Original Research Article

An Automatic Sliding Door: Leveraging Locally Sourced Materials for Innovation

ABSTRACT

A door is an essential component of a building. It provides security and access to the different parts of a building. In the modern era, when people want everyday life to be completely automated so that work can be done easily in a short amount of time without wasting energy, automatic doors have continued to be fashionable. In addition to being effective and efficient as automation continues to develop rapidly, automatic doors are essential to curbing the transmission of infectious diseases like Ebola and COVID-19. While automatic doors are available in Nigeria, they are imported, thereby shrinking the nation's foreign exchange. Not only that, they cost more when imported compared to when they are manufactured locally. In this work, therefore, a cost-effective automatic sliding door was developed using locally sourced materials from Nigeria. The door uses a passive infrared sensor (PIR) to detect a human or an object in a doorway and automatically opens and closes the door by signalling a microcontroller to activate a DC motor, which drives a belt pulley mechanism. The conceptual design of the system was designed and simulated using SolidWorks. Based on the design, calculations were made to determine the appropriate materials to source. The DC motor model was simulated using MATLAB SIMULINK as a physical model to observe how it would behave in the presence of noise, and the PID controller was tuned to give optimal performance using MATLAB Auto tuning. Some materials were locally purchased, while others were constructed through standard workshop methods. A cost-saving advantage of 95.77% and 89.13% were achieved when compared to imported equivalent types from the USA and China, respectively. The siding door was assembled and subjected to a functionality test, and it was observed that the automatic sliding door successfully detects humans and objects and actuates the motor to open and close the door after the object is out of the set sensing range of 50cm. This work is a step forward in boosting local innovation in Nigeria.

Keywords: Infrared Sensor, Microcontroller, Automatic Sliding Door, PID, DC Motor, Automation, Innovation

1. INTRODUCTION

Nowadays, people want an everyday life that is completely automated [1-2]. While developing rapidly, automation encourages people to innovate by creating tools that are more effective and efficient [3-4]. An automatic sliding door is one type of innovation applied in shopping malls, public buildings, airports, hospitals, theatres, and so on [5]. They are electro-mechanical doors that open automatically when someone enters and do not need to be opened manually with a touch point like a door handle, door push, lift buttons, flush buttons, taps, and lock [6-7]. Available research has confirmed that manually operated doors pose a risk of transmission of infectious diseases like COVID-19, Ebola, and so on, particularly in places where a significant proportion of users might be ill with a virus [7][8-9]. Therefore, for easy entrance and to limit the risk of disease transmissions, manually operated doors are re-designed to be sensitive to persons or objects in a doorway as they approach, causing the door to open and close automatically after the person or object has gained entrance. Since they could have manuals override mechanisms, such doors can still be operated manually in the event of automation failure due to power loss or a mechanical problem. These measures ensure that automatic doors are safe [10].

The demand for these automatic doors includes situations where both hands of the pedestrian are needed other than the opening of the door itself or when an equipment operator needs to come down from the equipment to open the door, thereby increasing production time and cost [11]. A public environment with a cleanroom concept requires the installation of an automatic door to avoid external and cross-contamination [12]. Also, people with disabilities in their hands and arms need someone to give them access to facilities with conventional doors. However, having automatic sliding doors installed will help improve the lives of the disabled population so they can use shopping malls and other infrastructures more effectively [13][14].

Recent studies have shown various innovative techniques and materials for constructing automatic sliding doors [15]. [1] utilized RFID and Arduino for enhanced security-focused automatic door access. This method represents a cost-effective solution for door automation using RFID tags for door access control and integrating them with an Arduino microcontroller to automate door operation. This approach emphasizes security and convenience, as the door only opens for recognized RFID tags. [5, 12] proposed a cost-effective automatic sliding door system with locally sourced materials and simple circuitry using infrared sensors to detect the presence of a person or object near the door. [5] developed the system to improve energy efficiency and user convenience. [12] incorporated a simple belt drive mechanism for door operation, replacing more complex and expensive components like rack and pinion systems.

