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Research article

Design and simulation of eco-friendly smartphone controlled forklift

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A R T I C L E I N F O

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A B S T R A C T

The recent revolution in industrial technology increased the demand for unmanned forklifts that can be operated remotely. Unmanned forklifts eliminate the effort needed to train a highly qualified operator and reduce the accident rate due to driver fatigue. Currently, the operation of forklifts depends on either hydraulic systems or gasoline which has a negative impact on the environment. The increased awareness of the environmental threats urged the manufacturers to replace conventional forklifts with electrical ones. Unmanned electrical forklifts have a high cost that is considered a burden for developing countries, especially when being used in small warehouses. Thus, this paper presents an innovative approach for designing a semi-automated eco-friendly forklift suitable for small warehouses operated using a smartphone application. The forklift is designed to lift a maximum load of 200 N using a ball screw feed mechanism, characterized by its light weight and its ability to withstand corrosion. The structural stability of the forklift has been investigated using SolidWorks simulation. The designed model has been imported to MATLAB Simulink to estimate the suitable battery size required for forklifts' operation in addition to calculating the total energy consumed during one complete work cycle. It is found that only 6.7 % of the energy is dissipated which promotes the energy-saving capabilities of the designed forklift.

1. Introduction

Warehouse logistics plays a vital role in running day-to-day industrial facilities activities. The effectiveness of any warehouse logistic system depends on the selection of suitable internal means of transportation between its different sectors. The usage of appropriate transportation ensures a smooth flow of goods and reduces the time and cost needed [1].

Forklifts can be considered one of the most material-handling equipment used in factories or warehouses [2]. They can be used for the loading and unloading of machines in addition to internal transportation of goods [1]. Forklifts exist in various forms and devices, the selection of the most suitable type depends on several factors such as the surrounding working environment, the characteristics of the load, the destination of the goods, the nature of the goods to be transported, and finally the required operator's skills [3,4].

Hydraulic systems and internal combustion engines are usually used in forklift loading and unloading processes. These systems have a negative impact on their surroundings because hydraulic systems might cause oil leakage leading to serious issues during the transportation process. In addition, a large amount of energy is wasted on heat without any chance of recovery during the process of

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lifting products or tare fork, speeding up, and braking of hydraulic forklifts. Internal combustion forklifts produce large amounts of carbon dioxide emissions causing serious health issues [5–7].

The increased demand for environmental awareness has promoted the use of electric forklifts, which can be considered an eco-friendly means of material handling equipment. Electric forklifts produce zero harmful emissions and do not require oil for operation [2,6,8]. Moreover, it was proved that replacing the hydraulic system with an electric one can improve energy-saving efficiency to 82.3 % using loads up to 3 tonnes [6].

The operation of conventional forklifts depends on manpower, which can be very exhausting and impair the operator's situation awareness causing forklift accidents. Such accidents are more likely to occur in crowded small warehouses or when surrounded by other operators performing different tasks at the same time [9,10]. Thus, the operation of forklifts by highly qualified operators has become an essential need to ensure the efficient and safe operation of the forklift and its surroundings. The training of such operators requires a significant amount of time to ensure that all limitations and capabilities of the forklift, and the necessary safety precautions are carefully understood and followed. To eliminate the drawbacks of man-powered forklifts, automated forklifts have been promoted [11].

Autonomous forklifts can avoid obstacles, detect, and manipulate loaded pallets from truck beds or on the ground without operator intervention. In addition, autonomous forklifts can safely execute tasks that require human interaction with hazardous objects or in an unknown environment [9,11,12]. However, the usage of autonomous forklifts may represent a burden on developing countries as it has high installation and maintenance costs. Thus, manufacturers promoted the concept of semi-automatic forklifts by enabling remote control of the forklift for its motion and operation. The operator will only control the motion and operation of the forklift with minimal direct interaction using remote-control technology reducing the need for a highly trained operator. Also, remote control improves the visibility of the operator reducing the chances of collision accidents. As, the operator can walk beside the forklift while controlling its movement, increasing the available vision area [13,14]. Several researchers successfully developed the available electric forklifts to be controlled either using Wi-Fi, radio frequency identification, or even autonomously [14–17]. For small warehouses, the usage of either Wi-Fi or radio frequency identification remotely controlled forklifts is preferred over autonomous ones, to reduce the high installation and maintenance costs required by autonomous forklifts [18].

