Development and performance evaluation of an oil palm harvesting robot for the elimination of ergonomic risks associated with oil palm harvesting

Ayodeji Nathaniel Oyedeji,[1] Umar Ali Umar,[1] Laminu Shettima Kuburi,[1] Albright Abu Edet,[1] Yau Mukhtar[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria;
[2]Equipment Maintenance and Development Centre (EMDC), Ahmadu Bello University, Zaria, Nigeria

Abstract

This study was aimed at developing and evaluating the performance of an oil palm fresh fruit bunch harvesting robot that will eliminate the possible risks associated with oil palm harvesting. The result of this study showed that the average height of oil palm trees in the study area was 5.531 m, which shows the unsuitability of the existing traditional methods in the harvesting process. This study also used a geared DC motor to develop an oil palm harvester, solving the stability issue encountered by previous researchers during the harvesting process without necessarily reducing the climbing speed by a wide margin. In addition, the use of geared DC motor help in the production of high torque for the climbing process, and due to this high torque, instability during the harvesting process was reduced.

Correspondence: Oyedeji Ayodeji Nathaniel, Department of Mechanical Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.
E-mail: oyedejiayodeji@yahoo.com; p17egme8023@abu.edu.ng

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Introduction

The oil palm is a perennial crop that originated in the tropical rainforest of West Africa, whose cultivation spread to South America in the 16th century and to Asia in the 19th century (Maluin *et al*., 2020). There is an increase in the cultivation of oil palm across America, Asia, and Africa, and one of the reasons is the broader use of palm oil biodiesel as an alternative energy source, and its demand is further strengthened as more countries establish mandates on the use of biofuels (Lau, 2009). Another major factor contributing to this increase is a more rapid rise in per capita human consumption of vegetable oils in the past 30 years than any other food, as vegetable oils are used for food, feed waste, and industrial consumption (Akande *et al*., 2013). The palm oil tree has been the most productive edible oil crop, with a productive cycle between its 4th and 30th year, and in this period, it can grow up to 12.2 m tall (Vijay *et al.*, 2016).

Although palm oil is the most productive edible oil crop (10 times the next most productive), accounting for about 33% of total oil production (Saeed *et al*., 2012), it is one of the food crops that today is not mechanically harvested. As a result, it is estimated that about 500 million US dollars' worth of palm oil has been lost due to the inefficient harvesting practices currently in use (Bronkhorst *et al*., 2017). The existing traditional harvesting method involves the use of a sharp flat blade which is attached to the end of a bamboo stick for short young palm trees (1-3.5 m), while for trees within the range of 3.5 m and 5 m, a sharp blade is attached to the end of a long adjustable pole to achieve the harvesting process. For taller trees (5 m and above), the palm fruit is harvested by using the single rope and cutlass method (SRC) or the double rope and cutlass method (DRC). In both methods, the farmer climbs the tree physically via the use of the single or double rope around his torso, and once within arm-reach of the crown, the farmer uses the cutlass to cut the fronds and subsequently, the fresh fruit bunch (FFB).

Even though oil palm originated from West Africa, the production of oil palm has not increased relative to other countries like Indonesia and Malaysia. Between 1961 and 1965, world oil palm production was 1.5 million tons, with Africa accounting for 78% (Gold *et al*., 2012), and 43% of this total world production was from Nigeria. However, about 50 years later, the production rate in Africa dropped to 10.33%, with Nigeria accounting for only 1% of the world's oil production of 77 million tons. This trend results from the traditional harvesting method that is predominant in these regions, which becomes difficult to use when the oil palm trees have grown to a specific height of more than 3.5 m. Using these methods has both ergonomic and safety issues and where harvesters are unavailable, the trees are abandoned or cut down, leading to wastage of the oil palm.

Similarly, during the rainy season, the bark of the oil palm tree becomes very slippery, and the climbers experience difficulty in climbing, while in some cases, there exists the problem of child labour and unsafe working conditions, especially among the smallholders (Myzabella *et al*., 2019), which make up 80% of Africa oil palm production. In the long term, if these risks are not minimised, it may tilt the balance of sustainability.

Automation of agricultural processes is now a necessary attribute rather than a luxury, especially with technological advancement (Juman *et al*., 2016). The literature review showed that implementing robotic harvester into palm FFB harvesting process is a developing research area and although several works have been done, two gaps need to be filled. First, the design of a wireless palm tree harvester by Prasad *et al*. (2016) faced the problem of vibrations during the cutting process, which further resulted in the shift in the positioning of the harvester. Second, the design of an inchworm locomotion form of tree climbing robot by Praveenbabu *et al*. (2017) was characterised by better stability during the harvesting process; however, the climbing speed was low. Hence, this study was aimed at developing and evaluating the performance of an oil palm harvester with good stability during the harvesting process and a relatively high climbing speed by using geared DC motors. It is believed that with these two improvements, the system will be more effective while eliminating the ergonomic risks of traditional and manual harvesting methods.

Materials and methods

Description of materials

In selecting materials for the various components that made up this study, several factors such as availability, weight, durability, power consumption, *etc*. were considered. Table 1 shows the various components and the materials used.

The Geared DC motors

Geared DC motors can be characterised as an augmentation of DC motors that previously had their inner details modified. A geared DC Motor has a gear assembly appended together to the motor. The gearing system aids in expanding the torque and diminishing the speed. Utilising the right mix of gears in a geared motor can decrease its speed to any desired value. This concept of using gears to reduce speed and increase torque is known as a gear reduction system.

