PROTOTYPE OF AUTOMATED TUBULAR CLEANING SYSTEM

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ABSTRACT

Handling heavy pipes manually during cleaning poses significant risks to workers' health, including long-term damage to muscles and joints and sudden injuries from accidents. However, recent advancements in technology have greatly improved this situation. The implementation of automation in tubular cleaning is still very new in the industry and not widely used. The latest technology in industry is semi-automated whereby human intervention is still required in monitoring the whole cleaning process. The focus of this project is to enhance the cleaning system by transitioning from a semi-automated system to a fully automated one, utilizing infrared sensors as proximity sensors to control the operation. When the sensors detect the presence of a pipe, they reverse the direction of the DC motor and return the pipe for subsequent operations. The results show that a higher PWM setting of 90 for the motor produces better cleaning effectiveness compared to a lower PWM setting. Additionally, a heavier pipe weighing 1.2 kg requires a higher PWM to complete the task compared to a lighter pipe weighing 0.4 kg. This project demonstrates the potential of automation in the tubular pipe cleaning industry.

Keywords: *automation system, prototype, pipe tubular cleaning system*

1.0 INTRODUCTION

Pipes are tubular section/hollow cylinders that are often attached to become a piping system that conveys fluid from one place to another. Pipes are manufactured from various materials, with steel being the most commonly used in industrial applications. The pipes transports liquids and compressed gases that can be hot or cold. A typical pipeline in an oil industry can measure up to 18 – 25 feet long with a diameter of 4 to 48 inches. Different kinds of fouling may occur to the pipelines due to environmental factors or introduction of unwanted particles which can result in corrosion, obstruction of fluid flow or pitting. These damages become threats to the environment and are able to impose catastrophic consequences on people, environment, asset and company reputation [1]. A crack or spillage can initiate fire or explosion and oil spills can also cause harm to human health by contaminating the water supply [2]. In 2011, the rupture of gas carrying pipe had caused 47 million cubic feet of gas to escape which lead to a massive explosion in San Bruno, California [3]. To prevent the accident from happening again, cleaning of pipes must be done as a preventive measure and as an approach to ensure that the pipe satisfy the minimum integrity requirement [4].

Prior to the widespread implementation of Industry 4.0 technologies, pipe cleaning processes were predominantly performed manually [5]. Human labours were widely used to complete the task as in Figure 1. Manual handling is known to be very time consuming, and it also deals with multiple heavy pipes that are covered with unknown chemicals which could impose high risks to workers' health such as gradual and cumulative deterioration of musculoskeletal system and acute trauma due to accidents.

Figure 1: Manual Cleaning

The automated tubular cleaning system is increasingly used but still requires human control and monitoring, limiting its autonomy. While it eliminates physical cleaning, operators must guide its operation. Adding infrared sensors would enable full automation, increasing efficiency and aligning with Industry 4.0 standards. The selection of appropriate cleaning technology is crucial in ensuring the effectiveness of the cleaning system. To select the most effective method, it is essential to possess a solid understanding of the available cleaning techniques and their respective capabilities. Tube cleaning is done on-line and off-line. On-line is defined as operating the pipeline under normal conditions while cleaning and off-line with the pipeline out of serve and depressurized [6][7]. Off-line tube cleaning is known to have a more effective and faster-cleaning method. There are two main options when it comes to cleaning foul tubes which are chemical and mechanical cleaning [8][9].

Water jet cleaning is the process of removing contaminants with pressurized water. According to Jalalirad et al. [7][10], high-pressure generator creates a high-pressure water is that is ejected through the nozzle. The cross-section for the jet pipe is initially large making the water to have low velocity and high pressure, the cross-section is then reduced thus resulting in low pressure with high-velocity jet. The visualization on the relationship between the cross-section are of pipe and velocity can be seen in Figure 2.