The automatic doors market size is estimated to grow at a Compound Annual Growth Rate (CAGR) of 6.75% between 2022 and 2027, and the size of the market is projected to grow by USD 7,390.33 million. The market surge depends on factors such as the gaining traction in the construction market, the innovations in hardware components, and the increasing Infrastructure projects in developing countries like Nigeria [10]. Africa has the lowest adoption rate, while Asia–Pacific (APAC) and South America have more than double of Africa's rate to be the highest adopters of automatic doors. The key purchase criteria of automatic doors are innovation and quality, which are the highest and lowest criteria, respectively [12]. Currently, automatic doors are imported into Nigeria, and the maintenance needs are taken care of by foreign manufacturers and technicians. [16] discussed the impact of Chinese manufacturing investment in Nigeria. It focuses on how this investment is influencing technology transfer and shaping the industrial sector of the country. This reflects the gap in innovation between Africa and other continents.

This paper proposes a cost-effective automatic sliding door that detects a human or object using a passive infrared sensor (PIR) on a doorway and automatically opens and closes the door. The proposed technique uses the PIR to signal a microcontroller to activate a DC motor, which drives a belt pulley mechanism.The following is the structure of the paper: In Section 2, the automatic sliding door model was developed based on first principles, and a conceptual design for the door was done using SolidWorks. The DC Motor was modeled in SIMULINK; the materials were selected and assembled based on the design. Section 3 covers the simulation result of the DC Motor was presented, and a functionality test of the constructed door was carried out. In Section 4, a summary of the research outcomes is provided.

2. MATERIAL AND METHODS

Fig. 1 displays the sliding door setup, which comprises multiple parts, including a timing belt, door drive wheels on both the right and left, Pulleys for both Drive and Idler, Bearings, and a DC motor. The door drive wheels hold both sliding doors in place, and when the motor powers the belt, the door drive wheels move, x(t), either positively or negatively, causing the doors to slide open or close. Fig. 2 and Fig. 3 show an isometric view and front and back views of the proposed door system designed using SolidWorks.