Several studies were conducted to improve the energy-saving properties of the forklift during its operation. P. Zajac et al. [2,19], presented a technique that can be used to estimate the effect of different travel parameters on the consumed energy for a man-powered forklift using MATLAB Simulink. Moreover, Cheng et al. [20], predicted the energy management performance by integrating fuzzy neural network technique with MATLAB Simulink.

Further developments were conducted to replace the hydraulic and the internal combustion operated forklifts with electrical ones that are operated using rechargeable batteries. These prototypes successfully replaced ariel lifts and cranes to lift workers to higher places in addition to transporting goods and materials [5,21,22]. However, they did not present a solution for smooth material handling in warehouses having small storage areas and limited space for movement. This is because electric forklifts are typically larger and heavier than conventional forklifts, which makes the maneuvering process difficult in tight spaces. As a result, investigations for developing electrical forklifts suitable for small warehouses have been promoted [17]. Moreover, to enhance the real-time performance of forklifts failure predictions, and diagnosis models have been developed by J. Lee et al. [23]. These models aimed to predict the effect of abnormal loading conditions that can cause rollovers or structural failures.

This paper presents a novel approach for forklifts designed and controlled remotely suitable for small warehouses with an area of less than 45 square meters. The proposed prototype is controlled using a Bluetooth module through a smartphone application. The chassis of the designed forklift is made of galvanized steel, which is characterized by its ability to resist severe environmental conditions while maintaining a lightweight design. The forks are made from 4 mm thick steel sheets with a yield strength of 180 MPa and a maximum load capacity of 200 N. The designed forklift is eco-friendly as its operation depends only on rechargeable batteries. The movement of the forklift and its handling process is remotely controlled using a smartphone application. The structural stability of the designed forklift was studied using SolidWorks. A force analysis on the designed forklift wheels was conducted using MATLAB Simulinkto estimate the suitable battery size. In addition, the amount of energy dissipated during a complete work cycle was calculated.

2. Design procedures

This section discusses the procedures of constructing a prototype to investigate the possibility of controlling a small-scale forklift without the use of wired remote-control devices. The control process is based on Bluetooth technology through using a smartphone. The prototype is designed to lift loads upto 200 N, utilizing a lifting mechanism composed of a ball screw and linear rolling guides. These components are characterized by their smooth operation, reduced friction, and low wear rates. The design process consists of two main sections. The first section discusses the ball screw mechanism, while the second section discusses the control system responsible for managing the lifting process and the movement of the forklift.

2.1. *Mechanical design*

This section discusses the procedures involved in designing the lifting mechanism's ball screw to ensure a successful lifting process. Since it is the only mechanism in direct contact with the load to be lifted, it can be considered the most influential parameter in the efficiency of the lifting process. The proposed design is based on a four-wheeled chassis made of 500 × 400 mm galvanized steel to resist corrosion. The lifting mechanism comprises a lift mast and a fork carriage with two fork arms, as depicted in Fig. 1. The forks can be adjusted on the lift mast to facilitate the positioning and holding of loads. The forks are mechanically moved via a ball screw feed mechanism to provide vertical linear motion. The lifting motor is considered the most critical parameter governing the successful operation of the lifting process. Its selection was based on the maximum load to be lifted. The torque (T) required for the lifting process was calculated using Equation (1) [21].

$$T = P.d_m.\tan(\varphi + \alpha) + \mu.d_c.P \quad N.mm \tag{1}$$

where:

