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Design and Feasibility Study of a Surface-Irregularities Adaptive Tracked Crawler based on Oil Palm Tree Morphological Features

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Abstract: In the oil palm industry, there is an exigent need for the development of climbing robots in order to cope with the impending shortage of manual labour for the pruning and harvesting operations. On tall oil palm trees, harvesting and pruning are extremely labor intensive processes. Therefore, research of this kind will potentially lead to an increase in productivity and efficiency in daily operation. Several relevant studies are discussed in this study to identify the trends and challenges in an attempt to identify the most suitable locomotive mechanism for an oil palm climbing robot. Morphological studies of oil palm trees and its surrounding environments were conducted to identify design challenges. Concept selection matrix was utilized to determine the most suitable locomotion followed by a force analysis of the tracked crawler. The developed prototype of the Polyurethane (PU) tracked crawler was presented. Finally, outdoor trials were conducted to study the effectiveness and feasibility of the tracked crawler design. The results indicates huge potential of the PU track being used on future climbing robots to climb irregular surface of oil palm trunks.

Key words: Tracked crawler, track propulsion, tree climbing robot, track-type locomotive mechanism, robots, matrix

INTRODUCTION

Palm oil is a very popular commodity in Malaysia. Globally, in 2016, Malaysia produces 23.29 million tonnes of palm oil products (MPOB., 2017). It is a versatile product and rich in nutrients (Ekwenye, 2006). In order to improve Malaysia's competitiveness in this sector, huge emphasis has to be placed on increasing the harvesting efficiency and reducing country's dependence on foreign workers.

The standard method of harvesting involves a pole with a chisel or sickle attached to its end can be used for short and tall trees, respectively. A newer technology, Cantas was introduced by Jelani *et al*. (2008) as a mean to mechanize the cutting process. However, its use is still limited to trees below the height of 7 m with the commercially available Cantas. At its matured stage, oil palm trees can grow as tall as 18-20 m. An extension pole is required in order to reach the oil palm fruits and this adds considerable weight to the whole unit. Handling and manoeuvring the long flexible pole that is a few times the length of human body with sickle cutter at its end is an extremely difficult, arduous and hazardous task. Moreover, it also consumes a lot of energy. Therefore, research on application of climbing robots in the oil palm plantations has to be intensified.

Research on tree climbing robots has so far been limited on a small array of applications such as in the forest management and coconut industry. To climb trees with smooth trunks, typical robots developed by researchers often share a few similarities. For this type of surface, wheel is the preferred choice of locomotive mechanism. Tree climbing robots that utilize wheels for climbing were developed by Kawasaki *et al*. (2008), Ishigure (2013) and Mani and Jothilingam (2014). Climbing is achieved in a vertical or spiral manner. Woody is another robot designed to climb straight trees to remove tree branches. To improve the traction of the climbing robot, small spines are added to each wheel to provide more adhesion to the surface in order to prevent slippage (Ren *et al*., 2014).

Only one paper discusses the development of oil palm tree climbing robot (Shokripour *et al*., 2010). Instead of using rubber wheels this robot uses sprockets to climb. However, there is no mention of whether it can successfully climb tree trunks full of frond stubs.

Having discussed several important features of the tree climbing robot above, it is imperative to look into

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another challenging aspect of climbing oil palm trees. The trunks grow around 30-40 cm each year and produces around 25 fronds each year. Therefore, pruning is necessary before harvesting process can take place. Standard and conventional method of pruning does not remove the fronds completely from the trunk. These frond stubs form irregular surface along tree trunk that presents a huge challenge for robots. None of the robots mentioned above was designed to successfully cope with this. They were only designed to perform well on trees with smooth or some minor irregularities on the tree trunks.