Description of the system/working principle

The working principle of the palm oil FFB harvester is such that (Figure 1):

The App control and screen system (an android phone) was the interacting point between the harvester and the operator. The operator gives instructions such as “climb,” “stop,” and “descend” to the motors of the harvester wheel while instructions such as ‘cut,’ ‘stop,’ ‘armrest,’ and ‘armFwd’ are given to the cutter arm and cutter blade motors. The app control system gives these instructions via screen touch on the phone in which these instructions are transferred to the Arduino Package through the Bluetooth module: i) the Arduino activates the motor driver, amplifying the motors’ power for the various actions that will be carried out; ii) the camera screen system acts as the operator’s feedback system, which will assist in decision making by providing information through a real-time view of the sections of the tree, and then actions can be sent in the form of signals to the motors of the harvester wheel and the cutter; iii) to ensure harvester’s stability during the harvesting process against the effect of vibration, geared DC motors were used for the harvester wheel. These motors tend to act as a gripper through the combined effort of the compression springs, which comes into play once the harvester stops moving vertically.

The flow chart of the harvesting process of the oil palm FFB harvester is given in Figure 2, while a view of the app interface is shown in Figure 3, and the conceptual sketch of the palm FFB harvester is shown in Figure 4.

Table 1. Components and materials.

S/No	Component	Materials used
1	Aluminium frame	6063 aluminium alloy rectangular profile
2	Guiding plate frame	1 mm mild steel sheet metal
3	Geared DC motor plate	20 grade mild steel sheet metal
4	Upper and lower cutter arm	3 mm polypropylene material
5	Climbing motor	Geared DC motor
6	Cutting disc	2 mm mild steel plate
7	Cutting motor	DC motor
8	Climbing sprocket wheel	Plain carbon
9	Compression springs	Hard drawn steel
10	Development board	Arduino Uno (ATmega328P Microcontroller)
11	Communication sensor	Bluetooth module HC-05
12	Motor driver	L293D IC
13	Breadboard	Plastic breadboard
14	Power source	12V DC battery
15	Fasteners	Bolts, nuts, and screws
16	Cutting arm motor	Servo motor
17	Jumper wire	Copper wire
18	Feedback system	USB OTG Camera 1080p

Design assumption

This harvester was designed based on the following design assumptions: i) due to the need to avoid climbing the tree to determine tree's minimum (crown) diameter, a general relationship between crown diameter and the maximum diameter (diameter at breast height, DBH) was used; ii) there are no branches along the trunk of the oil palm tree; iii) the control of the harvester is only through the application installed on the android phone from which functions of the harvester can be operated; iv) there is a similar working condition with respect to the tree trunk and wheel for all the geared DC motor wheels.

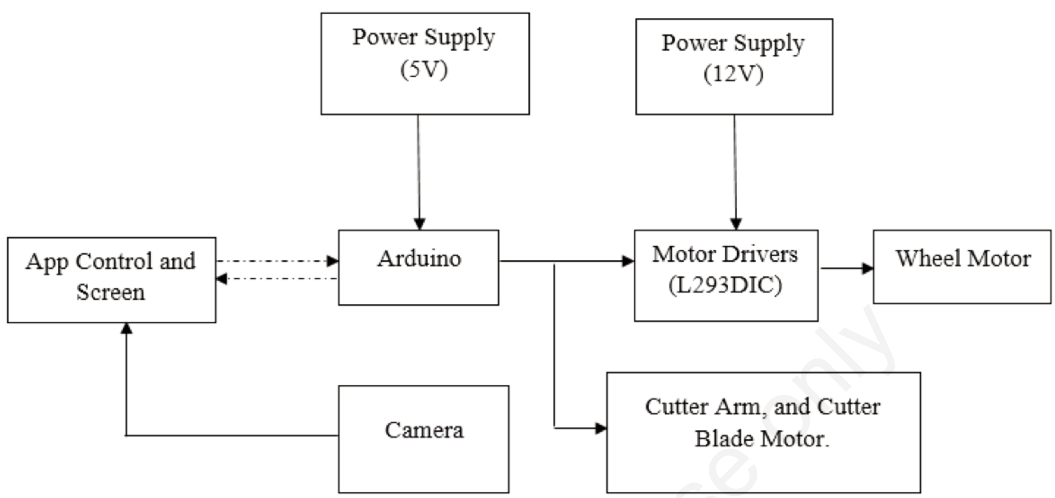

Figure 1. Block diagram showing the working principle of the system.

