Development of a Bluetooth-Controlled Automated Screw-Jack: A Mobile Device to Reduce Tyre Replacement Drudgery

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ORIGINAL RESEARCH

Abstract- Replacement of vehicle tyre is a challenge for many people especially women, the aged or the physically challenged when it has to be done using traditional (manual) screw-jack. In this work, a Bluetooth-Controlled automated screw jack is developed to reduce the drudgery involved in lifting a vehicle in the process of changing tyres. The developed device is unique because it uses Bluetooth technology from a mobile device to wirelessly connect to a microcontroller (Arduino Nano) which in turn switches an electromechanical relay. This relay switches ON and OFF the motor responsible for lifting and lowering the mechanical screw jack. The developed automated screw-jack was tested with five different models of Toyota vehicles with weights ranging from 1186 kg to 1143 Kg. The evaluation revealed an average lifting speed of 231.4 rpm and a lifting time of 50 seconds. This study also revealed that once a critical distance of 10 m (line-of-sight) between the user-friendly application on the Android mobile phone and the automated screw-jack is exceeded, the performance of the automated screw-jack deteriorates in terms of speed and stability of measured values. The device has the advantage of maintaining safety when vehicular lifting is taking place and would enable women, children and the physically challenged to easily replace their tyres with minimal effort.

Keywords- Automated screw-jack, Bluetooth, vehicle lifting

1 INTRODUCTION

The task of lifting objects manually requires much effort. Manual lifting of heavy objects with hands or with conventional jacks had done more harm than good in the past. According to the Health and Safety Executive of the United Kingdom Health and Safety Executive (2022), manual handling had caused over a third of all workplace injuries. These include work-related musculoskeletal disorders (MSDS) such as pain and injuries to arms, legs and joints, and repetitive strain injuries of various sorts. The term manual handling covers a wide variety of activities including lifting, lowering, pushing, pulling and carrying. The danger is that if any of these tasks are not carried out appropriately there is a risk of injury. Injuries that result from manual handling can have serious health implications for the employer and the person who has sustained it. This implies that the conventional way of lifting automobiles and heavy objects must be discarded.

A screw jack can be referred to as a portable device that raises or lowers a load using a screw mechanism (Mashelkar and Tikoo. 2018). The manual jack requires a lot of human effort and intervention to work in the event of tyre puncture, car servicing, or during the lifting of heavy loads as opposed to the motorized screw jack. The screw jack that is motorised offers the advantage of comfort, fast and safety for the user. The weight lifting is quick and effortless, which can reduce physical fatigue that can impact negatively the user (Najeeb et.al, 2021).

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Section B- ELECTRICAL/COMPUTER ENGINEERING & RELATED SCIENCES
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Hence the design and development of an automated motorized screw jack that has the capability of solving the problem of manual way of lifting and lowering heavy objects, and prevent the occurrence of such injuries at the workplace and for car owners. The screw jack power can be harnessed through the pressure that is applied to the lead screw that is helical in design through the prime mover (DC motor). A DC motor converts electrical energy stored in a battery into mechanical energy. The moment electrical energy is applied to a DC motor, it develops a torque as a result of the energy conversion. Through the coupling interface, between the DC motor and the helical spring, the rotational movement is converted to translational movement. This implies a conversion from angular displacement to linear displacement (Barewar et al., 2018).

Different researchers have worked in the area of automated screw-jack. Through research reviewed, some methods had been used for lifting and lowering heavy objects and automobiles without human intervention. Advancement in technology has practically decreased manual effort (Barewar et al., 2018). Various technologies have been deployed to remove the difficulty that is associated with manual lifting and lowering. Binary Dominance Matrix analysis has been used to evaluate and determine the best solution for further development into a detailed design in which Solid works 2016 software was used to simulate the operation and loading of the resultant design Ignatio and Tapiwa (2019). In the work of Ramesh et al., (2021), in an attempt to solve the same problem using Arduino Uno with a control interface constructed as MIT App maker. In Babu et al., (2021), Arduino Uno was used to control all the motors by obtaining signals from the application with the help of a Wi-Fi module (ESP8266). This technology comes with the operational cost of Internet access when the availability of data is met. The hi-tech jacks are available in the market but due to high cost. This is a limiting factor, it cannot be owned by everyone (Abhishek et.al, 2018). This is true for people in developing countries, with low GDP.