Essentially, there are six categories of locomotive mechanism in climbing robots, namely: legged, cable, wheel, track, translation and combined type (Chu *et al*., 2010). In addition, Chu *et al*. (2010) also stated that there five types of adhesion mechanisms: suction, gripping, magnetic, rail-guided and biomimetic type. Without implementing a proper adhesion technique to suit the climbing surface, the chosen locomotive mechanism will not enable the robot to travel from one location to another. Most of the robots discussed above use wheels and sprockets as the mode of locomotion. However, tracked-type system has proven to be more suitable for unstructured environments and difficult terrains such as rocky surface or rubble of a collapsed structure. Its main advantage is that it can passively adapt to multitude of terrain surfaces. Numerous tracked-type robots have been developed over the years such as the wheel and track hybrid robot (Kim *et al*., 2010), HELIOS-VI (Hirose *et al*., 2001), ROBHAZ-DT3 (Lee *et al*., 2004), Gunryu (Hirose *et al*., 1996), Nanokhod (Klinker *et al*., 2007), OT-4 Serpentine Robot (Borenstein *et al*., 2007) and AZIMUT (Michaud *et al*., 2005). In addition, numerous research have been conducted to study the interaction between tracked-type locomotion with various types of surfaces (Liu *et al*., 2005; Xiong *et al*., 2015; Li *et al*., 2015; Kim *et al*., 2010; Gao *et al*., 2017; Yu *et al*., 2011).

In this study, the focus is on development of a tracked crawler to determine its feasibility in climbing surface irregularities on oil palm trunk. To achieve this, morphological features of oil palm trees are studied. This way, the criteria and requirements of the track system can be specified before the analysis and design phase. Finally, experimental results conducted from outdoor trials will be presented.

MATERIALS AND METHODS

Study on morphological features of oil palm trees: It is of utmost importance that challenges and problems pertaining to machinery operations in oil palm plantations are identified in order to come up with the most efficient and optimal design. This is the most fundamental step in building a new climbing robot. Therefore, several observations have been recorded.

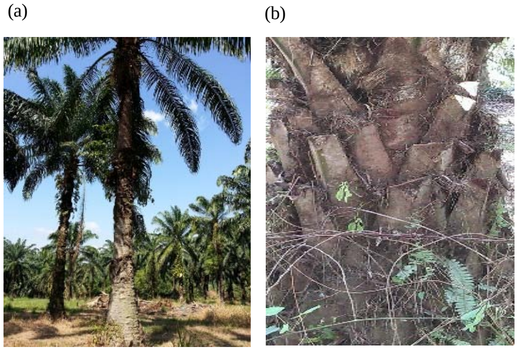

Fig. 1: Physical characteristics: a) Variation of trunk diameter and b) Typical irregular surface of oil palm trunk

Height of the oil palm trees: Oil palm trees can grow as tall as 18-20 m. As a result, harvesting has to be performed at this extreme heights too.

Variation of trunk diameter: The diameter and cross section of an oil palm trunk vary with its height. The largest diameter can be found at the base of the tree as it tapers gradually towards the top of the tree (Fig. 1a). On trees with heights between 7 and 15 m, the diameter of the oil palm trunk ranges from 45-65 cm, measured 1.50 m above ground level.

Irregular tree surface: As shown in Fig. 1b, oil palm tree trunks are usually covered with remnants of chopped fronds which will be referred to as frond stubs in this study.

Habitats for plants and insects: Figure 2a-c show the typical obstacles commonly found on trunk surfaces of some of the oil palm trunks. One can usually spot moss and parasitic plants on the tree trunk. Sometimes, even bee hives and bird nests can be found on it. Factors such as trunk surface, shade and shelter attract all kinds of insects and plants to inhabit these tree trunks.

Wet and dry surfaces: Harsh surroundings in the plantation area and unpredictable weather in Malaysia makes the trunk surfaces vulnerable, thus, they deteriorates over time. Dust, debris, wet and slippery surface are common on the trunk surface.