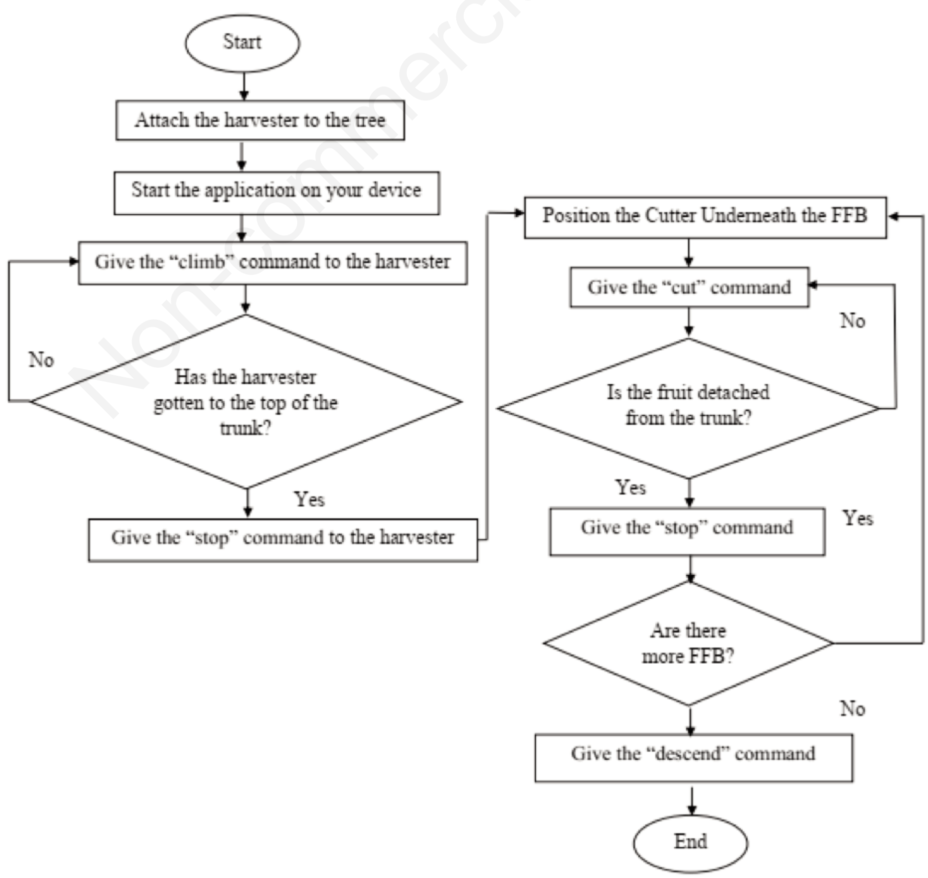

Figure 2. Flow chart of the harvester.

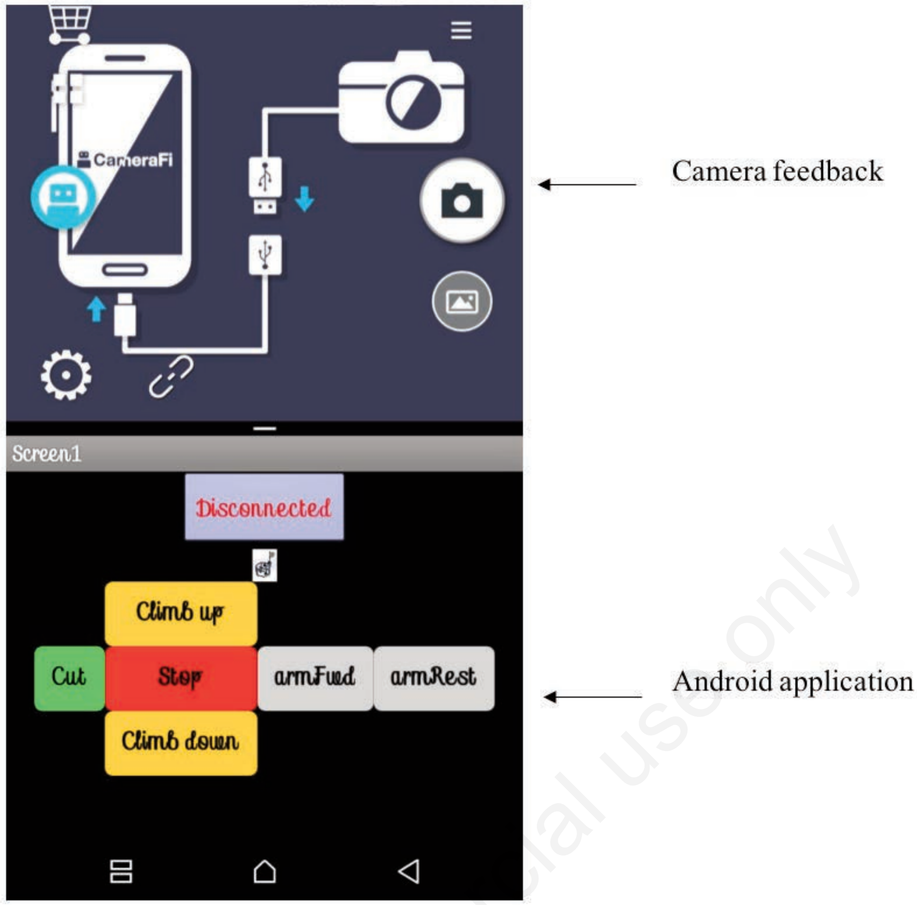

Figure 3. App control view.

