azwan et al., 2017). Limited operation time is not favourable for plantation operation as it could lower productivity. Longer operation time, wireless control and adaptation to oil palm field conditions are critical parameters for oil palm direct control teleoperation systems. On the other hand, a direct mechanical drive is not suitable for long-range control in agricultural conditions due to the complexity of simultaneous control of the vehicle's mechanical system. Incorporating hydrostatic transmission and electronic systems can control internal combustion engine vehicles through teleoperation.

Hydrostatic transmission (HST) is a system that transmits engine power through hydraulic fluids. HST machine is excellent for crop-type agriculture conditions as it provides greater torque, speed and control. HST with track-type tyres has a better-floating ability to reduce soil compaction due to its larger weight distribution area. HST could be easily integrated with a radio-controlled system and provide longer operational time. The advanced HST technology is the integrated hydrostatic transmission (iHST) system, where the hydrostatic motor and pump are integrated as one component and no external connection is required. It provides flexibility in terms of space and effectiveness to agriculture machinery. Thus, this study evaluated an iHST machine's technical and economic viability with teleoperation function in oil palm plantations for weed management operation. A cost comparison

TABLE 1. TELEOPERATION MODE

No.	Principle types	Description
1	Direct control teleoperation	Direct control is a short-distance communication between the operator and the machine. Typically, a traditional controller such as a joystick will be the primary input of the machine or actuators for navigation. It is also known as a forced or master-slave control system. The feedback system could comprise several methods, including real-time video streaming.
2	Supervisory teleoperation	The system involves two control methods: Direct control and autonomous action. The fusion of sensors helps the system to make certain decisions, such as turning, collision avoidance, automatic tracking, swarm control, and others. The command centre could be placed at a distance for direct control. Thus, a good communication network is required.
3	Multimodal teleoperation	The system incorporates systems such as augmented reality (AR) and virtual reality (VR) as the interface for the operator. The multi-sensory system offers a variety of options for machine navigation and could lead to higher precision.

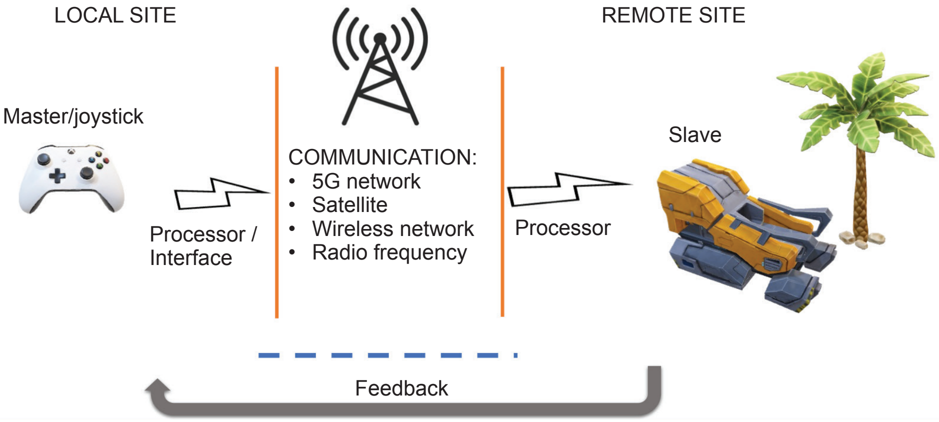

Figure 1. General configuration of the teleoperation system.

of the proposed system with chemical herbicide spraying was analysed in this study, as it is the current practice in the industry. The study's novelty is integrating electronic control with the iHST system in oil palm plantation conditions.

MATERIALS AND METHODS

Prototype of Teleoperation Hydrostatic Transmission Machine

A prototype with a teleoperation function was developed and utilised in the performance test (*Figure 2*). The prototype was built based on a commercial push-over flail mower chassis with its drivetrain modified with an iHST and transaxle. The specifications of the prototype are shown in *Table 2*. The machine was compact and had zero turning radius, and it had a flail mower with a maximum cutting width of 700–800 mm attached to it.