The fabrication of a screw jack that is automatic aimed at achieving the same purpose in the work of Barewar et al., (2018) used a control switch as the medium of control. This technology is analog in design as the switch was manually actuated. Dhomne et al., (2021) designed and fabricated a motorized hydraulic jack that worked based on the principle of pascal's law without considering the medium of control of such a device. Such design of motorized type of hydraulic jack lacked Automation which puts the safety of the end user at risk. Even though there are electrically controlled jacks that have employed diverse controllers, they have not fully harnessed the strength/capability of Bluetooth as a medium of control for motorized type.

Najeeb et al., (2021) in an attempt to automate a screw jack used NodeMCU that has Wi-Fi capability but did not use Bluetooth technology. There is a new awareness regarding a cheaper way of actualizing the same lifting and lowering concept using the available local technology that is efficient and reliable. Even though Ramesh et al., (2021) opined that ESP8266 outperforms the Bluetooth-based technology, the work however did not take cost and size into consideration. This work focuses on modifying the design that is already in existence through the instrumentality of advances in a smartphone, Bluetooth, and Arduino Nano microcontroller technology. Its advantage is that it achieves the same purpose of automation with an emphasis on cost minimization and size which guarantees availability, comfort and safety of the user. During the software design, Arduino integrated development environment (IDE) was used to develop the code and compiled it before it was uploaded to the Arduino controller while Diagram.net interphase was used to draw the diagrams that were used in the project documentation.

Different devices are used to provide communication technologies for automated screw-jack such devices include Bluetooth modules (Kandasamy et al., 2019), Wi-Fi modules (Saravanan et al., 2022), NodeMCU ESP8266 Najeeb et al., (2021). Using these devices, the operator of the screw-jack can stand at a safe distance and control the upward and downward vehicular movement remotely using a mobile phone or other forms of remote-control gadgets. Previous works have been done on automated jack lifting without wireless communication Pawar et al., (2020); Pradhan et al., (2022), others have used Bluetooth technology as a means of communication in the development of automated screw-jacks Kandasamy et al., (2019); Najeeb et al., (2021). The authors did not carry out enough evaluation of the performance of the developed devices. The novelty of this approach is that it provides an approach to removed drudgery in tyre replacement and carries out performance evaluation of the proposed device on different models of Toyota vehicles.

The rest of the paper is arranged in the following order. Section 2 is the methodology, section 3 considers results, the discussion of results is in section 4, and concludes with section 5.

2 Research Methodology

The methodology for this work would be considered under three sub-heading namely the hardware, software and the mechanical analysis

2.1 Hardware Design

Fig. 1 is the block diagram of the developed device. The system is comprised of five main components: the Mobile device, which initiates the control input, the (HC-05) Bluetooth module, Arduino microcontroller, four-channel relay and the DC motor in connection with the screw jack for upward and downward movement. The mobile phone used in this work is Techno Android phone with 4GB random access memory (RAM), 32GB storage capacity with an in-built Bluetooth module. The mobile phone hosts software downloaded from the Google Pay Store that provides users with a user-friendly interface to initiate screw-jack control.

The Bluetooth module at the screw-jack side is an HC-05 Bluetooth module. It is purposely designed for wireless communication and operates at a range of less than 100 m. It uses a serial port to communicate with a microcontroller. Through a personal area network created by the HC-05 Bluetooth module, it created a communication path between the Android mobile phone and the microcontroller. The microcontroller used in this work is the Arduino Nano microcontroller. The choice of this device was based on its compactness, flexibility and breadboard-friendliness. It has the same functionality as the Arduino Uno but is more compact in size. To switch on and off the DC motor to generate upward and downward movement, a 4-channel relay is used. The direct current (DC) motor used in this work is from the vehicle battery rated 12V, 15 A that provides power for the DC Motor. The screw jack used in this work is a scissor screw jack.