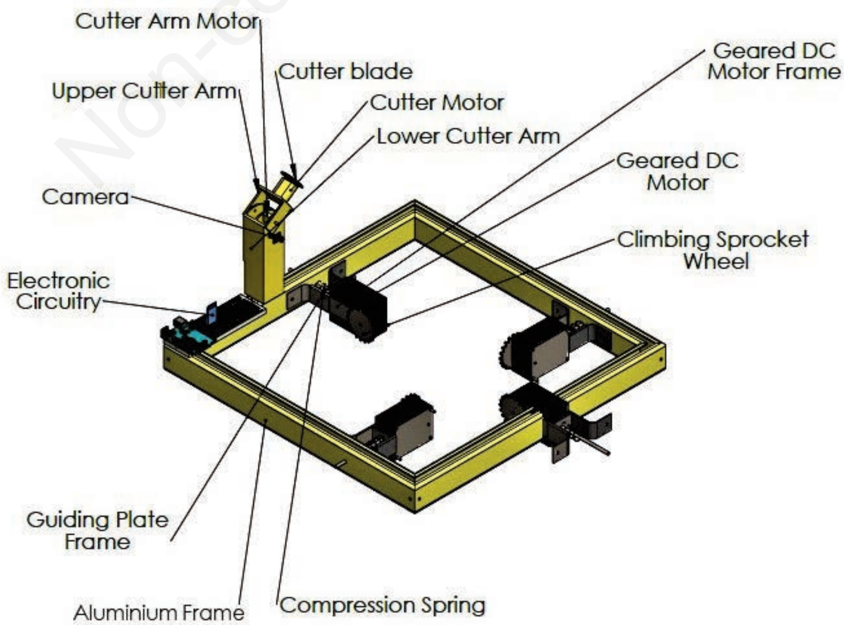

Figure 4. Conceptual sketch of the oil palm fresh fruit bunch harvester.

Design calculation

Determination of trees parameters

The random sampling method was used to sample the oil palm trees from a sample size of 98 trees from the biggest oil palm-producing state in Nigeria (Oyedeji *et al.*, 2021; 2021). The tape rule was used to determine the maximum circumference so that the maximum diameter in metres (D_{max}) (also known as diameter at breast height, DBH) was determined, while the crown diameter and DBH general relation as determined by the regression analysis of Keramat *et al*. (2007) was used to determine the minimum diameter in metres (D_{min}):

$$P_{m,max} = \pi D_{m,max} \quad (1)$$

$$D_{m,min} = 0.57977\ (D_{m,max}) + 0.15077 \quad (2)$$

where:
$P_{m,max}$ is the mean maximum circumference (m);
$D_{m,max}$ is the mean maximum diameter (m);
$D_{m,min}$ is the minimum diameter (m).

The height of the tree was determined using the clinometer, which was used to obtain the angle of elevation of the tree from the observer, and a tape rule was used to obtain the horizontal distance of the observer from the tree, as illustrated in Figure 5:

$$H_m = h_{m,1} + h_2 \quad (3)$$

$$M\ h_{m,1} = R * Tan\ (\theta_m) \quad (4)$$

where:
H_m is the mean tree height (m);
$h_{m,1}$ is the height of the tree from the observer level (m);
h_2 is the height of the observer (m);
R is the horizontal distance of the observer from the tree (m);
θ_m is the mean angle of elevation of the observer (degrees).

Then the average value of the maximum diameter of the tree $D_{m,max}$ in metres, the minimum diameter of the tree $D_{m,min}$ in metres, and the height of the tree (H_m) in metres were obtained from the results of the 98-sample size of the palm tree.

Static analysis of the wheel in three-dimensional space

Figure 6A and B illustrates the top and front perspective of the moments and forces acting on the robot when in a static state, and the frame cling to the oil palm tree trunk without consuming power:

$$\sum F_H = F_1 + F_2 - F_3 - F_4 = 0 \quad (5)$$

$$\sum F_v = F_1\mu_1 + F_2\mu_2 + F_3\mu_3 - F_4\mu_4 = mg \quad (6)$$

where:
F_1, F_2, F_3, and F_4 are the direct forces which are applied on the four wheels (N);
μ_1, μ_2, μ_3, and μ_4 are the coefficient of static friction;
F_H is the resolved horizontal force (N);
F_v is the resolved vertical force (N);
m is the robot's mass (kg).

Based on the assumption of similar working conditions between the trunk and the four wheels, then $\mu_1=\mu_2=\mu_3=\mu_4=\mu$, and $F_1=F_2=F_3=F_4=F$. Hence from Eq. 6:

$$(F_1 + F_2 + F_3 + F_4)\mu = mg \quad (7)$$

$$4F\mu = mg \quad (8)$$

$$F = mg/4\mu \quad (9)$$

where:
F is the force exerted by each wheel on the oil palm tree trunk to keep it stationary without using any external power source (N).

The coefficient of friction between metal and wood of coarse surface, μ, is given as 0.650 (Kuwamura, 2011); and the mass of the harvester, m, was determined from CAD design as 1.89 kg.

Dynamic analysis of the wheel for vertical climbing

For the wheel to perform vertical climbing, three major resistances needed to be overcome. This includes the *resistance to rolling* of the wheel, the *gravity effect of the robot*, and the *resistance to acceleration*.

- *Resistance to rolling.* Rolling resistance is encountered at the point when the wheel attempts to turn on the tree surface, in this