The relationship between the cross-sectional area of a pipe and the velocity of fluid flow can be demonstrated using the Bernoulli equation and the principle of continuity. The continuity equation states that for an incompressible fluid, the mass flow rate remains constant, meaning the product of cross-sectional area (A) and velocity (V) is the same at any two points in the pipe:

$$A_1V_1=A_2V_2 \quad (1)$$

This implies that if the cross-sectional area decreases ($A_2<A_1$), the velocity must increase ($V_2>V_1$) to maintain the same flow rate. According to Bernoulli's equation:

$$P+1/2\rho V2+\rho gh=constant \quad (2)$$

where P is pressure, ρ is fluid density, V is velocity, g is gravitational acceleration, and h is elevation, an increase in velocity (V) due to a smaller cross-sectional area corresponds to a decrease in pressure (P). This inverse relationship between area, velocity, and pressure highlights the importance of pipe dimensions in fluid dynamics, crucial in applications like pipe design and nozzle flow analysis.

Impact force and shear force are produced on the fouling layer due to the high-velocity jet targeted to the surface of the pipe. The layers are then eroded, penetrated, broken down and peeled off from the surface and resulting in a clean surface. Although the use of high-pressure water can be effective, the movement of jet nozzle along the tube must be done slowly to avoid the damage of tube sheet and coatings. Otherwise, the cost of fouling removal can be equivalent to the cost of a new tube [11].

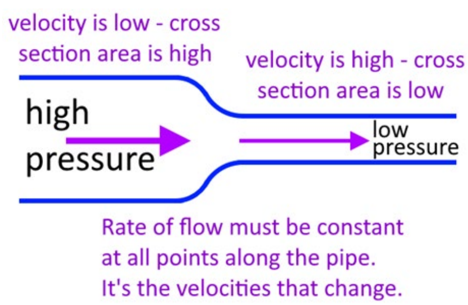

Figure 2: Relationship between cross-section of pipe and velocity

Power brushes are often used to remove burrs and cleans impurities off various surfaces [12]. Brush cleaning is usually performed on the material's surface before surface finishing processes are performed. There are varied types of wire brushes available in the market such as wheel brushes, cup brushes, and end brushes. Yuan et al. [13] noted that wire brush is not a metal removal tool and it is not designed to accomplish the tasks of an abrasive grinding disk. Thus, eliminating the possibility of surface defects on tubes. The wire tips are in contact with the tube surface thus separating the surface contaminants from the base materials. It has a true selective cutting as these brushes act as an impact tool removing surface contaminants with millions of tiny hammer blows without cutting away any base material as abrasives. According to Grand et al.[14], wire brushes are non-loading thus they do not clog with particles and debris when removing paint and similar coatings. It is also known to be the only surface cleaning and conditioning tool that is tough enough to cope with prolonged, heavy use. However, the downfall of the wire brush increases the surface roughness of the tube hence reducing the corrosion resistance of the pipe. It is also ineffective as the contact could be non-uniform.

2.0 Prototype Fabrication

2.1 Operational Flow Chart

Figure 3 shows the general flowchart of this project. The flowchart illustrates an automated process for handling pipes using a conveyor system. It begins with a human operator placing a pipe onto the loader hook. A servo mechanism then deposits the pipe onto the conveyor. The process continues as IR_1 (infrared sensor) detects the presence of the pipe. If detected, the conveyor moves left until IR_2 confirms the pipe's position. If not, the conveyor continues moving right to adjust the pipe's alignment. Once IR_1 detects the pipe again in the correct position, the unloader lifts the pipe to complete the process. This system ensures precise pipe handling for further operations.

2.2 Frame of the Structure

The main part of the frame as shown in Figure 4 uses aluminium profile 3030 (30mm by 30mm dimension). It is readily available and offered at a reasonable price. Aluminium profile can be used for a wide range of applications including machine frames, conveyors and multi-axis positioning systems. Some L bracket joints are used to join every parts of the aluminium profile. Plus, the aluminium profile is already manufactured with a definitive cross-sectional profile for a wide range of uses. With a proper fastened and jointed screws and L bracket, the frame will become very rigid, sturdy and very reliable.