P: maximum applied load	200 N
d_m: mean diameter of power screw	20 mm

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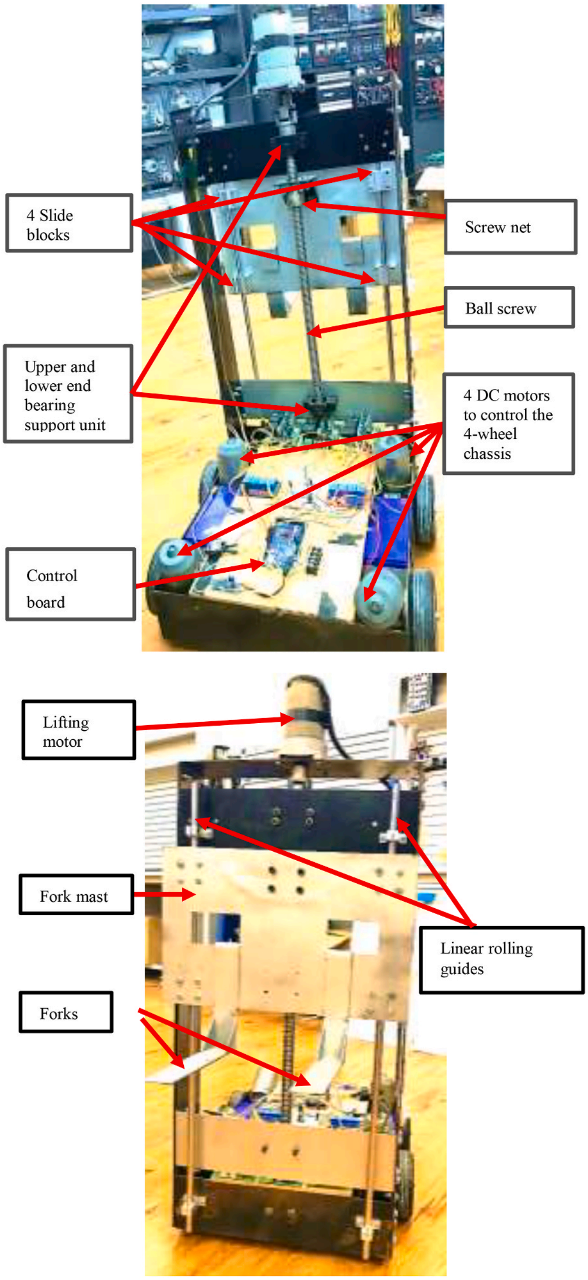

Fig. 1. Details of forklift and ball screw feed mechanism for vertical linear motion.

(*continued*)

d_c: collar diameter	7 mm
φ: friction angle [21]	20°
α: helix angle [21]	5°
μ: Coefficient of friction	0.2

A preliminary design was created using the classical design equations and then modified using SolidWorks optimization case studies to reach the optimum design. The forks and ball screws are crucial components that directly affect the success of the forklift's operation, as they are in direct contact with the load being lifted. To ensure the structural stability of the forklift, both classical design equations and SolidWorks simulation case studies were utilized.

The ball screw was designed to avoid failure due to buckling and the generated stresses. To prevent the occurrence of buckling, the maximum applied load was compared with the critical buckling load calculated using Euler's buckling equation (2) [24]. The forks were designed so that the resulting deflection and stresses upon maximum loading could be minimized as much as possible. The anticipated deflection of the forks was calculated using Equation (3) [5].

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad N \tag{2}$$

$$\Delta = \frac{P.L^4}{8.E.I} \quad mm \tag{3}$$

where:

P_{cr}: critical buckling load, N
E: Young's modulus of elasticity, 200 MPa
I: least second moment of area, mm^4

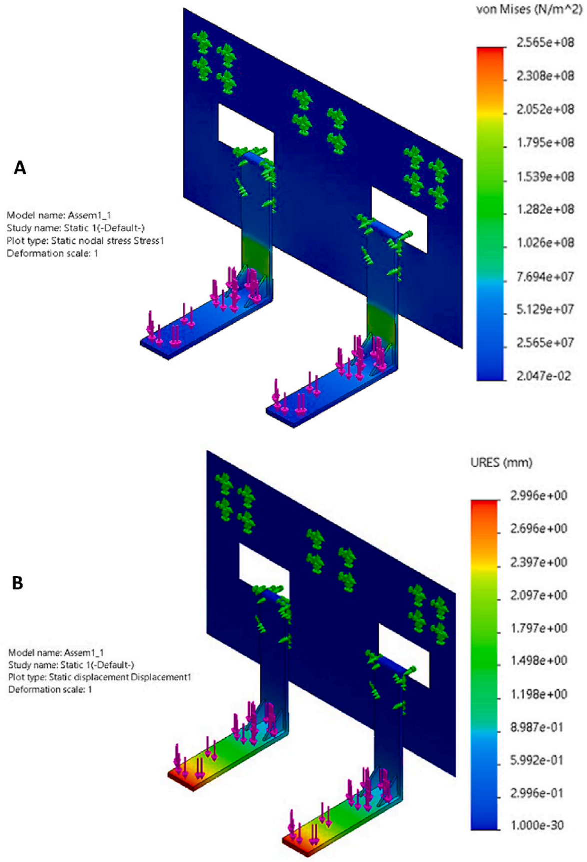

Fig. 2. Effect of distributed load on the fork mast and forks. (A) Generated stresses on the fork assembly, (B) generated deformation on the fork assembly.