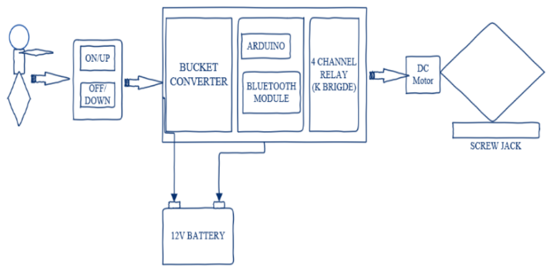

Fig. 1: Block diagram of the developed system

Fig. 2 is the system circuit diagram. 12 V energy supply derived from the car battery is connected to a buck converter. The buck converter receives the 12 V and steps it down to 5 V needed by the Arduino Nano microcontroller. The Bluetooth module's reception (RX) and transmitter (TX) terminals are also connected to the microcontroller through its digital input/output pins 3 and 2 respectively. This allows the system to provide input command signals and receive feedback to and from the microcontroller. The 4-channel relay also connects to the Arduino nano microcontroller through its digital input/output pins 4 to 7 as shown in Fig.2. 5 V digital signal is sent from the digital input/output pin of the Arduino Nano to the input pin of the relay. The relay

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sends out 12 V to energise the DC motor for rotational movement.

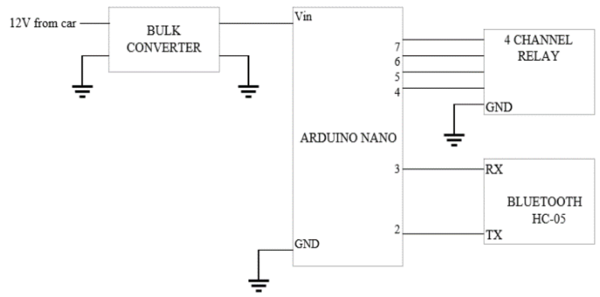

Fig. 2: Circuit Diagram showing Connection of Components

2.2 Software Design

When the system is switched on, it goes through the process of initialisation waiting for user to decide which direction the vehicle should move. If the user decides on up, through his mobile device, he initiates the operation pressing "up" which sends the command required for operation of the jack. This signal is delivered over Bluetooth via a Bluetooth module connected to the microcontroller to facilitate wireless reception and transmission. When the input signal reaches the Arduino, it operates the DC motor that is directly attached to it in a clockwise direction. The screw jack is then pushed up or down in response to the input command until the desired high is reached. The same operation goes for the downward movement if the user presses down until the car is lowered back to the ground. The flowchart describing the operation of the developed device is shown in Fig.3 while the user-friendly interface is shown in Fig. 4. The developed algorithm is uploaded to the Arduino Nano microcontroller for operating the screw jack.

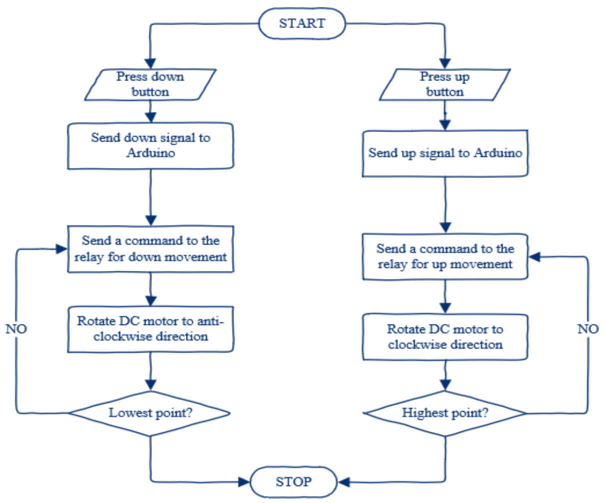

Fig. 3: System Flowchart

Fig 4: Bluetooth interface for automated screw-jack control

2.3 Mechanical Design Analysis

Screw jack design was based on the following parameter: coefficient of friction $(\mu) = tan\emptyset = 0.1$, maximum load (W) = 17.658kN, screw pitch (r) = 4mm, screw mean diameter (d) = 10 mm shown in Eq. 1 to 9. Fig.5a shows the cross-sectional profile of the screw and nut. The effort (P) moves clockwise to lift the load (W). Fig.5b shows the relationship between the pitch (r), helix angle (α) and circumference of the mean diameter (πd) while Fig.5c shows free body diagram showing different forces acting on the screw and nut when effort (P) is applied to raise the load (W).