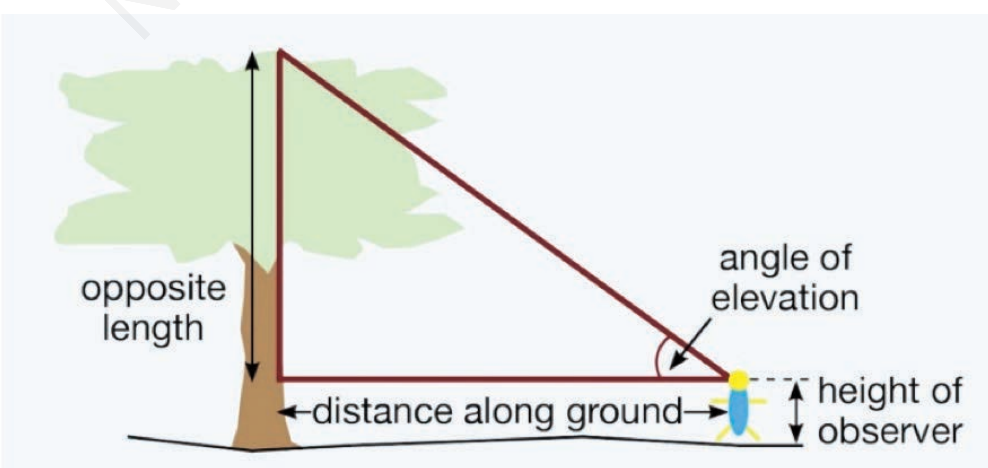

Figure 5. Determination of the height of the tree.

manner creating a contact fix because of the resultant normal force F and the frictional force F_f in Newton. When the tire enters the contact fix, miniature spring-damper units are compacted and released afterward. This compaction and release process disseminates internal energy in the form of frictional heat, characterised as hysteresis losses. As a result, rolling resistance force F_{rr} is given by (Lam and Xu, 2012):

$$F_{rr} = C_{rr} * F \tag{10}$$

where:
F_{rr} is the rolling resistance force (N);
C_{rr} is the coefficient of rolling resistance.

The coefficient of rolling resistance between wood and wheel was taken as 0.7 (Kuwamura, 2011).

- *Gravity effect of the robot.* Robot mass is a basic factor to be considered in the design of a climbing robot because it directly influences the estimation of the robot's gravitational force. Under various conditions, this gravitational force can accelerate or decelerate the robot's speed and mechanical behaviour. The absolute mass (m) of the designed oil palm FFB harvesting robot in this study was approximately 1.89 kg, as the *computer-aided design* (Solidworks) determined after applying similar materials with the experimental fabrication.

- *Resistance to acceleration.* At the start of the tree climbing process for the oil palm harvester from its static position, the four geared DC motors are required to overcome the inertia force brought about by the robot mass. The acceleration resistance of a climbing robot is given by (Lam and Xu, 2012) (Figure 6C):

$$F_a = a*m / N_m \tag{11}$$

where:
F_a is the acceleration resistance of a climbing robot (N);
a is the desired acceleration rate of part (m/s^2) The desired acceleration rate is taken as 0.25 m/s^2 (Chinchkar *et al*., 2017);
N_m is the number of drive motors.

Torque analysis of the climbing motor

As mentioned early, the three major resistances that needed to be overcome by the robot wheel are *rolling resistance*, *robot grav-*

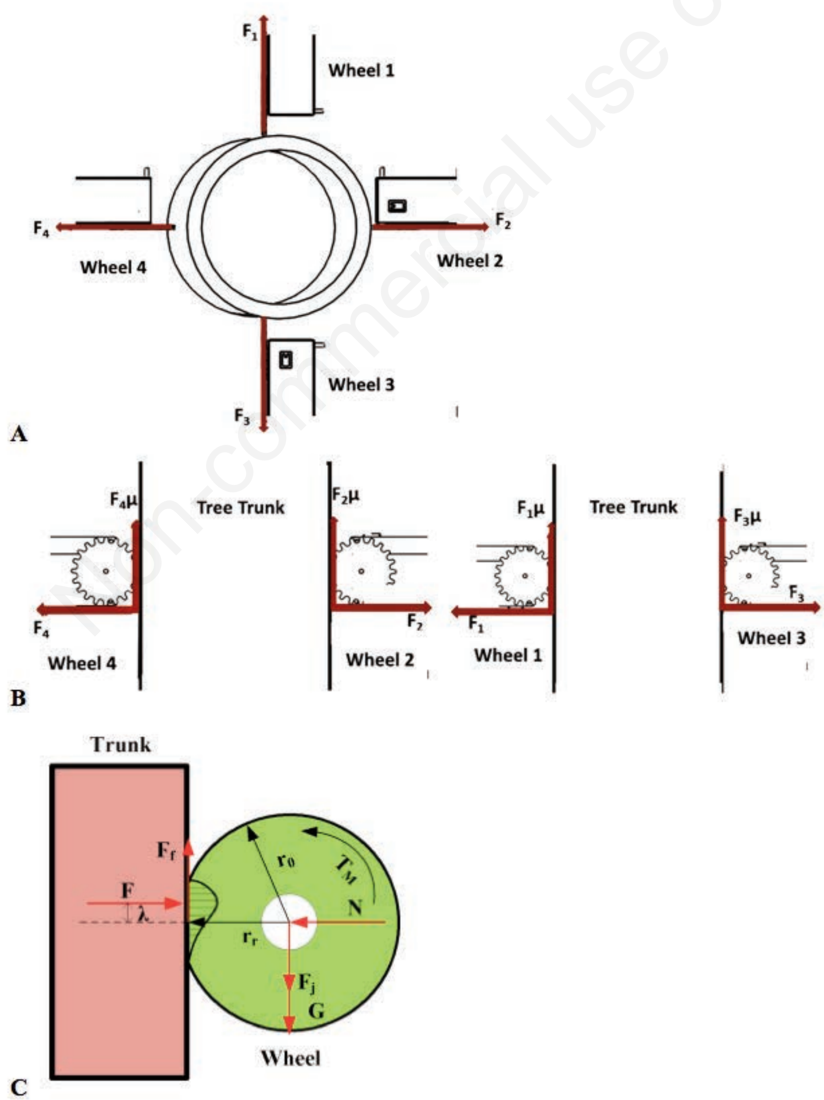

Figure 6. A) Top view of the climbing robot force.; B) lateral view of the climbing robot force; C) acceleration resistance acting on a wheel.