K: effective length factor, 2
L unsupported length, mm
δ: maximum deflection due to distributed load, mm
P: applied load, 200 N

To validate the structural stability of the critical components of the forklift, the results obtained from Equations (1)–(3) were compared with results obtained from the SolidWorks simulation. This simulation process was used to assess the behavior of different key components, such as the fork mast, forks, and ball screws, under applied loads. The stability of the fork assembly was studied, as shown in Fig. 2(A) and (B), in terms of resultant stresses and generated deformation. Fig. 2(A) indicates that the resultant stresses are within the allowable limit for the fork assembly. Furthermore, using Equation (3), the maximum permissible deflection for the fork was determined to be 1 mm, which is consistent with the allowed deflection range shown in Fig. 2(B) varying from 0.001 to 3 mm.

The ball screw's static stability was studied under generated stresses resulting from compressive loads, bending moments, and twisting moments. Additionally, a buckling simulation was performed to ensure that the applied compressive load would not cause the screw to buckle. The result of the buckling simulation, shown in Fig. 3, was compared with the result calculated using Equation (2). It was found that the applied load was significantly less than the load required to cause buckling failure. Thus, the structural stability of the ball screw under generated torsional, bending, and compressive stresses were investigated, as depicted in Fig. 4(A)–(D). Fig. 4 demonstrated that the generated stresses resulting from the applied load were significantly less than the yield point of the selected materials.

2.2. Control system

The forklift control system is based on an Arduino microcontroller board that receives instructions from a smartphone device via Bluetooth to control the forklift movement. The movement of the forklift is driven by five DC motors, four motors for the four wheels, and one motor for the lifting mechanism. The Arduino board controls the forklift's movements by sending commands to the motor drivers which control the forklift's four DC motors and the lifting mechanism DC motor. Three H-bridges are used as motor drivers to allow the bidirectional control of the five DC motors. Two H-bridges are used for controlling the four-wheel motors and one H-bridge is used for controlling the lifting mechanism motor. The power required for operation is supplied through a 24 V - 12 Ah battery. A step-down DC-DC converter is used to step down the battery's output voltage from 24 V to 9 V, which is required by the control circuit. For safety precautions, a LED is added to indicate that the forklift is in motion. Fig. 5 shows the details of the used control circuit.

Arduino code is used to establish a Bluetooth connection between the forklift and a smartphone application. It receives commands from a smartphone application and controls the appropriate motor. Fig. 6 shows the interface of the used smartphone control application. It governs the forward, backward, right, and left movement of the forklift in addition to the lifting action. Fig. 7 shows a block diagram for the proposed control system. Preliminary testing was conducted to test the accuracy of the proposed wireless control

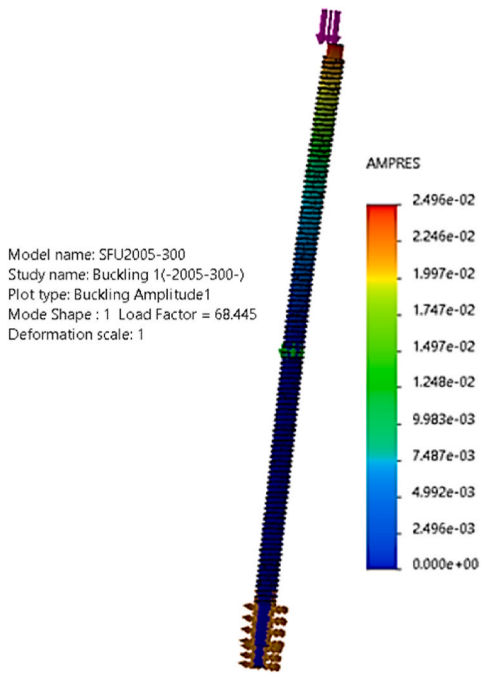

Fig. 3. Behavior of ball screw against buckling loading.