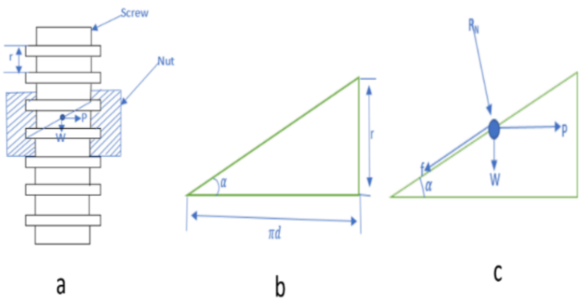

Fig. 5: (a) Cross-sectional profile of the screw and nut (b) Relationship between the pitch (r), helix angle (α) and circumference of the mean diameter (c) free body diagram showing different forces acting on the screw and nut when effort (P) is applied to raise the load; Where f = limiting frictional force between screw and nut; W = weight to be lifted; R_N = normal reaction; P = effort needed to raise the load; d = screw mean diameter; r = pitch of the screw; α = helix angle

From Fig. 5b

$$tan\ \alpha = \frac{r}{\pi d} = \frac{4}{\pi 10} = 0.127$$

$$F = \mu R_N \tag{1}$$

Resolving forces along the plane (Fig.5c)

$$Pcos\alpha = Wcos\alpha + F = Wcos\alpha + \mu R_N \tag{2}$$

Resolving forces perpendicular to the plane (Fig.5c)

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$$R_N = Psin\alpha + Wsin\alpha \quad (3)$$

Substituting Eq. 3 into 2

$$Pcos\alpha = Wcos\alpha + \mu Psin\alpha + \mu Wsin\alpha \quad (4)$$

Power required to raise the load (W)

$$P = W \times \frac{sin\alpha + \mu cos\alpha}{cos\alpha - `\mu sin\alpha} \quad (5)$$

$$\mu = tan\emptyset$$

$$P = W \times (\frac{tan\alpha + tan\emptyset}{1 - tan\alpha tan\emptyset}) \quad (6)$$

Substituting the value of W, $tan\alpha$ and $tan\emptyset$ into Eq. 6 to obtain P as P= 4.061 kN. Therefore, the required Torque to raise 17.658 kN

$$T = P \times \frac{d}{2} \quad (7)$$

T=20.31 N-m

Mechanical Advantage (M.A) of the screw jack is the ratio of load raised to the effort applied

$$M.A. = \frac{W}{P} \quad (8)$$

M.A = 4.35

MA of 4.35 implies that the speed and distance are increased by approximately four times and the effort needed to carry out the job decrease by four times.

Motor selection: Power of the motor (P_m) required to produce a torque (T) of 20.31 N-m with a speed of 250 rpm

$$P_m = T\omega \quad (9)$$

$$\omega = \frac{2\pi N}{60} = 26.18\ rad/s$$

$$P_m = 0.532\ kW$$

Based on the P_m calculation a motor of 1 horsepower DC motor was selected being the closest standard motor. Fig.6 is a prototype of the developed system being coupled together.

Fig. 6: Labelled diagram of the prototype system.

2.4 System Operation

When the start key is pressed by the operator on his mobile phone user-friendly interface, the Bluetooth module on the mobile phone creates a personal area network (PAN) between the mobile phone and the Bluetooth module connected to the microcontroller circuit that is in attachment with the screw-jack thereby initiating the screw-jack remote control. This signal initiated by the operator is delivered over a Bluetooth communication path to the microcontroller to facilitate wireless signal reception and transmission. When the input signal reaches the Arduino, it energises the relay to operate the DC motor that is directly attached to it. As a result of the rotation of the DC motor, the screw jack is then pushed up or down in response to the input command. This up-and-down movement is fed back to the mobile device via the Bluetooth PAN where it is utilized for monitoring. This process is repeated indefinitely unless the user interrupts it. From the physical upward and downward car movement and feedback from the mobile device, the operator may decide to stop the movement by pressing the stop key on the mobile phone interface. The vehicle stops moving in response. This way, the remote forward and reverse buttons are utilized to move the motor in the desired directions.