ity, and *acceleration resistance*, all in Newton. Hence the total force the climbing motor must overcome F_M is given by:

$$F_M = F_{rr} + G/N_m + F_a \tag{12}$$

Hence, the torque required of the climbing motor in *N/m* is:

$$T_M = T_{rr} + T + T_a = (F_m)r \tag{13}$$

where:
F_M is the total force the climbing motor must overcome (N);
G is the gravity force of the climbing robot (N);
T_M is the total torque required of the climbing motor (N/m);
T_{rr} is the resistance to rolling torque (N/m);
T is the gravity torque of the climbing robot (N/m);
T_a is the resistance to acceleration torque (N/m);
r is the radius of the wheel rolling radius (m).

Cutting mechanism selection

In the design of the cutting mechanism, the pitch diameter, circumferential stress, and power requirement of the cutting mechanism were considered. The average force required for cutting oil palm fronds (taken as F_c) is approximately 18,048 N (Jelani *et al.*, 1998). Based on the availability of materials and standard sizes of cutting disc, a circular cutting disc of diameter D_b=10 cm was selected, having a mass M of 66 g. The minimum velocity of the cutter (V_c), circumferential stress (σ_c) and torque exerted on the cutter (T_c) are given by (Khurmi and Gupta, 2006):

$$V_c = \sqrt{\frac{F_c D_b}{2M}} \tag{14}$$

$$\sigma_c = \rho V_c^2 / g \tag{15}$$

$$T_c = F_c D_b / 2 \tag{16}$$

where:
V_c is the minimum velocity of the cutter (m/s);
σ_c is the circumferential stress (N/m^2);
T_c is the torque exerted on the cutter (N/m);
ρ is the volumetric mass of the material;
g is the acceleration due to gravity.

Electronic circuitry design

The electronic circuit design that constitutes the harvester's circuitry and control was made up of major components such as the Arduino Uno ATmega 328 microcontroller, the main control unit, Bluetooth Module HC-05, L293D IC, DC motor, servo motor, camera, *etc*. These electronic components were selected based on their suitability with the Arduino microcontroller. The schematic of the component connection is shown in Figure 7.

Firmware design

The firmware design comprises the codes created and embedded in the microcontroller to control the robot framework and the android application for the control and feedback system. The inte-

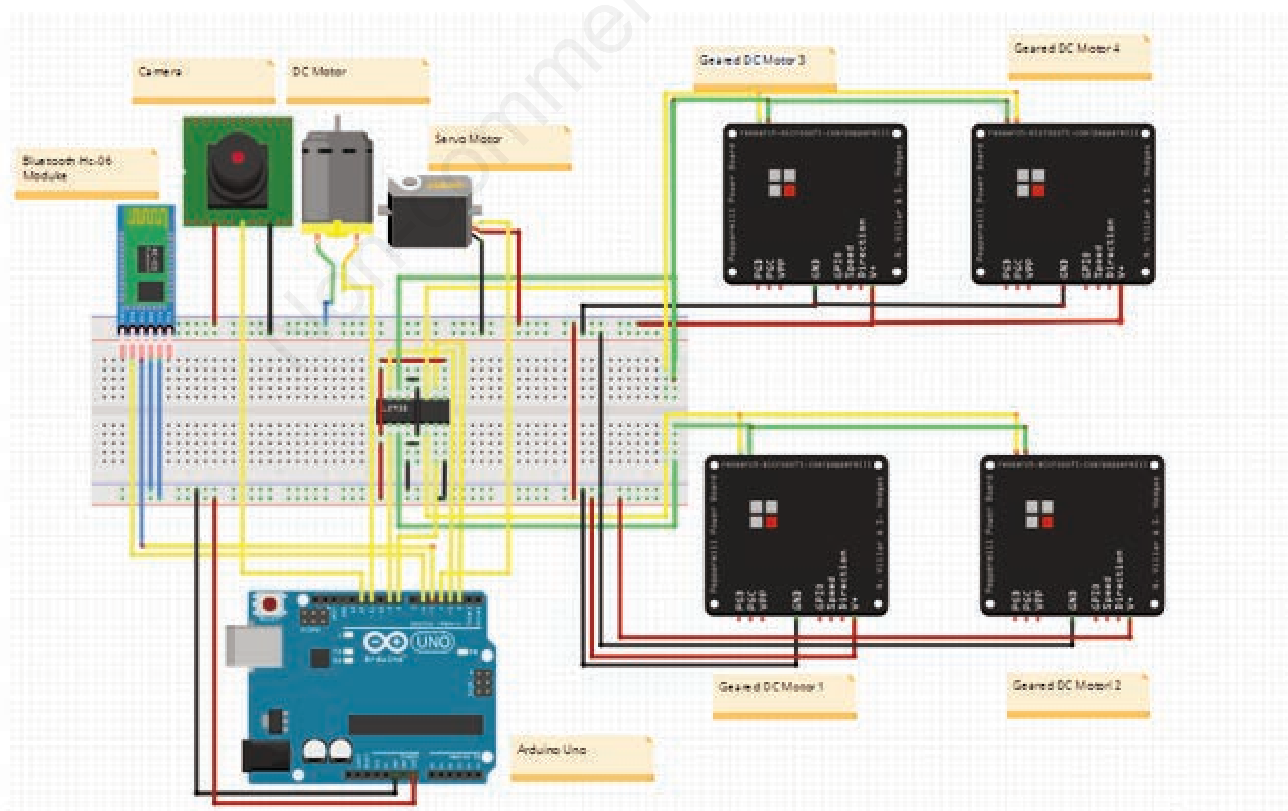

Figure 7. Schematic of component connection (source: Fritzing).