TABLE 2. SPECIFICATIONS OF THE PROTOTYPE

No.	Components/ Parameters	Specification
1	Dimension (W x L)	950 x 1,450 mm
2	Weight	200 kg
3	Flail cutting height	50–80 mm
4	Engine	Water-cooled petrol 10 hp (Mitsubishi GB290PN)
5	Working engine speed	3,000 rpm
6	Hydrostatic	10 cc Integrated HST

A customised electronic control board was specially designed to control the machine. The board was configured to manage a set of linear 12V-DC servo actuators connected to it. Two servo actuators were designated to manoeuvre the machine's HST for steering, while another actuator was responsible for regulating the fuel throttle. In addition to directional control, the iHST could also adjust the speed of the machine. By setting the HST knob lever to a specific position, the vehicle's maximum speed could be limited to ensure safety. The machine manipulated three 2.4 GHz radio transmitter channels directly integrated into the controller board. A standard-resolution first-person view (FPV) camera of 720 × 576 @ 25 fps is attached to the prototype.

Time Motion Study of the Prototype in Actual Field Environment

The prototype's capabilities were evaluated in a 3 ha plantation in Bagan Datuk, Perak, Malaysia. The study selected the site for a preliminary study to validate its performance in an actual scenario. The prototype was anticipated to manoeuvre in tight spaces and perform in terrace areas due to its small size and comparable engine power with existing machinery in the terrace area (10 hp engine). The research plot had 10 year old palm trees. A maximum weed height of about two feet was available during the test along the harvesting or mechanical paths, and the topography was predominantly flat with inland-type soil. The paths were undisturbed and connected, making them ideal for the test. The

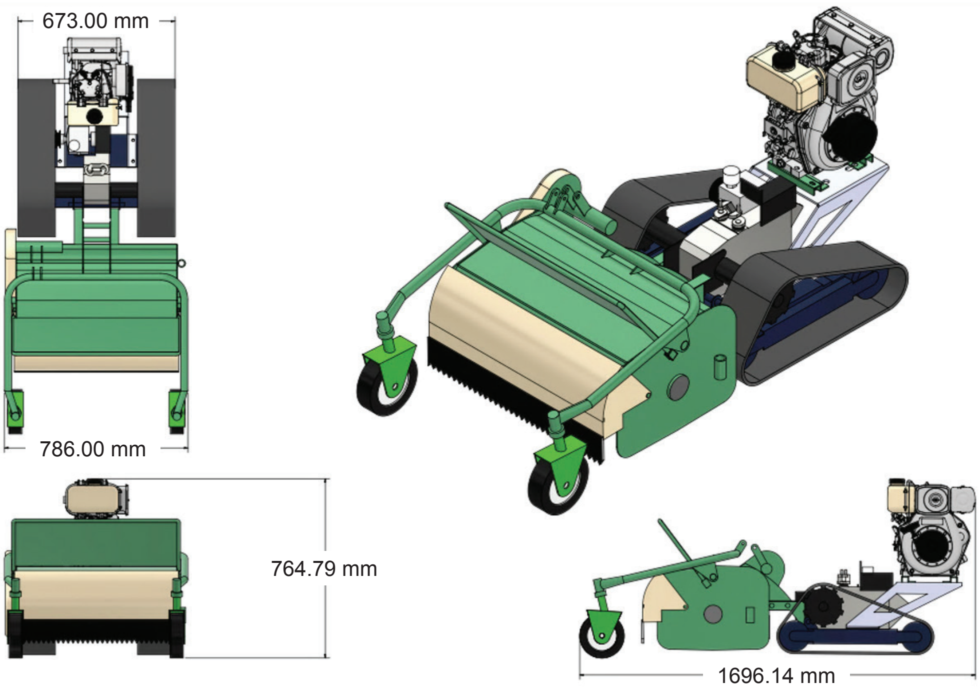

Figure 2. CAD drawing of the prototype.

weeds consisted mainly of grass with narrow leaves and fibrous root systems. Tests were conducted under dry conditions.

The machine could cut grass along the harvesting paths and around the palm circles. Thus, two time-motion studies were conducted: Mowing on the harvesting path in a straight line and circling palm trees.