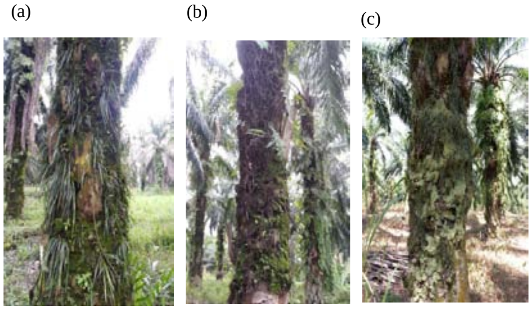

Fig. 2: Typical obstacles on oil palm trunks: a) Small parasitic plants; b) Obstacles in the form of old frond stubs and c) Trunk covered with moss

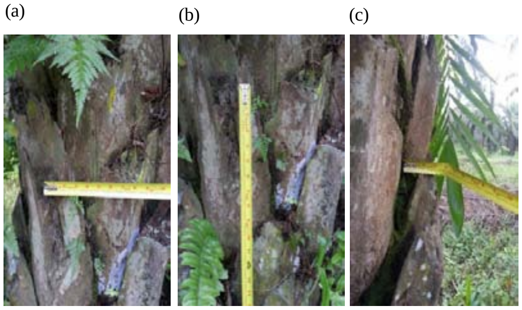

Fig. 3: Surface structure of the oil palm trunk: a) Horizontal distance; b) Vertical distance and c) Recess in between frond stubs

Design requirements of the locomotive mechanism: The locomotive mechanism is evaluated based on several design requirements: durability, design complexity, agility, optimal contact surface, surface conformity, shock and vibration absorption, ease of use and speed. These are the most significant criteria to address and overcome the challenges discussed in the previous study. The following paragraphs discuss only three of the design requirements that are deemed most crucial and relevant to the morphological features of the trunk.

Optimal contact surface: In order to climb, firstly, the area that provides the needed traction has to be identified. Usually, frond stubs leave a rough chopped cross section that can be used as contact points for climbing. As shown in Fig. 3a, b different measurements that were taken in the field. The average lateral and longitudinal distance between two adjacent chopped fronds are approximately 8±1 inches and 12±1 inches, respectively. Therefore, the track that will be developed have to be at least 7 inch wide and 11 inch long.

Figure 3c illustrates the depth of the recess on the trunk. Irregularities on the trunk surface due to uneven frond stubs can form a recess as deep as 4 inches or 101.60 mm. These recesses are a hindrance to the wheel-type locomotive mechanism. When the wheel is stuck at this position it has to generate sufficient traction to climb out of it. This is made harder because the upper frond stubs are inclined outwards at an average between 10°-13° from vertical. Not only does the robot has to produce upward driving force, it has to provide enough horizontal gripping force as well. Thus, it is important to tune the system to prevent the horizontal components of the upward force and the horizontal force from expending unnecessary energy that partially cancels each other. Most importantly, the observation above will have a significant influence on the dimensions of the track.

Surface conformity: To gather sufficient traction, it is important for the chosen locomotive mechanism to be able to conform to the extremely uneven surface of the tree trunk. There are recesses and protrusion formed by the frond stubs which pose a huge challenge for any climbing robot. In order to achieve surface adaptability, a flexible, tough and durable material has to be used such as polyurethane. This is to allow the locomotive mechanism to either wrap itself around the frond stubs or flex and sink itself in the recesses. These are significant features for the climbing robot to maintain hold on the tree trunk.

Shock and vibration absorption: Having discussed the challenges of climbing oil palm trees, it is of utmost importance to incorporate a shock and vibration absorption feature onto the robot. Due to the uneven surface of the tree trunk, the instability of the climbing process and unexpected slip and fall, this feature will dampen and minimize some of these effects. As a result, it could prevent catastrophic failure and damage to the machine. Complex mechanism with springs, damper and linkages can be designed for this purpose but this would add significant weight to the climbing robot.

Selection of the locomotive mechanism: Out of the six locomotive mechanisms mentioned by Chu *et al*. (2010), only three locomotive mechanism show the most potentials, namely wheels, tracks and legs. Table 1 shows the concept selection matrix that compares a number of design candidates that ultimately leads to the best locomotive mechanism that meets the design requirements. Each criteria is assigned with a score ranging from 1-3. A criteria that positively and heavily affect and influence the robot’s performance to the least influential are assigned different scores in descending order. Different signs such as 0, - and + denotes “baseline”, “worse than the baseline” and “better than the