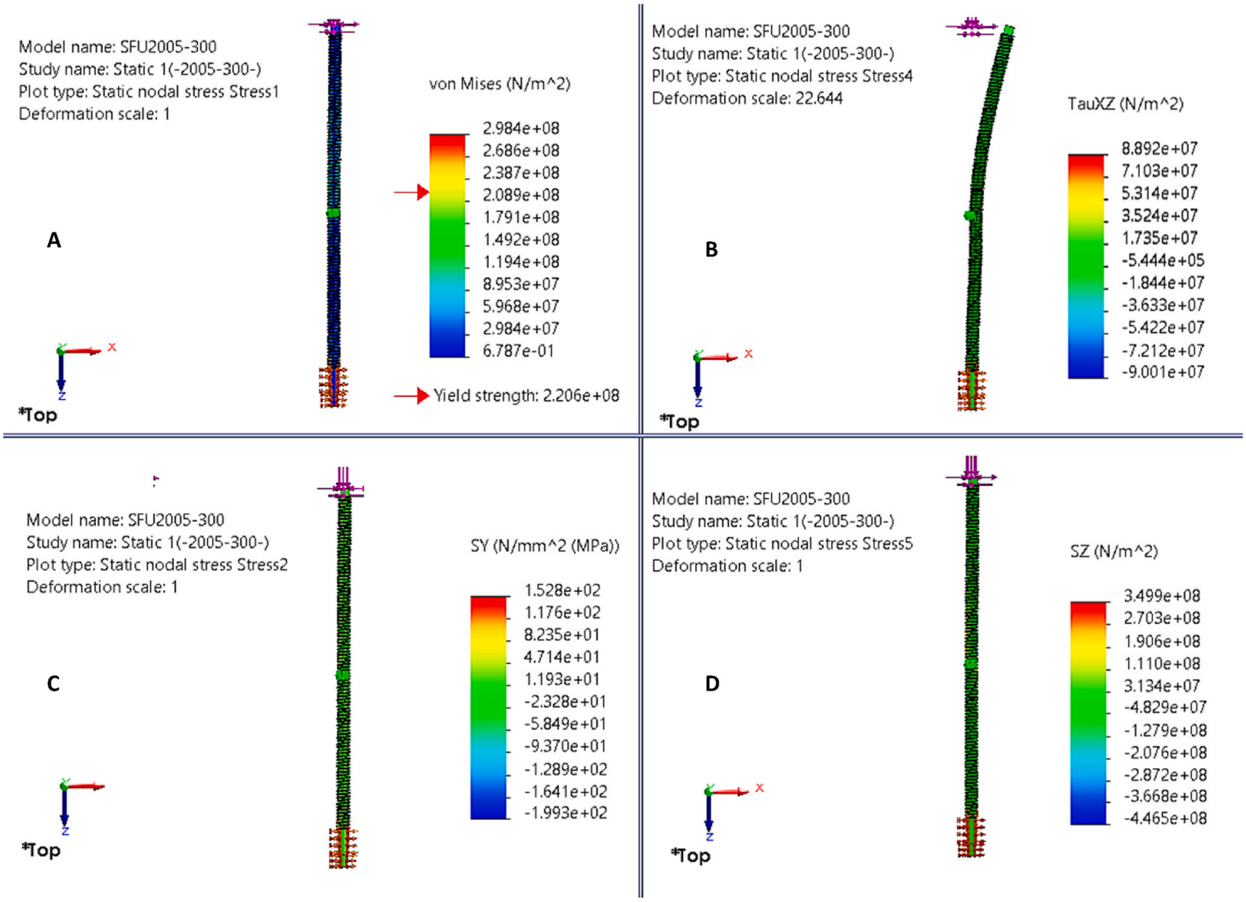

Fig. 4. Behavior of ball screw against generated stresses; (A) the effect of resultant stresses against von mises failure criteria; (B) the effect torsional shear stress; (C) the effect of bending stresses; (D) the effect of compressive stresses.

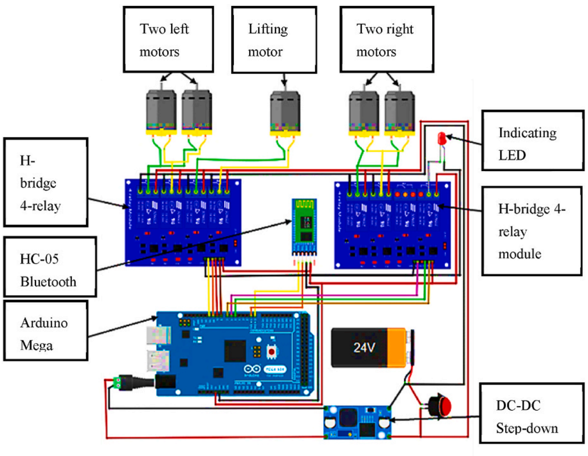

Fig. 5. Forklift control circuit.