Mowing on the harvesting path (Straight line movement). The prototype traversed in a straight line on the harvesting paths or between palm tree rows. The machine was controlled at a low speed (about 3 km/hr), and all obstacles, such as fallen fronds, were removed. The distance between the palms was about 9.0 m apart and planted in a triangle formation. The width of the machine is 0.8 m and requires to be traversed several times to cover the entire harvesting path. In this study, the machine traversed three trips back and forth to cover 2.4 m of the harvesting path width, where the area was heavily infested with the mentioned grass. Sectional zones were created and named alphabetically for every 10 palms in a row, as depicted in *Figure 3*. Besides, the operator could get better views when operating the machine within a zonal area (about 100 m range). The area covered by the machine was about 192 m^2 for traversing the zone thrice. The assessment was conducted for 15 zone areas.

Mowing around oil palm trees (Circle movement). The palm circle mowing was carried out by circling the machine around the palm to clear weeds. Each circle was timed, and three repetitions were carried out equivalent to almost a 2 m radius distance from each palm. The time-motion study was carried out for ten palms. Thus, an average timing could be calculated.

The data collected was sufficient to simulate the performance of the prototype. The average data for each category would be used to estimate the machine's average field capacity. This process is depicted in Equation (1).

$$\text{Effective field capacity (ha/hr)} = \frac{\text{Area (ha)}}{\text{Time (hr)}} \quad (1)$$

Operational Cost Estimation

The study adopted the American Society of Agriculture and Biological Engineering (ASABE) standard to assess the economic feasibility of the proposed system. This standard enabled the economic justification of agricultural machinery to be evaluated during the study. Thus, a cost comparison with current practice could be made. A detailed description of the cost parameters is shown in *Table 3*.

All costs associated with its operation (*Table 3*) were divided by the estimated number of operating hours and the total value determined as hourly operational costs (HOC) (Azwan et al., 2017). The metric refers to the total costs incurred to operate a machine for 1 hr (RM/hr). It also refers to the economic efficiency of machine operating. Meanwhile, the total effective cost (TEC) was assessed based on the HOC rate divided by the machine's effective field capacity (EFC), as depicted in Equation (2).

$$\text{TEC (RM/ha)} = \frac{\text{HOC (RM/hr)}}{\text{EFC (ha/hr)}} \quad (2)$$

RESULTS AND DISCUSSION

Prototype of the iHST Mower with Teleoperation Function

Integrated hydrostatic transmission (iHST), connected to the engine via a pulley, is an essential component of the system (*Figure 4*). The pulley

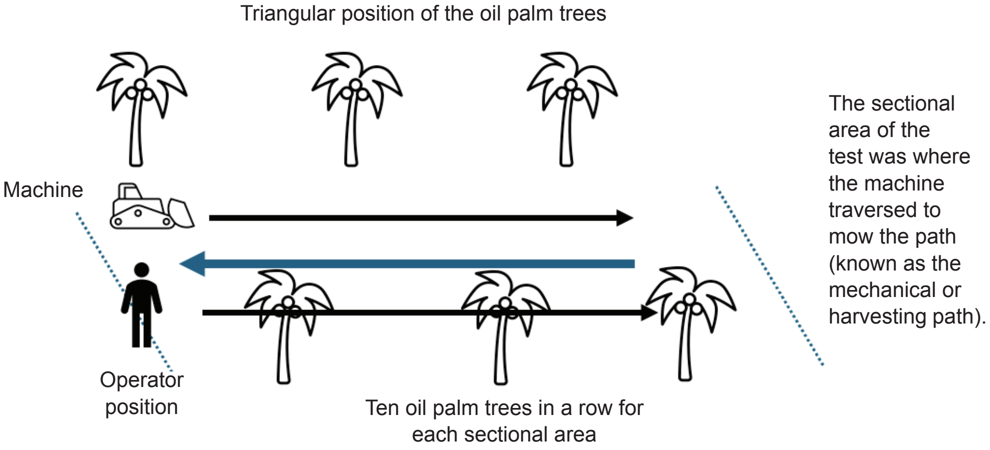

Figure 3. Illustration on weed clearing time-motion study on paths.