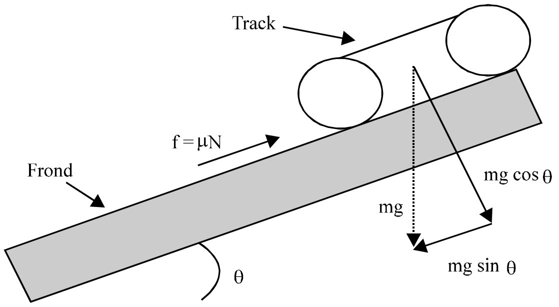

Fig. 4: Setup to determine the coefficient of friction between frond and track

Table 1: Concept Selection Matrix to select the best locomotive mechanisms

Criteria	Weight	 Wheels (datum)	 Tracks	 Legs
Durability	3	0	+	-
Design complexity	2	0	0	-
Agility	1	0	-	+
Surface conformity	2	0	+	0
Contact area	3	0	+	0
Shock absorption	3	0	+	+
Ease of use	1	0	-	-
Speed	1	0	+	-
	+	0	12	4
	0	8	1	2
	-	0	2	7
	Score	0	10	-3

baseline", respectively. A common wheel locomotive mechanism in this case is referred to as the reference concept. It is chosen as the datum (base concept) where all its corresponding criteria are set as the baseline that corresponds to the value of 0. Then, other types of locomotive mechanisms are evaluated according to their strengths and weaknesses against the datum (base concept). With the different criteria evaluated against different types of locomotive mechanisms, the design selection matrix requires all the scores to be aggregated with the highest total scores being the best design candidate.

Analysis on climbing effort: Frictional force is given by:

$$f = \mu N$$

Where:

N = The normal force perpendicular to the trunk surface acting on each track

μ = The coefficient of friction between each track and the trunk

Experimental setup to determine the coefficient of friction is shown in Fig. 4.

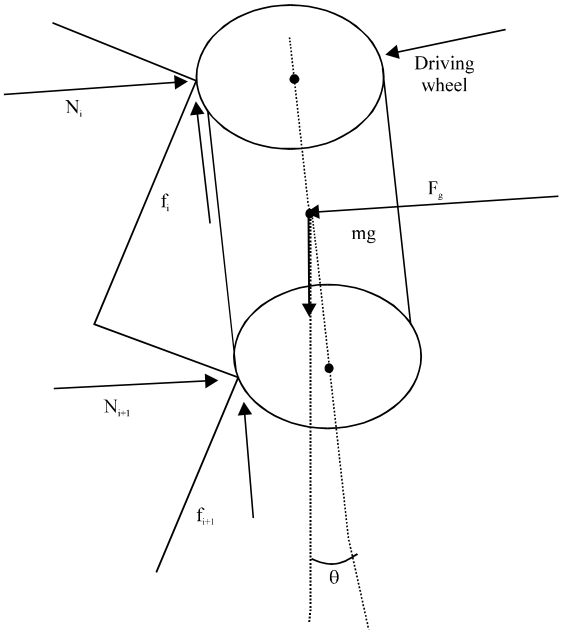

Fig. 5: Free body diagram of tracked crawler on the trunk

From the free body diagram shown in Fig. 4, Eq. 1 can be derived. Next, coefficient of friction, μ can be obtained using Eq. 2:

$$mg \sin\theta = \mu\, mg \cos\theta \quad (1)$$

$$\mu = \sin\theta / \cos\theta = \tan\theta \quad (2)$$

Upon testing the track on fronds with wet and dry surfaces, the calculated coefficient of friction on wet and dry surfaces are 0.67 and 0.95, respectively.

The strategy used by the tracked crawler for climbing are a combination of friction contact and interlocking contact. In friction contact case, tractive effort is a product of the weight and the coefficient of friction between the track and the surface as described above. Meanwhile, in interlocking contact case, the principle design parameter is the shear strength of the contact region instead of the coefficient of friction. As a result, the tractive effort is a function of several parameters expressed by Eq. 3:

$$F = 2nwL\tau \quad (3)$$

Where:

w = The width of the track

n = The number of treads that are in contact with the trunk

L = The length of track in contact

τ = The shear strength of the trunk

During climbing process, the interaction of the tracked crawler and the trunk is depicted using the free body diagram depicted in Fig. 5. In this system