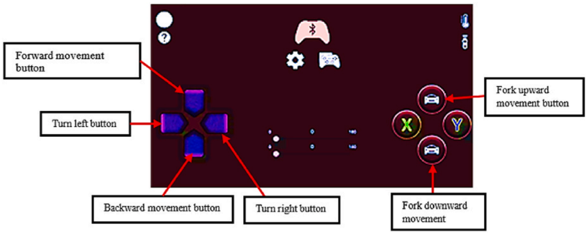

Fig. 6. Interface of the developed smartphone control application.

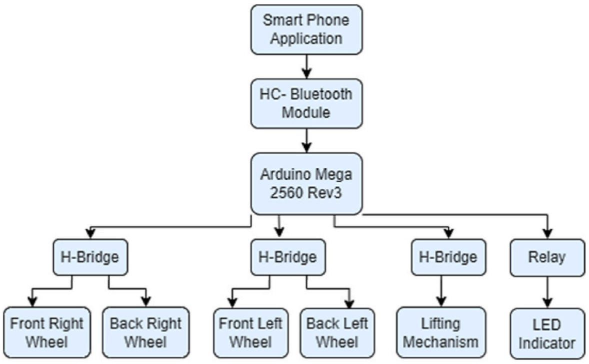

Fig. 7. Forklift control system block diagram.

of the forklift. It was found that the proposed control technique operates with acceptable accuracy when the distance between the smartphone and the forklift is less than 100 m.

3. MATLAB simulation

This section discusses in detail the MATLAB Simulink model developed to estimate the size of the battery needed for the forklift operation. The battery size was estimated based on the forces generated on the four wheels. In addition to estimating the energy consumed by the forklift during one work cycle. The energy consumption data was used to determine the amount of energy dissipated due to the frictional forces generated on all wheels during one work cycle.

3.1. Simulink model

The forklift's SolidWorks model was imported into MATLAB Simulink, as shown in Fig. 8. The Arduino control panel is used to control the forklift's movement in the warehouse, as shown in Fig. 6. The left set of buttons controlled the forward, backward, left, and

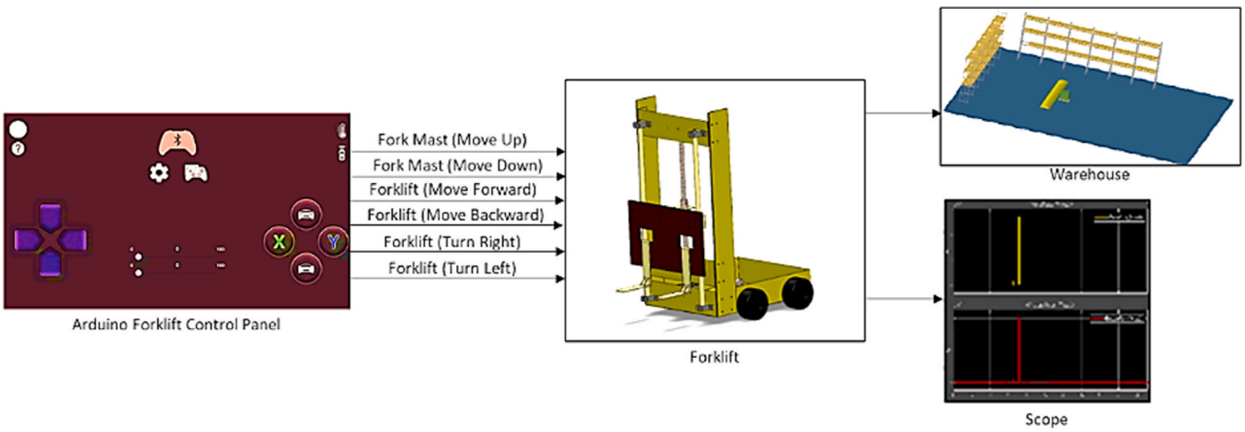

Fig. 8. Forklift control model in MATLAB/Simulink.

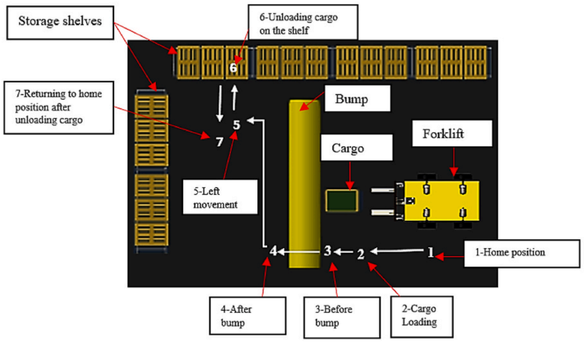

Fig. 9. Forklift work cycle in the warehouse.