TABLE 3. COST PARAMETER

No.	Cost parameters	Description
1	Depreciation	Depreciation covers the decline in the machine's value over its life.
2	Interest on investment	Interest covers the cost of investing funds in the machine.
3	Shelter and insurance	The parameter covers the requirement to minimise the machine's liabilities and prolong its functionalities.
4	Repair and maintenance	The parameters cover parts replacement, installation charges and general maintenance.
5	Fuel and lubrication	Fuel charges were based on current fuel prices. Lubrication costs were figured at a certain percentage of fuel cost.
6	Labour	Labour charges were based on Malaysia NUPW (National Union Plantation Workers) per hour.

and belt system becomes crucial as it provides a mechanism to split the power transmission in case of unexpected obstacles. This ensures the machine can function safely and effectively under diverse operating conditions. Power from the engine drives the hydraulic flow within the iHST. Another pulley connects the engine to the flail cutter. A servo attached to the iHST allows precise control over the hydraulic flow, facilitating forward and reverse movements. This hydraulic power is then converted into mechanical output to operate a gear system in the transaxle. The gear selection component in the gearbox provides the capability for left and right movements. The comprehensive system is detailed in *Figure 5*. A FPV camera is integral to the system, whereby a 5.8 GHz FPV camera is positioned on the vehicle, offering real-time feedback to the machine's operator, enhancing their field of view and operational control.

Infield Performance Test

The time-motion studies assessed the prototype's performance in carrying out the intended operation. The tests took place in an oil palm field with predefined parameters and were operated by a skilled research technician. The operator controlled the machine operation from a distance; no other tasks were required. It was noted that weed infestation was faster in mechanised paths than in shaded palm circle areas, likely due to direct exposure to the sun. Thus, separate time-motion studies were conducted for grass-cutting activity on the mechanised paths and within the palm circle.

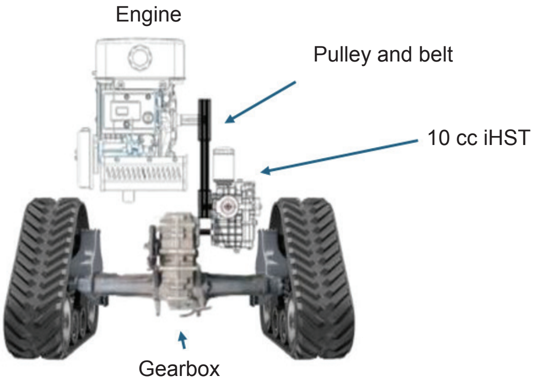

Figure 4. Location of the main components on the prototype.

Preliminary evaluation of weed mowing was carried out on a plot of land exceeding 3 ha along the mechanised paths. The findings from this evaluation are depicted in *Figure 6.* The prototype had to traverse the middle area of the roughly 2,500 mm path three times due to its 800 mm flail width. As the machine traversed along the paths, it cut the weed 50–80 mm in height from the ground. A statistical data analysis yielded valuable insights, as shown in *Table 4*. This analysis offered valuable information on the variation and consistency of the data obtained from these repeated measurements.

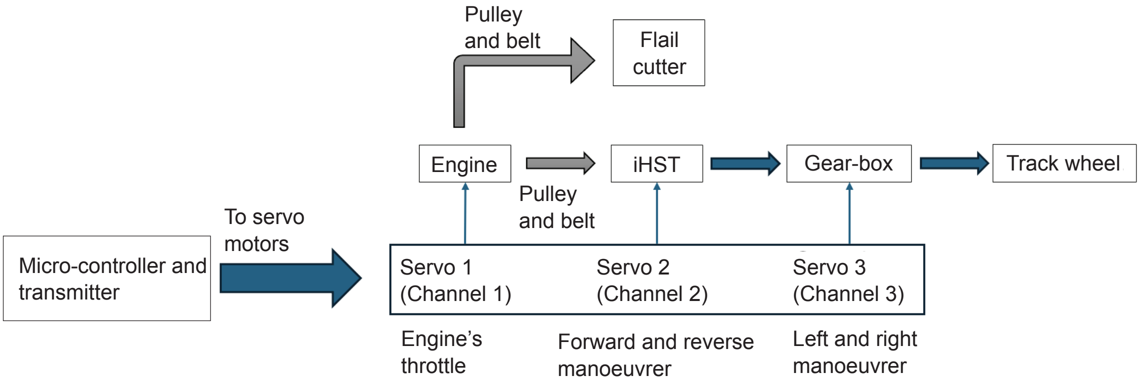

Figure 5. Control flow diagram.