grated development environment (IDE) utilised was the Arduino IDE 1.8.5. An IDE is a product application that gives extensive facilities and utilities to programming improvement. The Arduino IDE contains a word processor where codes are composed, a message region, a text console, a toolbar, and a progression of menus. The Arduino IDE was utilised to programme the robot using the C++ programming language. After that, the code was uploaded into the Arduino Uno ATmega 328 microcontroller.

Android application development

An android application was created from MIT application Inventor - a web application developmental environment. An application created from MIT Inventor is appropriate and perfect with essential microcontrollers like Arduino. The application was created through structure building blocks picked and put in the plan screen to frame tabs or windows and coded to execute a function when the tab or window is pushed on the android interface.

Performance evaluation

The performance evaluation of the harvester was based on the response accuracy of the geared DC motor to the control interface on the android device, Bluetooth module test, and climbing speed test.

Response accuracy of the Geared DC Motor to the control interface on the Android device

The response accuracy of the gear DC Motor test was carried out to determine the margin error between the initiation of a command on the android device and its actual actuation by the harvester geared DC motor climbing wheel. The set-up of this test was such that a line was marked on the tree (90 cm from ground level), and as the harvester climbing wheel got to the marked line, the 'stop' command was clicked on the Android interface. After that, the final position of the wheel was marked, and the distance of the final position was measured with the help of a tape rule. The setup of the test is shown in Figure 8.

Bluetooth module test

The Bluetooth module test was carried out to test the maximum distance range of each command on the control interface on the Android device for the intended purpose. Based on the encoded commands attached to each button on the control interface, data were sent to the Bluetooth module (HC-05) placed on a horizontal plane due to the conceptual arrangement of the test by using a successive distance of 5 m. After every successful distance, a further distance was moved until a point where the signals were not sensed.

The climbing speed test was carried out to determine the time the harvester took to climb a 1 m marked point on the tree model, and the time taken for the harvester to descend. The set-up of this experimental run consisted of using a tape rule to measure the 1 m point on the tree model and the timer to measure the time taken to climb.

For each of the performance evaluations, the statistical approach used was the average statistical approach to ensure the repeatability of the results. This is represented in Eq. 17.

$$\bar{X} = \frac{X_1+X_2+X_3+X_4+X_5}{5} \quad (17)$$

Results and discussion

Oil palm tree parameters

Based on the sampled oil palm trees, the result of the tree parameters showed that the average maximum circumference at breast height of oil palm trees in Nigeria was 1.27 m, which gave an average maximum diameter at breast height of 0.404 m (Figure 9A) while the average height of oil palm trees in the study area was 5.531 m in which the highest height recorded was 10.1 m and the lowest height was 3.47 m (Figure 9B).

From the obtained results, it was observed that there were some disparities between the oil palm tree parameters in Nigeria and that of Malaysia in which Tan *et al*. (2014) obtained the average DBH of oil palm trees in Malaysia as 1.3 m for mature oil palm trees and 0.1m for young oil palm trees. The reason for this variation in the values of the DBH of oil palm trees between these two studies can be attributed to the findings of Feldpausch *et al*. (2011), who discovered that trees' height and diameter, as well as their ratio relationship of the same type of tree, differs by geographic region and forest type.

Furthermore, the obtained results on oil palm tree parameters gave an average height of 5.531 m, which suggests that the use of the manual method in the harvesting of oil palm FFB will be dangerous and ineffective since the average height is more than twice the average West Africa male heights of 1.65 m (Roser *et al*., 2020). Similarly, the result showed that some forms of mechanised harvesting methods (Ckat, Cantas, and harvesting machine) could be used for harvesting oil palm FFB. However, due to the farming methods in this region in which, 80% of the production of oil palm in Nigeria comes from dispersed smallholders who are usually local farmers (Bankole *et al*., 2018), this method may not be affordable by the farmers.

From the results obtained (as shown in Table 2), it was discovered that an average error margin of 2.38% exists between the geared DC motor and the control interface on the android device. This value is evaluated as being accepted and in good agreement

Figure 8. Experimental set-up of Geared DC motor accuracy and Bluetooth module climbing speed test.

Table 2. Response accuracy of the Geared DC motor to the control interface on the Android device test.

Tests	Marked distance (cm)	Actual distance (cm)	Error distance (cm)
Test 1	90	92.4	2.4
Test 2	90	91.6	1.6
Test 3	90	91.9	1.9
Test 4	90	92.3	2.3
Test 5	90	92.5	2.5

Table 3. Bluetooth module (HC-05) range test.