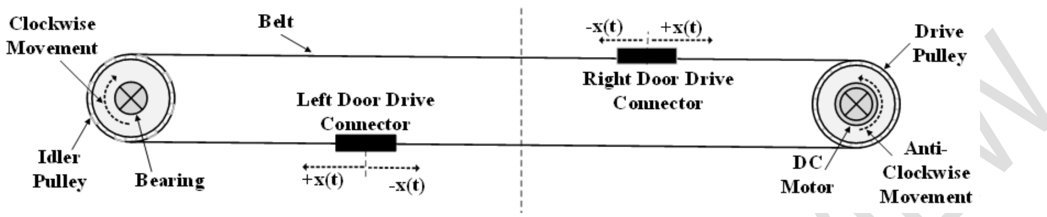

Fig. 1.Schematic diagram of the belt and the two pulley systems

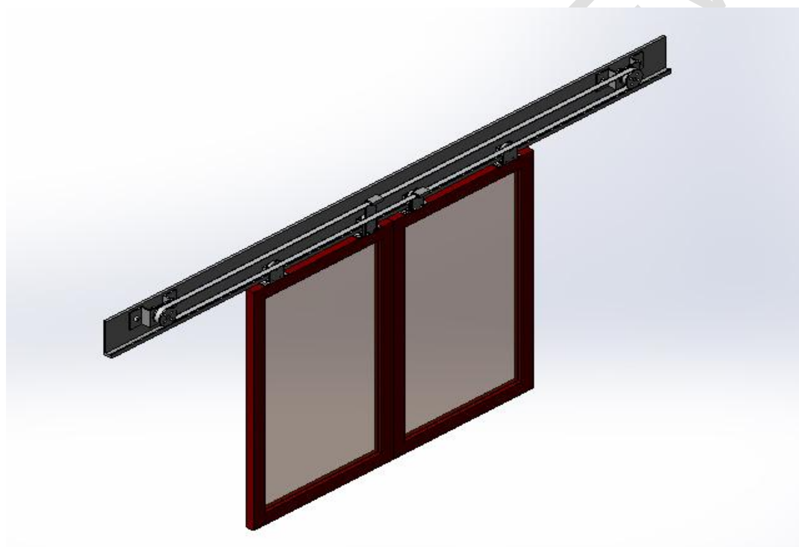

Fig.2.Isometric view of the sliding door

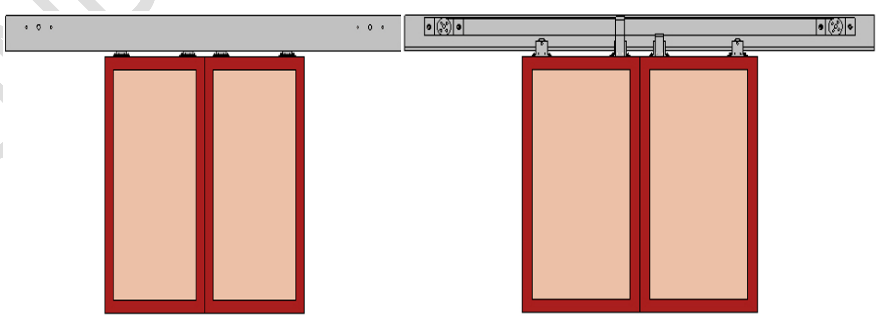

Fig.3.Front and back views of the automatic door system

2.1 Sliding Door Design Calculations

2.1.1 Power required to drive the belt with respect to the Speed of the DC motor

For this project, a 12-volt bipolar DC motor was utilised, specifically a windshield wiper motor with a loaded RPM of 147. The motor's angular speed, ω, and corresponding translational maximum velocity, *v,* and acceleration, *a,* are represented by equations (1), (2), and (3), respectively.

$$\omega = \frac{2\pi \mathrm{RPM}}{60} \quad (1)$$

$$= \frac{2 \times 3.142 \times 147}{60}$$

$$= 15.3958 \text{ rad/s}$$

$$v = \omega r \quad (2)$$

$$= 15.3958 \times 0.055$$

$$= 0.8468 m/s$$

$$a = \omega^2 r \quad (3)$$

$$= (15.3958)^2 \times (55/1000)$$

$$= 13.0367 \text{ m/s}^2$$

According to [17], the power required for acceleration of the sliding doors along their sliding surface, P_b is defined as follows:

$$P_b = F_b v = m_p a v \quad (4)$$

$$= 0.7 \ x \ 13.0367 \ x \ 0.8468$$

$$= 7.7083 \ Watts$$

where F_b is the applied force on the belt, and m_p is the pulley mass (0.7kg)

2.1.2Applied moments of the pulleys

The sliding door is modelled based on the Newtonian mechanism, which is responsible for the motion of the doors. The relationship between the applied moment of inertia and acceleration of the sliding doors along the horizontal guide is defined in (5), where friction is considered.

$$M(t) = 2rmpa + 2\mu rv \quad (5)$$

$$= (2 \times 0.055 \times 0.7 \times 13.0367) + (2 \times 0.61 \times 0.055 \times 0.8468)$$

$$= 1.0606 \text{ N.m}$$

where $\mu$is the coefficient of friction (μ = 0.61)

2.1.3Total weights of the doors

When the door is being mounted on a track with the help of rollers, it exacts a downward force known as weight. This weight is defined in (6).

$$W = m\ x\ g \quad (6)$$

$= 3.05\ x\ 9.81$

$= 29.9205\ N$

where m is the mass of the body ($m_1 = m_2$ = 3.05 kg), and g is the acceleration due to gravity (9.81 m/s^2)
Total weight of doors = 2 x 29.9205 = 59.841 N

2.1.4Door frictional force

An additional force is present between the door rollers and the track. In the event that the rollers undergo tangential motion relative to the track on which they are supported, the motion is counterbalanced by the interlocking characteristic of the projecting particles. Frictional force (ft), defined in (7), refers to this opposing force that operates in the opposite direction of the motion of the rollers.

$$ft = \mu R = \mu W \quad (7)$$

$= 0.61\ x\ 29.9205$

$= 18.2515\ N$

where R is the normal reaction of the roller (N)

2.1.5Timing belt tension

The effective tension on the timing belt, *T* is defined in (8) and the pre-tensioning of the belt and the two pulleys, T_P is defined in (9) according to [18].

$$T = (m\ x\ a) + (W\ x\ \mu b) \quad (8)$$

$= (0.7\ x\ 13.0367) + (0.7\ x\ 9.81\ x\ 0.5)$

$= 12.5592\ N$

$$T_P = 2\ x\ T \quad (9)$$

$= 2\ x\ 12.5592$

$= 25.1184\ N$

where µb is the friction coefficient for is Polyurethane and smooth steel pulley (µb = 0.5).

2.2Automatic Sliding Door Circuit Model

As shown in Fig. 4, there are various subsystems of the automatic sliding door circuit model which includes the power supply, AT89C52 Microcontroller, 16x4 liquid crystal display (LCD), receiver (light-dependant sensor), and actuator (12 volt bipolar DC motor). The microcontroller is a high-performance CMOS 8-bit microcontroller with low power consumption and 8k bytes of in-system programmable flash memory. It receives signals from the sensor through an analogue-to-digital-to-analogue (ADA) conversion system. When the controller receives a positive signal from the sensor, it activates the actuator.