The time-motion study conducted on the weed mowing process provides significant insights into the efficiency and consistency of the prototype being tested. As observed in *Figure 6*, the mowing time varies across different zone areas, with the time to mow decreasing progressively from Zone A to Zone O. This variation indicates the influence of uncontrolled factors, possibly due to the operator's unfamiliarity with the operations. However, the operator becomes more comfortable controlling the machine over a certain period, and the efficiency gains towards the end of the test.

Table 4 presents descriptive statistics, offering an understanding of the data collected. The mean time for path clearing was 663.600 s, with a standard deviation of 7.707 s. This low standard deviation indicates that the prototype's performance was relatively consistent across multiple trials, with only minor fluctuations in time. The minimum time recorded was 653.000 s, while the maximum time reached 676.000 s, demonstrating a range of 23.000 s between the fastest and slowest trials. The consistency in these results suggests that the prototype is reliable in maintaining a steady performance level, which is crucial for practical applications where time efficiency is paramount.

The data indicated that the average time required to mow a zonal area of the path was about 663.6 s. Based on the average value, it was estimated that for a 1 ha palm-planted area, the prototype required about 4,645.2 s or 77.4 min to carry out the mechanical or harvesting path mowing task. The value obtained by multiplying the average value by seven as seven zonal areas were equivalent to almost one ha of the planted area.

The prototype cut weeds in palm circle areas during the second testing. The test consisted of three repetitions involving weeds cutting in 10 palm circles. The test area had minimal weed infestation. Despite these conditions, the data collected was sufficient to analyse the prototype's performance and estimate its effective field capacity for maintaining palm circles. The test results are shown in *Figure 7*, while detailed statistical information is shown in *Table 5.*

Significant consistency in mean values and range across three repetitions was observed, suggesting consistency in measurement. While there were minor differences in standard deviation, they did not significantly impact the overall reliability and consistency of the measurements overall. Thus, the time-motion study provided valuable information on the capability of the prototype to undertake the palm circle maintenance activity within an average of 24 s for each palm. Thus, for a hectare of land with 150 palms, it was estimated that the time required for palm circle activity was 3,600 s.

The prototype's effective field capacity (EFC) to carry out the tasks is depicted in *Table 6* and explained by Equation (1). The EFCs were 0.78 and 1 ha/hr, respectively. However, the EFC was 0.44 ha/hr if the machine needed to cover both path and palm circle operations.

The prototype was estimated to cover only 4 ha of a path and palm circle mowing operation daily (9 hr of working time a day). On the other hand, a mechanised spraying system with a three-wheeler vehicle could cover more than 10 ha/day (Azwan et al., 2016). However, a teleoperated mechanical mower could benefit from high-speed

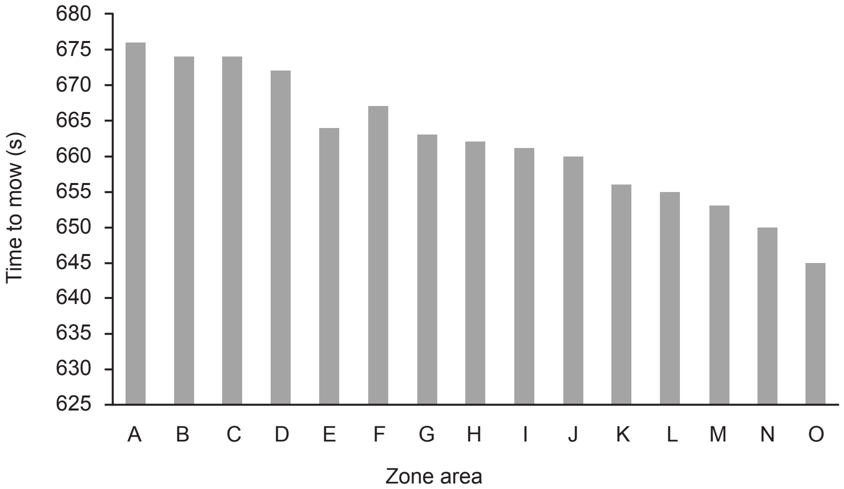

Figure 6. Results of the time motion study for the path mowing.