Table 1
Work cycle actions of the forklift in the warehouse.

Point		Action	Time s	
From	To		From	To
1	2	Driving forward at 0.2 m/s	$t = 0\,s$	$t = 2.5\,s$
2		Braking from 0.2 to 0 m/s	$t = 2.5\,s$	$t = 3.5\,s$
2		Fork Mast lifting the carriage	$t = 3.5\,s$	$t = 4\,s$
2	3	Driving forward at 0.2 m/s	$t = 4\,s$	$t = 14\,s$
3	4	Pass over a bump	$t = 14\,s$	$t = 20\,s$
4		Driving at a curve (turn right)	$t = 20\,s$	$t = 26\,s$
4	5	Driving straight forward at 0.2 m/s	$t = 26\,s$	$t = 44\,s$
5		Braking from 0.2 to 0 m/s	$t = 44\,s$	$t = 46\,s$
5		Fork Mast lifting the load to the shelf level	$t = 46\,s$	$t = 47\,s$
5	6	Driving straight forward	$t = 47\,s$	$t = 49.5\,s$
6		Placing the carriage on the shelf	$t = 49.5\,s$	
6	7	Driving Backward to take the forks out of the rack	$t = 49.5\,s$	$t = 53\,s$

right movements of the four wheels, while the right set of buttons controlled the upward and downward movement of the fork mast.

The developed model is generic as it can be customized to fit a specific forklift and dimensions of the warehouse work cycle. The work cycle needed to complete the route in the warehouse is divided into seven stages, as depicted in Fig. 9. Table 1 displays the time taken for each action, which corresponds to the distance travelled at a constant speed of 0.2 m/s.

3.2. *Results and discussion*

The developed model analysed the movement of the forklift as it travelled at a constant speed of 0.2 m/s to reach its destination in the warehouse. The model estimated the different forces generated between the forklift wheels and the ground during loading and unloading positions. Figs. 10–12 illustrate the driving, normal, and frictional forces generated on each wheel during one cycle, respectively. The distance from the beginning point up to less than 1 m represents the empty fork state. From 1 m up to less than 10 m represents the loaded state of the fork. While the fluctuations shown in all figures represent the passage of the forklift over the bump.

From Fig. 10 it can be observed that the maximum driving force required during one work cycle is 652 N and 470 N during loading and unloading, respectively. Also, it can be observed from Fig. 11 that the normal forces acting on the front wheels are higher than that on the rear wheels during loading. This is due to the fork mast position which is near to the front wheels. Moreover, Fig. 12 illustrates that the effect of frictional forces occurs during the passage of the forklift over the bump. The total energy required for one work cycle is 5633 N m, equivalent to 1.56 Wh. It is calculated by integrating the area under the curve of the driving, normal, and frictional forces against the travel distance, respectively. Thus, the 24 V-12 Ah rechargeable battery selected in section 2.2 would be sufficient for the forklift operation in addition it could complete 184 work cycles. The energy losses is calculated to be 377 N m based on the frictional losses between the wheels and ground while ignoring the effect of friction losses in the lifting mechanism. As its operation is based on a ball screw and linear guideways that are characterized by their smooth operation and reduced friction as mentioned in Section 2. The energy loss percentage due to frictional forces during one cycle is estimated to be 6.7 % using Equation (4).

$$PEL = \frac{E_{loss}}{E_{total}} \times 100\ \% \tag{4}$$

where:

PEL: The percentage of the energy loss during work one cycle

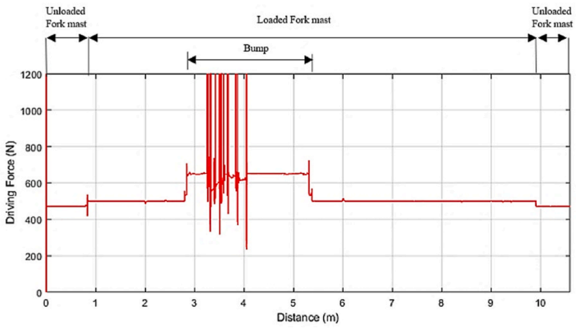

Fig. 10. Driving Force required for each Wheel against travel distance.