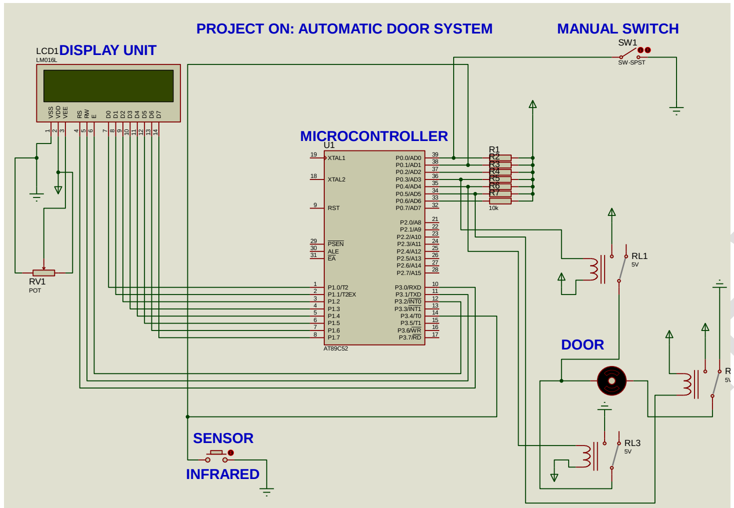

Fig.4.Automatic sliding door circuit diagram

2.3Automatic Sliding Door Algorithm

The flowchart in Fig. 5 describes the operational logic of the automatic sliding door system. At first, the system displays information and scans the environment. If an object is detected at the door, the system activates the DC motor in a clockwise direction to open the door. Otherwise, the motor is activated in the reverse direction, ensuring the door remains closed. The system will then re-scan the area to confirm if it needs to open or stay closed, before eventually stopping the process. This logical sequence ensures that the door operates efficiently, opening for authorized entry and remaining closed otherwise.

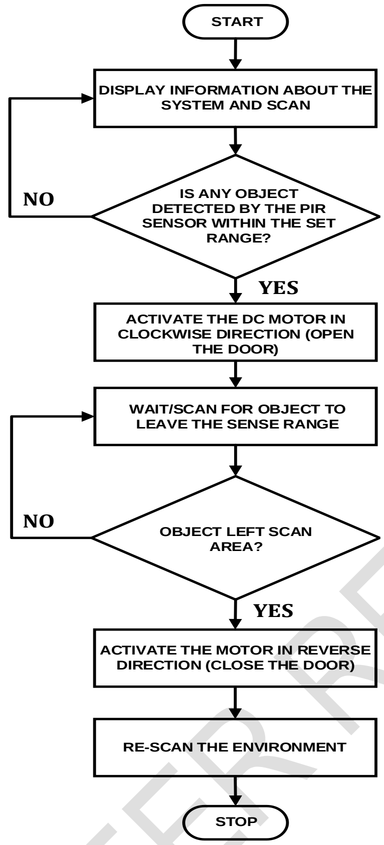

Fig.5.Automatic sliding door flowchart

2.4DC Motor Control Model

The wiper DC motor control was modelled using the PID controller in the Simulink environment, as shown in Fig. 6. The transfer function between the applied voltage and the motor speed is defined as [19]:

$$G(s) = \frac{nx K_1}{J(Ls^4 + Rs^3) + (Lb + K_2)s^2 + Rbs} \quad (10)$$

where n is the gear ratio, K_1 is the motor torque constant, K_2 is the back EMF constant, J is the inertia of the motor, load, and gear train, L is the motor inductance, R is the motor resistance, and b is the viscous friction coefficient. The error difference between the DC motor angular position and a set reference was minimized using the PID controller as defined in (11).