TABLE 4. DESCRIPTIVE STATISTICS FOR PATH CLEARING TIME (s)

	N	Minimum (s)	Maximum (s)	Mean (s)	Std. deviation (s)
Time-motion (s)	15	653	676	663.60	7.707

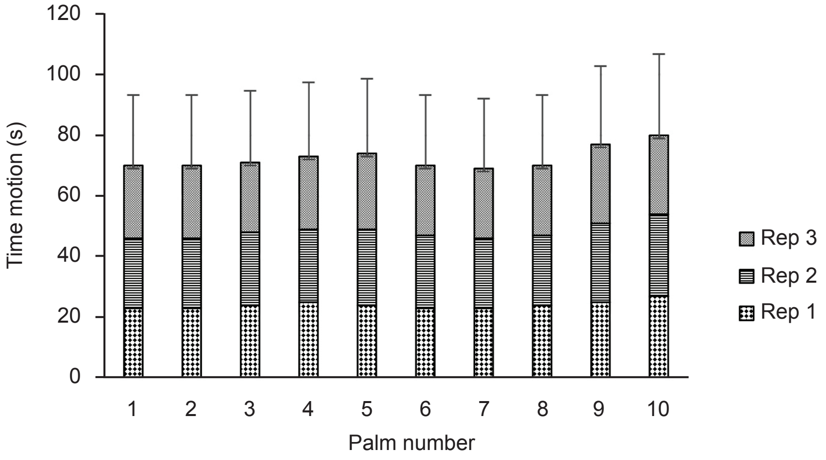

Figure 7. Results of the time motion study for the palm circle test.

TABLE 5. DESCRIPTIVE STATISTICS OF PALM CIRCLE TEST

	N	Minute (s)	Maximum (s)	Mean (s)	Std. deviation (s)
Rep 1	10	23	27	24.10	1.287
Rep 2	10	23	27	24.20	1.398
Rep 3	10	23	26	24.20	1.135

communication networks in the plantation if available, allowing long-range control for improved performance. This long-range communication would allow the operator to control the machine from the office or centre (remote operation), potentially increasing its working time and availability. Furthermore, the prototype could be enhanced by increasing its dimensions, specifically by expanding its width from 800 to 1,300 mm. This modification would allow it to cover a larger area and improve its operational reach.

Another observation found that the soft soil and uneven topography will affect the cutting performance. The machine could traverse those conditions, but the flail angle impacted the consistency of the cutting. Thus, it limits the prototype functionality.

TABLE 6. EFFECTIVE FIELD CAPACITY OF THE PROTOTYPE

No.	Field mowing task	Effective field capacity (EFC)
1	Path	1/4,645 ha/s or 0.78 ha/hr
2	Palm circle	1/3,600 ha/s or 1 ha/hr
3	Path and palm circle	1/6,915 ha/s or 0.44 ha/hr

Operational Cost Analysis

Operational cost analysis was done by determining the prototype's hourly operating expense. Based on the materials purchased during its development, the cost of the prototype was estimated to be RM30,000. Another assumption, detailed in *Table 7*, was made to facilitate the analysis. The data was referenced from previous studies on internal combustion engine machinery in oil palm plantations, which are almost consistent in their infield application and power source with the studied prototype.

The prototype's hourly operating cost (HOC) was RM11.24/hr, as depicted in *Table 8*. The values in *Table 8* were obtained from the initial assumption in *Table 7* and divided by the estimated operating hours of the machine per its entire economic life. Thus, the corresponding values of the operational cost could be obtained for the prototype's entire economic life at the time of study. Standards were made based on references from previous studies that assumed the current scenario while the future scenario, such as inflation rates, were not incorporated.