Command	5 m	10 m	15 m	20 m	25 m	Result
Climb up	Success	Success	Success	Success	Failure	The climbing wheels climb up the tree model
Stop	Success	Success	Success	Success	Failure	The climbing wheel stops climbing, and if the cutter blade is active, it stops
Climb down	Success	Success	Success	Success	Failure	The climbing wheels climb down the tree model
armFwd	Success	Success	Success	Success	Failure	The upper cutter arm moves toward the tree model
Armrest	Success	Success	Success	Success	Failure	The lower cutter arm moves away from the tree model
Cut	Success	Success	Success	Success	Failure	The cutter blade is actuated

with the marked distance since it is less than 5% (Othman *et al*., 2018). This result further shows the suitability of geared DC motor as a locomotion means of an oil palm harvester, alongside its stability advantage.

Bluetooth module range test

From the results obtained (as shown in Table 3), it was discovered that the maximum distance that the Bluetooth module HC-05 can receive and transmit data is within the 20 m and the 25 m range; however, for safety reasons, the maximum receiving and transmitting distance is taken as 20 m. This result agrees with a study on wireless communication using HC-05 Bluetooth module interfaced with Arduino carried out by Cotta *et al*. (2016), who stated that the range of Bluetooth Module HC-05 could extend up to 100 m with an increase in transmitting power. Furthermore, this result further strengthens the suitability of Bluetooth module HC-05 as a communication module in harvesting oil palm FFB remotely; this is because, as reported earlier, the maximum height of oil palm trees in the study area is about 10.1 m which makes this wireless communication sufficient for data transmission and receiving during the harvesting processes.

Table 4. Climbing up speed test.

Tests	Distance (m)	Time taken (sec)	Speed (m/s)
Test 1	1	26	0.038
Test 2	1	30	0.033
Test 3	1	28	0.036
Test 4	1	30	0.033
Test 5	1	27	0.037

Table 5. Descending speed test.

Tests	Distance (m)	Time taken (sec)	Speed (m/s)
Test 1	1	24	0.042
Test 2	1	20	0.050
Test 3	1	23	0.043
Test 4	1	21	0.048
Test 5	1	23	0.043

Climbing speed test

From the results obtained (in Tables 4 and 5), it was observed that the average time taken to climb a 1-metre mark on the tree by the harvester was about 28.2 sec which produced an average speed of about 0.036 m/s, while the average time taken to descend the tree model by the harvester was 22.2 seconds, which produced an average speed of about 0.045 m/s. The variation in the climbing speed and descending speed is associated with the impact of gravity on the harvester. Furthermore, from the result, it was observed

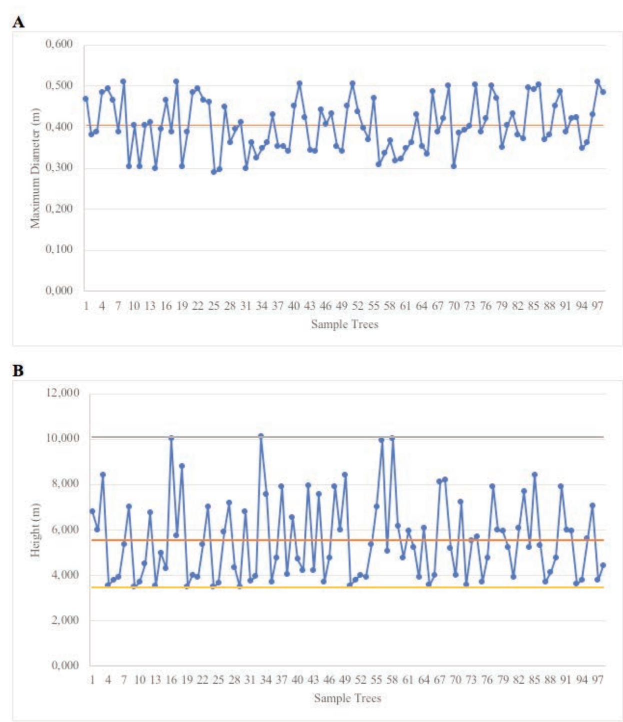

Figure 9. A) Maximum oil palm trees diameter trend in the study area; B) height distribution of oil palm trees in the study area response accuracy of the Geared DC motor to the control interface on the android device.

that the climbing speed of 0.036 m/s obtained is close to one obtained from the work of Pengfei *et al*. (2018) with a climbing speed of 0.042 m/s. The speed reduction is a result of the use of the DC motor in the previous study and the use of geared DC motor in this. The trade-off in the climbing speed provided an advantage in the stability of the harvester, which was not obtained in the previous work. Again, the climbing speed obtained from this study was higher than that obtained by Praveenbabu *et al.* (2017) with a climbing speed of 0.0021 m/s, though the harvester had better stability during the harvesting process due to the inchworm locomotion employed.

Conclusions

The result of this study showed the importance of oil palm harvesting in eliminating the ergonomic risk associated with oil palm FFB harvesting in which the average height of oil palm tree in the study area was obtained as 5.531 m, which shows the unsuitability of the existing traditional method in the harvesting process. This study also used a geared DC motor to develop an oil palm harvester, solving the stability issue encountered by previous researchers during the harvesting process without necessarily reducing the climbing speed by a wide margin. Furthermore, the use of geared DC motor help in the production of high torque for the climbing process, and due to this high torque, instability during the harvesting process was reduced. Furthermore, the response accuracy of the geared DC motor to the control interface on the android device, which gave a margin error of less than 5%, shows the suitability of geared DC motor to oil palm FFB harvesting. Also, the HC-05 Bluetooth module had a maximum range of 20 m which is higher than the maximum height of 10.1 m for oil palm trees in the study area, and this shows its suitability for the intended application.

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