3 Results and Discussion

Different tests were performed to evaluate the performance of the developed automated screw jack. Toyota vehicles of different models were used as shown in Fig.7. The choice of Toyota vehicle is due to its popularity in Nigeria. Statistics have it that 50 percent of Nigerian vehicles are Toyota brand (Naijaauto, 2022). The tests include: Critical distance Test under load and no-load conditions, test to evaluate system performance under weights of different models of Toyota vehicles and test to determine the effect of vehicle weight on the system performance.

3.1 Critical Distance Test

In Fig. 8, the developed automated screw-jack was operated without using it to lift any object while the distance between the mobile device and the screw-jack varied between 2 m and 14 m in a line-of-sight arrangement. The same experiment was performed by using it to lift a Toyota Ascent GL-i (2001) car with a weight of 1143.053kg. In both cases, 12 V DC power was sourced from the car battery in the bonnet for this experiment. This test was performed under a no-load condition as shown in Fig.8, a load condition shown in Fig.9.

From the graphs in Figures 8, it could be seen that under a no-load condition, the Bluetooth connection worked well until a critical distance of 12 m when the Bluetooth connection between the two devices failed. In the case of load condition with Toyota Ascent GL-i (2001), Bluetooth connection was still performing well until a distance of 14 m when it finally failed. However, from 10 m, a slight oscillation could be observed in the measured values until it finally failed at 14 m distance. This oscillation was more pronounced in the downward movement than the upward movement.

3.2 Test to Evaluate System Performance with Different Models of Toyota Vehicles

During this test, the developed automated screw-jack was used to lift five different models of Toyota vehicles of varying weights while different parameters such as the upward and downward speeds, voltage drop for the upward and downward movements, temperature rise and so on were measured. The speed of lifting for the upward and downward of the screw-jack was measured using an infrared tachometer and recorded. The electronic circuit of the screw-jack was also powered by

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the vehicle battery in the bonnet of the vehicles which was extended using electrical cable at a distance of about 4 m from the battery. The result of this test is shown in Fig.10. In Fig.10, it could also be observed that different models of Toyota vehicles with different weights were lifted with the developed automated Bluetooth-controlled screw-jack while operating the mobile device was placed at a distance of 4 m from the screw-jack. Different parameters about these vehicles such as vehicle weight, temperature, average upward speed, average downward speed, lifting time, lowering time and voltage drop were measured and recorded. Fig.11 also shows that the downward movement operated at a much lower speed compared to the upward movement and that the lift time for all the vehicles was shorter than the return time.

3.3 Test to Determine the Effect of Vehicle Weights on the Screw-Jack Performance

In this test, the performance of the developed automated screw-jack with the vehicle with the highest weight and the one with the lowest weight were compared in terms of upward and downward speed and lifting and descent time. It could be observed from Fig.11 that the Toyota I Camry (2001) with a maximum weight of 141.5 kg (scaled) produced the minimum upward speed of 143 rpm and the least downward time of 57.5 rpm when compared with the rest of the Toyota models. Whereas Toyota Corolla Ascent with a minimum weight of 114.3 kg (scaled) produced a maximum upward speed of 250 rpm and also had a maximum downward speed of 125.9 rpm.