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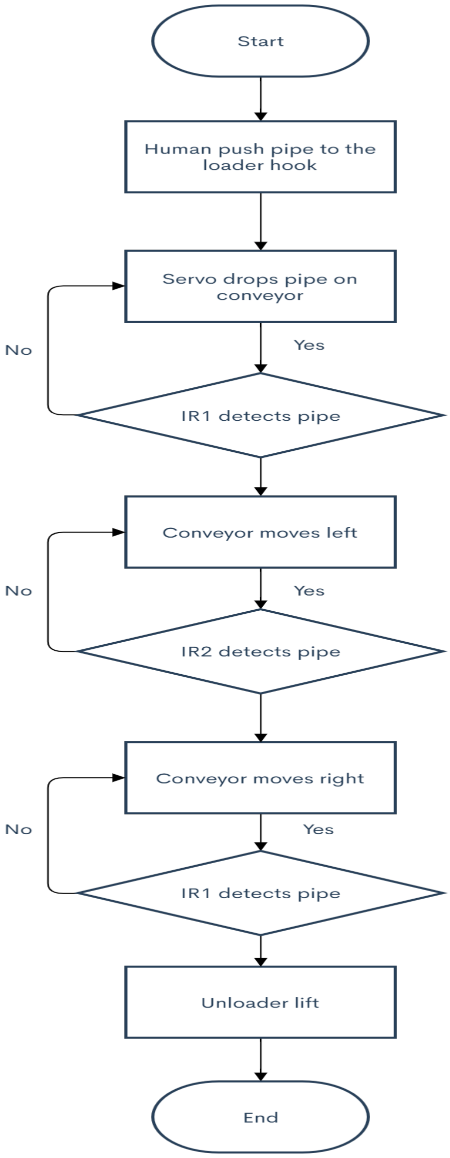

Figure 3: General flowchart of the whole system

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Figure 4: Main frame for automated cleaning machine prototype

2.3 Conveyor

The conveyor consists of multiple wheels placed at a 45º angle to ensure that the pipe will be spinning and rolling simultaneously. This is because when the wheels are arranged in a horizontal position it will roll the pipe either forward or backward as in Figure 5, whilst when the wheels are arranged in a vertical position, it will spin the pipe clockwise or anti-clockwise as in fig. 6. Hence, to have a precise movement of the pipe, the motor must have the combination of horizontal and vertical position from the frame.

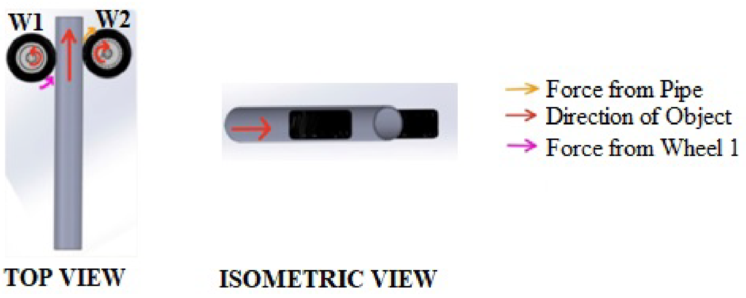

Figure 5: Rolling of pipe forward and backward

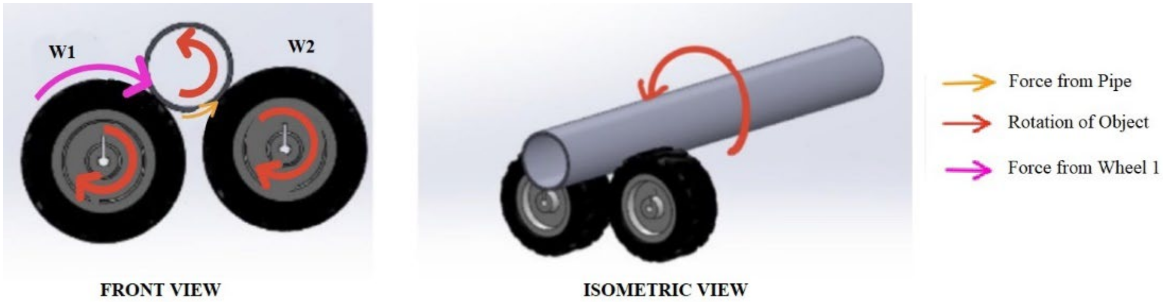

Figure 6: Spinning of pipe forward and backward

For external cleaning, housing designed to hold a brush and motor are attached to a linear rail that will move upward or downward when adjusted to the pipe size. The movement of the linear rail is illustrated in Figure 7. The movement of brush for both internal and external cleaning is done by using DC motor attached to a coupler and rod.