$$u(k) = K_P e(t) + K_i \int e(t) + K_D \dot{e} \quad (11)$$

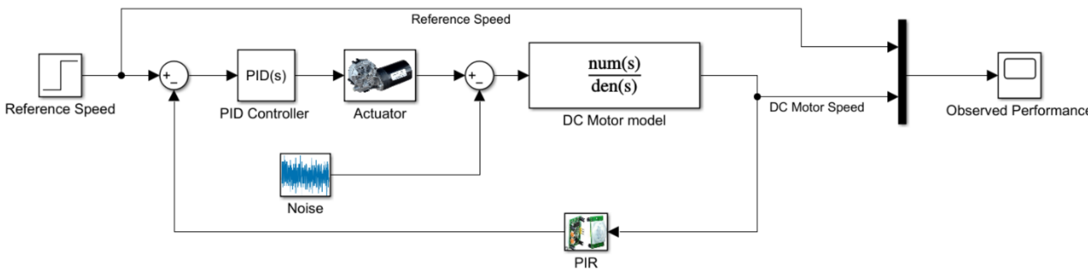

Fig.6.Sliding door DC motor control model

2.5Selection of Materials

The construction of the automatic sliding door involves selecting materials based on the design model and specifications. The materials used were locally sourced in Nigeria, as shown in Table 1. However, the table shows that by sourcing materials locally in Nigeria, there is a 95.77% cost saving compared to importing materials from the USA [20] and an 89.13% cost saving compared to importing from China [21]. This substantial reduction in cost demonstrates the cost-effectiveness of using locally sourced materials for the construction of an automatic sliding door.

Table 1. Compared prices of the automatic sliding door materials

Materials	QTY	Materials Sourced locally in Nigeria (Naira)	Materials Sourced from United States - Sanway E200 (USD)	Materials Sourced from China - OREDY ORD-180 (Yuan)
Pulley	2	N3,000.00	$36.00	
Belt	1	N1,500.00	$15.00	
Belt Connector	2	N1,000.00	$28.00	
Motor	1	N7,000.00	$250.00	
Controller + 2 Sensors + Electronic Components	1	N18,000.00	$385.00	Y1,425
Roller	8	N3,000.00	$112.00	
Track	2	N1,000.00	$200.00	
Door Stopper	2	N700.00	$10.00	
Battery + Power Switch	1	N15,900.00	$85.00	
Sliding Door	2	N25,000.00	$300.00	Y2,300.00
Total	**22**	**N76,100.00**	**$1,421.00**	**Y3,725.00**
Total cost conversion to local currency		**N76,100.00**	**N1,800,000.00**	**N700,000.00**

The description of the materials used for this design model is as follows:

1. **Frame**: This is the fixed part on which the movable doors are mounted. A wooden frame (an Iroko wood) was selected due to its durable and strong properties. And it also works pretty easy with power and hand tools, and it is ever ready to accept nails and screws.
2. **Sliding door:** The selected material for this part is an aluminum alloy and transparent flat blue glass. Aluminum alloy metal is known for its light weight, good corrosion resistivity and decorative applications. These properties made it the best choice for this part.
3. **Roller:** The roller used is a typical roller used in aluminum window work. It has the necessary features and configurations to keep the door well positioned on the track at all times. It is made of steel.
4. **Track:** This part serves as a runway for the sliding door. The upper and down tracks are made of aluminum alloy, which is hard enough to carry the weight of the door hung on both tracks without bending.
5. **Pulleys:** A camshaft pulley of a pieced engine was selected for the pulley. This may not have been the best option, but the fact that we avoided the high cost of producing a new one made it worth it. The timing pulley is made of stainless steel, and it has the necessary properties to transfer the torque from the motor, which made it the best suit for the design after all.
6. **Belt:** A timing belt of a pieced engine was chosen based on the selected timing pulley (Polyurethane material). Their pitch matched perfectly, and the belt was available and affordable. It possesses the required properties to transmit the torque, and the length is long enough for our sliding door.
7. **Belt Connector:**The selected material for this part is an aluminium alloy. It was shaped to different heights to fit the distance between the upper and lower sides of the timing belt and perforated for bolt passage used to fasten to timing belt and movable doors.
8. **Battery:** A 12V battery capable of running the motor at a desired speed was procured. It has a long running life and is suitable for the project.
9. **DC Motor:** A 12volt windshield wiper motor, which has the required torque needed to overcome the friction between the roller and the rail, was used to actuate the pulley-belt mechanism of the sliding door. It rotates clockwise and anticlockwise, making it suitable for double-direction movement of the sliding door. And most importantly, it is available and cost effective than procuring a stepper motor or other form of actuating device.

3. RESULTS AND DISCUSSION

The performance of the DC motor used for the actuation of the sliding door was simulated in MATLAB, as shown in Fig. 7. The DC motor was modelled as a physical system with noise in SIMULINK to observe how the wiper motor will perform when subjected to a reference speed of 2 rad/s. During the modelling, the PID was tuned using SIMULINK autotune at proportional gain, P = 4.255, integral gain, I = 1.694, and derivative gain, D = 2.519. However, the DC indicated with blue line was able to track the reference speed indicated by red dotted line at a stable rate at 8 seconds.