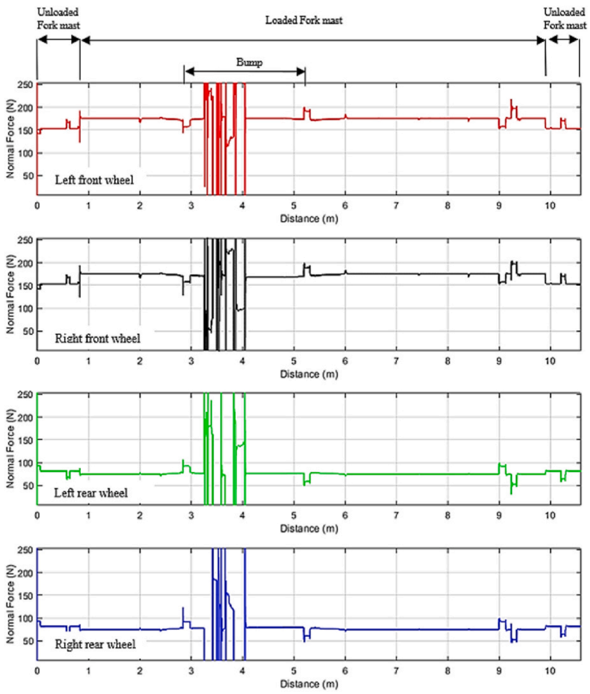

Fig. 11. Normal Force generated on each Wheel against travel distance.

E_{loss}: Energy losses due to frictional forces on all wheels.
E_{total}: Total energy needed for one cycle.

4. Conclusions

This paper presents an affordable solution for providing developing countries with semi-automatic electrical forklifts, as either importing these forklifts or using autonomous lifts represents a burden on their economy. The presented prototype is a semi-automatic eco-friendly forklift suitable for material handling in small warehouses. It is considered eco-friendly as its operation depends on rechargeable batteries instead of fuel which reduces harmful gaseous emissions. Also, it is characterized by its reduced operation costs through eliminating the need for highly trained operators by using a user-friendly smartphone control interface. The effectiveness of the prototype in terms of energy saving is validated using the MATLAB Simulink model. It is found that the amount of energy dissipated is 6.7 %.

The prototype can be further developed to be suitable for large warehouses and heavy-duty applications. In addition, the used control technique can be developed to promote autonomous control by integrating safety precautions such as collision avoidance sensors. Moreover, extensive real-time experimental tests are recommended to validate the accuracy of the proposed system in heavy-duty applications.

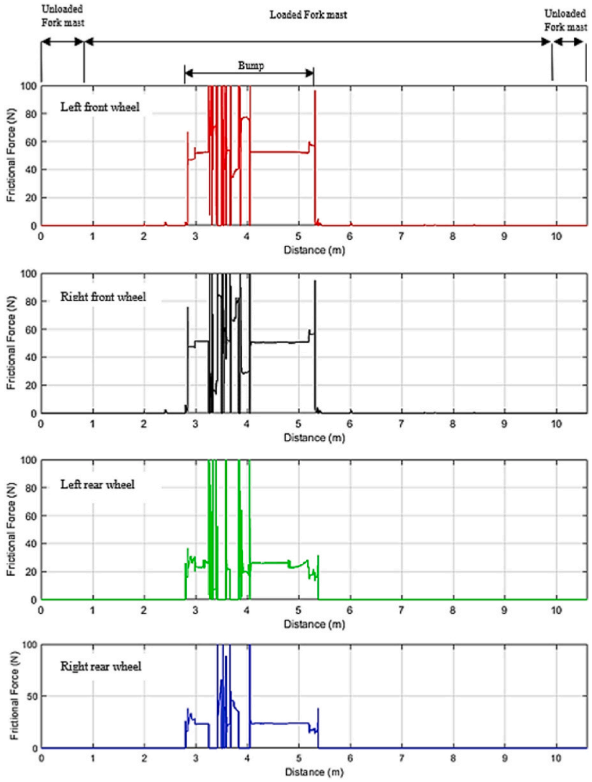

Fig. 12. Frictional Force generated on each Wheel against travel distance.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because clinical trials on patients or animals are not applicable in this study.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Hoda Abuzied: Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Nathalie Nazih:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Anwar Sahbel:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used [Sage/Proofreading] in order to [proofread the manuscript]. After using this Sage/Proofreading, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

List of Abbreviations

Not applicable.

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