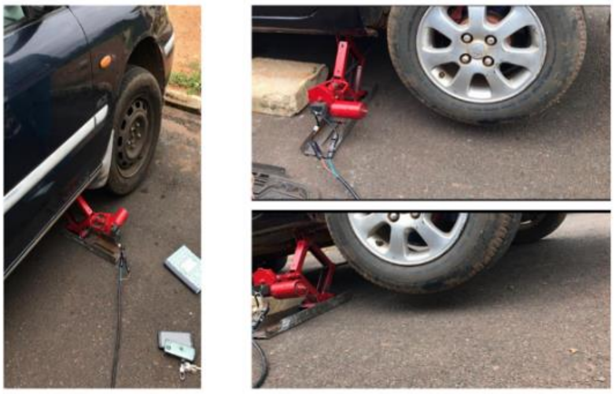

Fig. 7: Live lifting test of Toyota Accent 2002

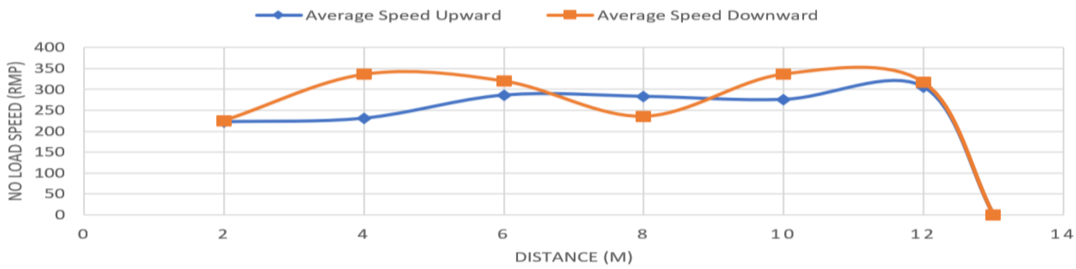

Fig. 8: Graph to determine maximum range of the Bluetooth network under a no-load condition

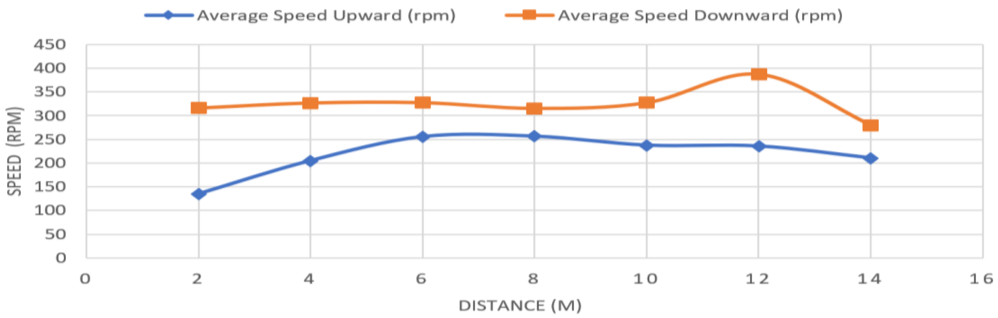

Fig. 9: Graph to determine maximum range of the Bluetooth network under a load condition

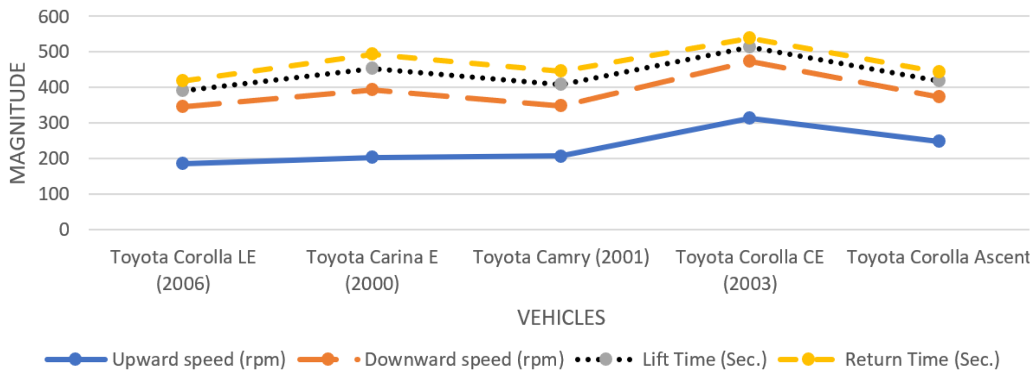

Fig. 10: Comparison of speed of automated screw-jack with different Toyota vehicle models