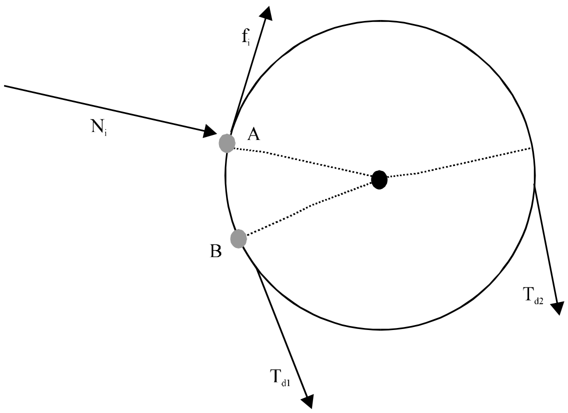

Fig. 6: External forces acting at different locations on the rim of the driving wheel

assumptions made for this analysis are the mass and the inertial effect of the track are considered negligible. The forces acting on the tracked crawler are the normal forces, N_i and N_{i+1} and tangential forces, f_i and f_{i+1} applied by the frond stubs on the two point of contacts. In addition, other forces include gravity, g, track tension around the driving wheel, T_d and the gripping force, F_g that will be supplied perpendicularly by an actuator attached to the robot chassis and the track tension around the driving wheel.

The driving force will be provided by the driving wheel as shown in Fig. 5. Analysis of the static relationship between the driving force, F_d of the driving wheel and the external forces can be described by:

$$F_d-\sum_{i=1}^{n} N_i-\sum_{i=1}^{n} f_i-Mg\cos\theta = 0 \qquad (4)$$

In Eq. 4, the value of n depends on the number of contact points between the track and the trunk, hence n = 2 for configuration shown in Fig. 5.

In Fig. 6, the external forces are shown acting at different locations on the rim. The external forces from the trunk may be acting at locations A or B on the rim. In other cases, trunk may not even made contact with the rim of the driving wheel. In order to obtain the relationship between the driving force of the driving wheel and the track tension around the driving wheel, summation of moment at the center of the driving wheel is made to equal zero. The resultant equations are shown in Eq. 5:

$$\begin{aligned} &F_d-(Td_2-Td_1) = 0 \\ &F_d-(Td_2-Td_1)-N_i = 0 \\ &F_d-(Td_2-Td_1)-f_i = 0 \end{aligned} \qquad (5)$$

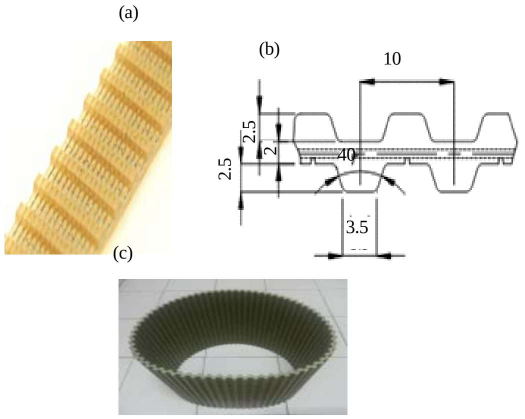

Fig. 7: Track: a) Steel cord reinforced track; b) T10 track dimensions; c) Endless polyurethane track

Tracked crawler hardware design: Long and wide track will help the crawler to climb over surface irregularities and recesses. The tread on the track improves the tangential force to enable it to clutch on the tip of frond stub. Durability is an important factor when selecting this track. The hardness of the PU track is rated at 88 shore A and the track is reinforced with 0.6 mm diameter steel cords as shown in Fig. 7a. This tread has 10 mm pitch and is able to maintain its shape and assist climbing whereas a larger and taller tread may buckle and add extra weight to the system (Fig. 7b). The small pitch helps to maintain continuity on the grips and avoid slippage. Figure 7c shows the Polyurethane (PU) track that is installed on the tracked crawler.

The wheel's dimensions are derived from a standard T10 pulley catalogue and further modifications were made to reduce its weight. At the middle of the chassis, a single 12.0 V, 1.96 Nm electric motor provides the propulsion power to drive the track. This is the heaviest component in the propulsion unit and it occupies a length of 151.9 mm. The chassis and the PU track weighs approximately 5.30 and 0.66 kg, respectively.