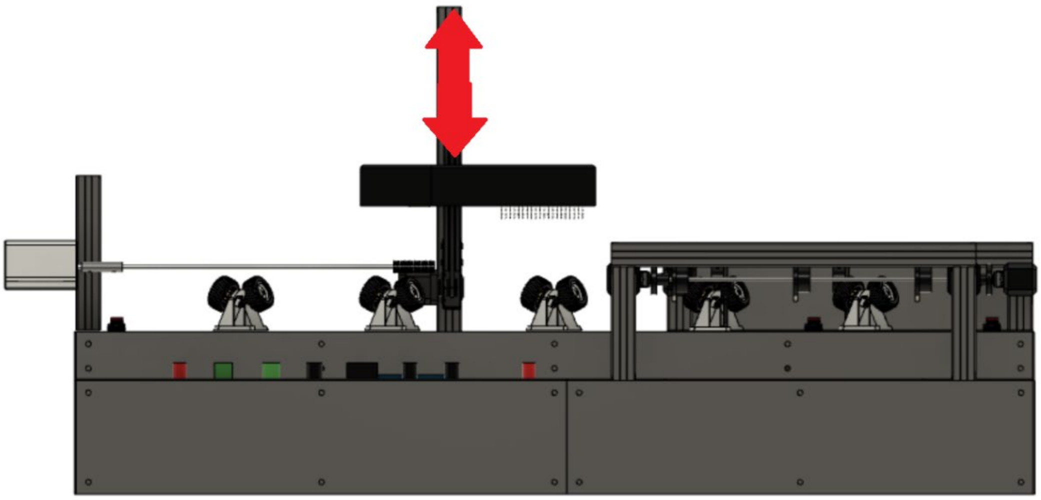

Figure 7: Movement of linear rail vertically up and down

For internal cleaning, a long rod locked to a brush is attached to a DC motor position along the conveyor at a certain height. As the pipe moves out of the external cleaning section, the internal diameter of the tube will enter the internal brush, and the brush will spin and cleans the internal surface. The main factor to consider is that the brush has at least one point in contact with the surface of the pipe. The approach for both internal and external cleaning is the same only that it targets different surfaces and uses different sizes as seen in Figure 8 and Figure 9.

Figure 8: Design layout for internal pipe cleaning system, highlighting the arrangement of components

Figure 9: Design layout for external pipe cleaning system, highlighting the arrangement of components

2.4 Power Supply

The machine operates from a fixed position. Thus, it can be powered by an AC 240V supply from the wall. The plug that is connected to the wall is built with a 10A fuse protection. This prevents high current flow to the circuit if an accident occurs. Considering the machine is operated using a DC voltage, an AC to DC converter had been integrated in this machine to convert the AC supply. An AC 240V to DC 12V 3.2A 38.2W Voltage Transformer Switch Power Supply had been used. This power supply has a steady and precise output voltage with a short circuit protection.

2.5 Printed Circuit Board (PCB)

The use of PCB is to ensure that the prototype has a neat circuit box and look more professional. The circuit is designed using a software called EAGLE developed by Autodesk. Figure 10 shows the schematic design of the PCB. A schematic diagram is crucial for visualizing, understanding, and communicating complex systems or processes. It simplifies intricate systems by breaking them down into symbols and flow structures, making them easier to comprehend. This clarity is particularly important for troubleshooting and maintenance, as it allows technicians and engineers to identify faults and diagnose issues efficiently.