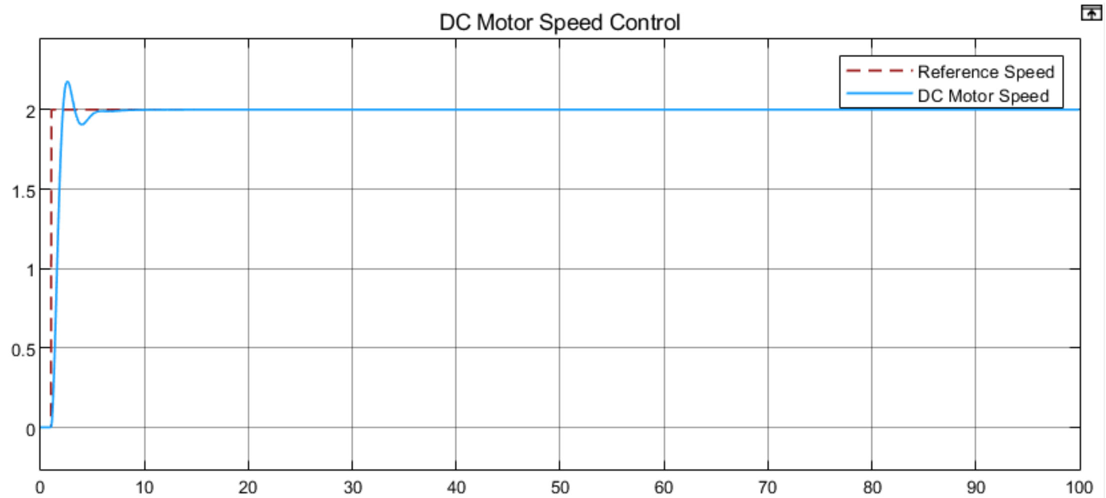

Fig.7.Performance of the DC motor model

3.1Functionality Test

The siding door was assembled and subjected to a functionality test using a PIR sensor to detect humans, as shown in Fig. 8 and Fig. 9. The PIR sensor has a wide lens range sensitivity of 7 meters and a 110-degree x 70-degree detection range. It has two slots, each one of them is made of a special material that is sensitive to infrared. When a warm body like a human or animal passes by, it first intercepts one-half of the PIR sensor at a set range of 50cm. This causes a positive differential change between the two halves. These change pulses are detected under operation situations like avoiding heating systems or warm air drifts. The sensor was calibrated to send a signal to the microcontroller whenever an object approached the sensing range, and the microcontroller actuated the DC motor to open the door through a belt pulley mechanism. The automatic sliding door successfully detects humans and actuates the motor to open and close the door after the object is out of the set sensing range. However, there is a manual operation mode incorporated in the design for situations whereby the automatic dictation by the PIR fails when the operation situations are not met. This mode uses a push button (switch) to open and close the door when an object enters and leaves the door. It is also considered as a save mode to avoid trapping the object or human when the operation in auto mode fails.

Fig.8.Front view of the model of an automatic sliding door

Fig.9.ack view of the model of an automatic sliding door

4. CONCLUSION

An automatic sliding door system was designed, constructed, and tested. The conceptual design of the system was designed and simulated using SolidWorks. Based on the design, calculations were made to determine the appropriate materials to source. The DC motor model was simulated using MATLAB SIMULINK as a physical model to observe how it would behave in the presence of noise, and the PID controller was tuned to give optimal performance using MATLAB Auto tuning. Some materials were locally purchased, while others were constructed through standard workshop methods. A cost-saving advantage of 95.77% and 89.13% were achieved when compared to imported equivalent types from the USA and China, respectively. The siding door was assembled and subjected to a functionality test to detect a human or object using a PIR sensor on a doorway and automatically opening and closing the door. The proposed technique uses the PIR to signal a microcontroller to activate a DC motor, which drives a belt pulley mechanism. It was generally observed that the automatic sliding door successfully detects humans and objects and actuates the motor to open and close the door after the object is out of the set sensing range of 50cm. This work is a step forward in boosting local innovation in Nigeria. As it will be cheaper for other African countries with new constructions and renovations to buy from Nigeria which will drive the externally generated revenue of the country.

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