Torque is transmitted from the DC motor, chains, sprocket, front drive shaft and finally to the wheels. Amplification of torque is achieved by using a gear reduction system which at the same time reduces the wheel's speed of rotation, (rpm). A complete set of a gearhead with a gear reduction system and a 12 V DC motor is found in the local market. Planetary gearhead of the IG-42 motor has a reduction ratio of 104: 1 and the rated torque specified in the datasheet is 20 kg.cm or 1.96 Nm. Power is transmitted via a roller chain which connects a big sprocket fixed at the wheel to a small sprocket fixed at the DC motor drive shaft with a ratio of 24:8. This increases the torque output of the motor shaft from 1.96-5.87 Nm at the track wheels. From the calculation, the rotational speed of the motor has been reduced from 63-20 rpm, respectively. At 20 rpm, the calculated climbing speed is 0.1 m/sec. The climbing speed is intentionally set at low speed since the focus of this research is to study the feasibility of the track locomotion on oil palm trunks. For future research, the speed can be increased easily by using different combination of motor and gear ratio.

RESULTS AND DISCUSSION

For testing purpose, a prototype of the tracked crawler was designed and fabricated. Then, trials were conducted to demonstrate the feasibility of this new concept of climbing with track-type locomotive mechanism. When conducting the experiment, to simulate the gripping force shown in Fig. 5, the prototype was slightly pushed perpendicularly against the tree as shown in Fig. 8. A normal force was generated which acted at the point of contact between the track and the trunk surface. Power was then supplied to the unit and observations were then recorded.

With this experimental setup, the tracked crawler was able to climb the tree without any major issues at an average speed of 10 cm/sec. This demonstrates that the track can indeed be used successfully to climb irregular surface of the tree trunk. There was a good traction between the PU track and the frond stubs and there was no noticeable slippage. To further test this prototype, the unit was made to carry a heavy payload as shown in Fig. 9. Weights were added until the track failed to climb due to slippage. The final successful climb recorded a payload of approximately 17 kg. This is quite a huge value on top of the unit's own weight which is measured at 6 kg.

Furthermore, climbing was also possible on myriad of surfaces and conditions. The tracked crawler was able to climb even on trunks covered with moss and small parasitic plants. Traction generated on wet surface was also sufficient to propel the crawler upwards. The carefully chosen size of the track on the crawler enabled it to traverse over recesses on the trunk with ease.

Using the existing prototype, several weaknesses was identified. Occasionally, dust, debris, soil and small twigs can be found on the roller chain, sprockets and inside the track. Although, this does not interfere with the climbing operation, prolonged use may damage the driving mechanism. For future prototype, the placement of motor inside the track could solve this issue. This means the sprockets and roller chain will also be located inside the track. The advantage of this design is that the track will protect the motor and the drive train and not leaving it exposed as in the existing prototype.

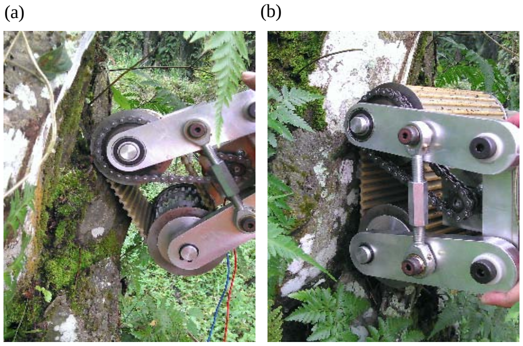

Fig. 8: Prototype testing on oil palm tree

Fig. 9: Tracked climber carrying a 17 kg payload

CONCLUSION

This study describes the morphological study of oil palm trees and the design of tracked crawler for climbing oil palm trees with irregular surface. The concept selection matrix was able to identify the best type of locomotion for this task. The first prototype of tracked crawler performed reasonably well during its first trials. It demonstrated the ability to climb irregular trunk surface in various conditions. In addition, it was able to carry additional payload of approximately 17 kg. This proves the feasibility of using the PU track on future oil palm tree climbing robot.

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