TEC could be obtained by dividing the HOC (RM11.24/hr) by the EFC (0.44 ha/hr) as in Equation (2). Thus, TEC was about RM25.55/ha. Assuming 24 working days per month and nine working hours daily, the ratio is one machine per 100 ha area. The machine is expected to visit the same area every month for ten months in a year. Only 10 months a year was anticipated for the operation due to the seasonal monsoon period. Therefore, the prototype's total effective cost per year was RM255.50/ha. The cost of herbicide applications was reported to be almost RM214.00 ha/hr at the current herbicide cost of RM30.00/L (Wahyu et al., 2010). However, the current

TABLE 7. INPUT TABLE

Parameter	Values	Reference
Bill of materials (RM/unit)	30,000	
Operating hours (hr/yr) - *Assume an availability factor of 50%*	4,380	Azwan et al. (2021)
Assume economic life (yr)	5	Azwan et al. (2021)
Salvage value @ 5th yr	10% from the initial value	Johari et al. (2020)
Shelter and insurance	2% from the initial value	Johari et al. (2020)
Interest on investment	10% from the initial value	Johari et al. (2020)
Fuel consumption (L/hr)	0.95	Based on the observation
Fuel price (RM/L)	2.10	Price at the time of study
Lubricant cost	15% of the fuel cost	Shuib et al. (2020)
Repair and maintenance costs	Total 5% of the initial cost	Azwan et al. (2021)
Operator wages per month	1,500	Azwan et al. (2021)

cost of glyphosate has increased to more than RM50.00/L, and the total effective cost of glyphosate application was estimated to be more than RM250.00 ha/hr. Thus, the TEC of the prototype application is almost similar to or slightly higher than that of the herbicide application for path and palm circle mowing operations.

TABLE 8. OUTPUT OF THE ECONOMIC ANALYSIS

Operational cost	Values
Salvage value (RM/hr)	0.14
Tax, shelter and insurance (RM/hr)	0.03
Interest on Investment (RM/hr)	0.14
Fuel cost (RM/hr)	2.00
Repair and maintenance cost (RM/hr)	0.07
Lubricant cost (RM/hr)	0.30
Operator cost (RM/hr)	8.57
Total hourly operating cost (RM/hr)	**11.24**

A combination of herbicide and mechanical mowing in oil palm plantations could lead to improved cost-effectiveness. Herbicide should be applied in areas where it is difficult for the machinery to operate, such as muddy and sloped areas, to achieve better cost-effectiveness. Furthermore, applying herbicide under the palm canopy or within the circle of mature palm trees where the weed infestation growth is slower could reduce the need for frequent mechanical mowing, subsequently increasing the TEC per year.

Mechanical mowing may require more frequent visits than chemical applications, but the work will be less arduous and safer. This, along with other advantages, can attract local operators. Working efficiency could also be enhanced by having multiple machines working simultaneously or using the swarm technique (Moniruzzaman et al., 2022; Peña et al., 2018; Vasconez et al., 2019). Establishing a local ground network is a potential solution for improved connectivity (remote operation). Localisation, big data transmission and low latency could enhance teleoperation performance in oil palm plantations.

CONCLUSION

The study showcased the successful implementation and validation of a hydrostatic transmission machine within the oil palm plantation with a specific terrain and other conditions mentioned in the test. This machine operated precisely along its intended path through teleoperation control and delivered the anticipated outcomes. Based on blanket area operation (path and palm circle), the machine's effective field capacity was 0.44 ha/hr, with an annual operating cost of nearly RM255/ha. Improvement could be achieved via hybrid applications involving mechanical mowers and herbicides. While its productivity was lower than mechanised spraying, integrating an advanced teleoperation system with an effective communication network in the oil palm field could lead to further enhancements (remote operation). These advanced systems offer enhanced distance control, reduced labour intensity, and extended work hours. Appropriate modifications could also benefit plantation operations, such as loose fruit collection, FFB evacuation and palm harvesting. Benefits such as attracting skilled local workforces into the industry, improved sustainability and modernisation in the oil palm field practice could be realised.

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