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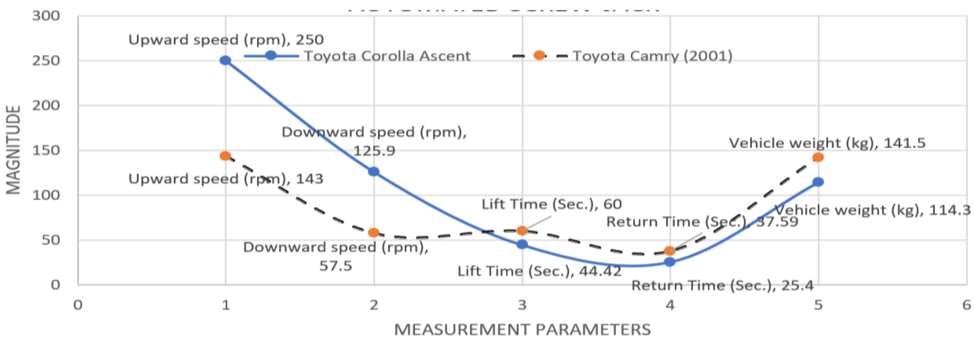

Fig. 11: Effect of vehicle weight on the automated screw-jack performance

3.4 Discussion of Results

The critical distance of Bluetooth communication with the screw-jack is 13m under no load condition and 14 m under a load condition. Even though the maximum Bluetooth operating range is 10 m, this distance could vary due to obstructions (Sony, 2022). One can observe that beyond 10 m, the oscillation experienced in the reading of the screw-jack developed which is confirmed by the fluctuating no-load and load critical distances which implies that the performance of the developed device deteriorates. Therefore, it is advisable that users of the device must operate it within the operating range of 10 m for optimal performance of the system. This would also provide a tolerance distance of 3 to 4 meters to accommodate any envisaged interference during the operation of the device.

In Fig.9, upward movement speed of the screw-jack which was lower than the downward movement could be because during the upward movement, the jack is carrying the weight of the vehicle and as such is working against the forces of gravity and friction. It could also be observed that from 10 m distance, the system experienced a sudden rise and fall (fluctuation) in the speed of the screw-jack and it was more pronounced in the downward movement than the upward. This fluctuation could be due to fluctuations in the communication of the Bluetooth network which operates at an optimal range of 10 m. A possible implication could mean that during the 10 m to 13 m distance, the efficiency of the device in car lifting is reduced.

The corresponding increase or decrease in the DC motor temperature and voltage drop in the automated screw-jack as the vehicle weight is in consonance. The ability of the developed automated Bluetooth-controlled screw-jack in the remote lifting of vehicles was confirmed in its ability to lift 1186 kg to 1143 Kg of vehicle weights. The fact is that many vehicles fall within this weight range in Nigeria combined with the fact that Toyota vehicles are highly patronized by most vehicle owners in Nigeria. It also implies that there is already a potentially high market for this device in Nigeria and the west African subregion.

In Fig.11, the low upward speed of the Toyota I Camry (2001) compared with Toyota Corolla Ascent and other models could be a result of the forces of gravity, inertia and friction acting against it. During downward movement, one would expect that the speed would be higher than the rest of the models since gravity is now in its favour. However, it still produced the least downward speed of 57.5 rpm. A possible explanation could be that much frictional force was acting against it. Another reason could be that the temperature rise as a result of vehicular lifting during the upward movement could reduce DC motor efficiency thereby resulting in low speed during the downward movement. In the case of the Toyota Corolla Ascent with the least weight, frictional force, as well as low efficiency due to temperature rise, will have less effect on its operation due to less weight.

4 Conclusion

In this work, a Bluetooth-controlled automated screw-jack is developed to assist drivers, especially the aged, women and physically challenged in the replacement of vehicle tyres. The developed device was able to successfully lift five different models of Toyota vehicles with weights ranging from 1186 kg to 1143 Kg using an Android mobile phone placed at a distance of 10 m. The study revealed a critical distance of 14 m beyond which the system could deteriorate in performance due to attenuation in the communication network. Future work would include improving device efficiency by reduction of friction resulting in greater efficiency.

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