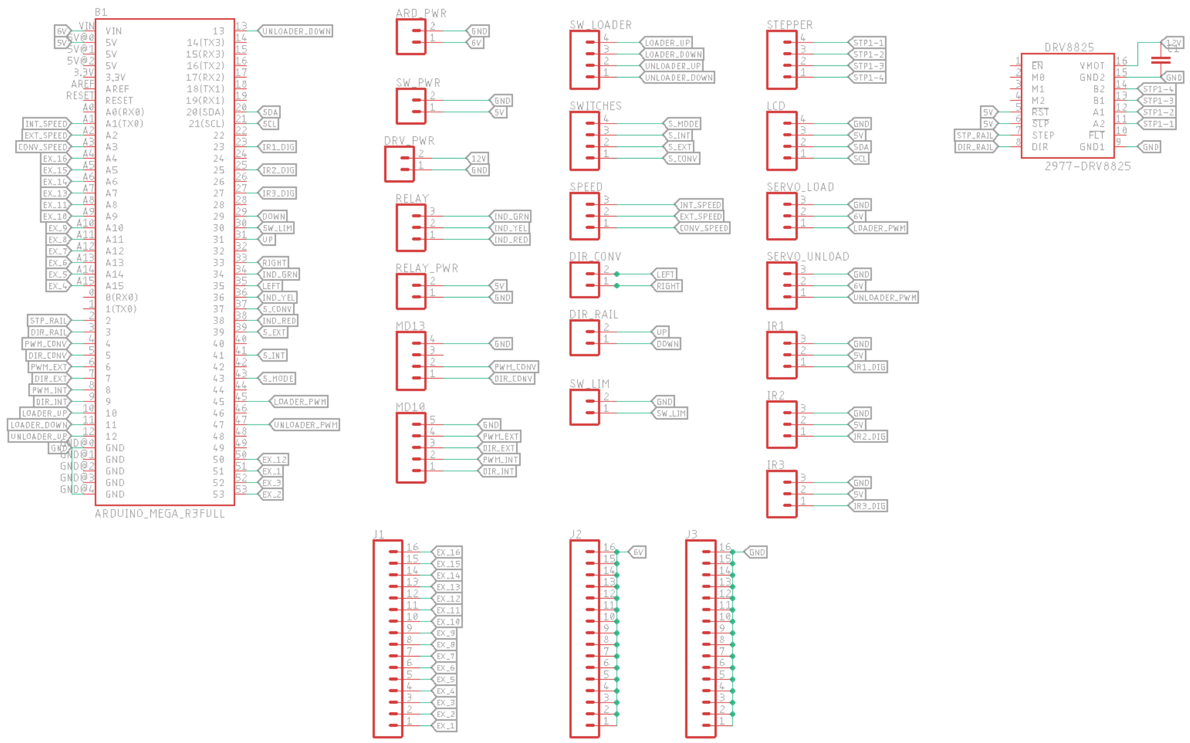

Figure 10: Schematic representation of the printed circuit board (PCB) design, illustrating the layout of electronic components, signal pathways, and connections to ensure optimal functionality and system integration

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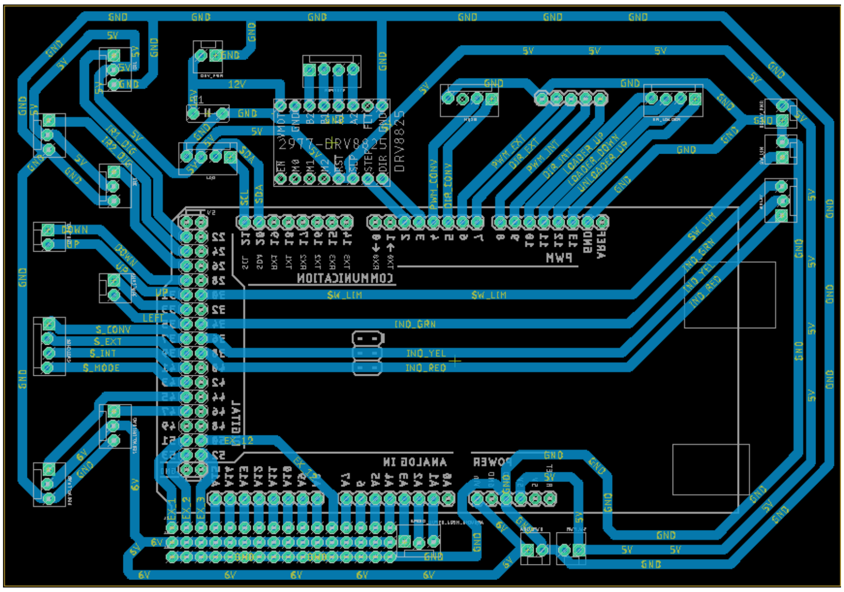

Figure 11: Detailed layout of the circuit board design, showcasing the placement of components, routing of electrical connections, and integration of features

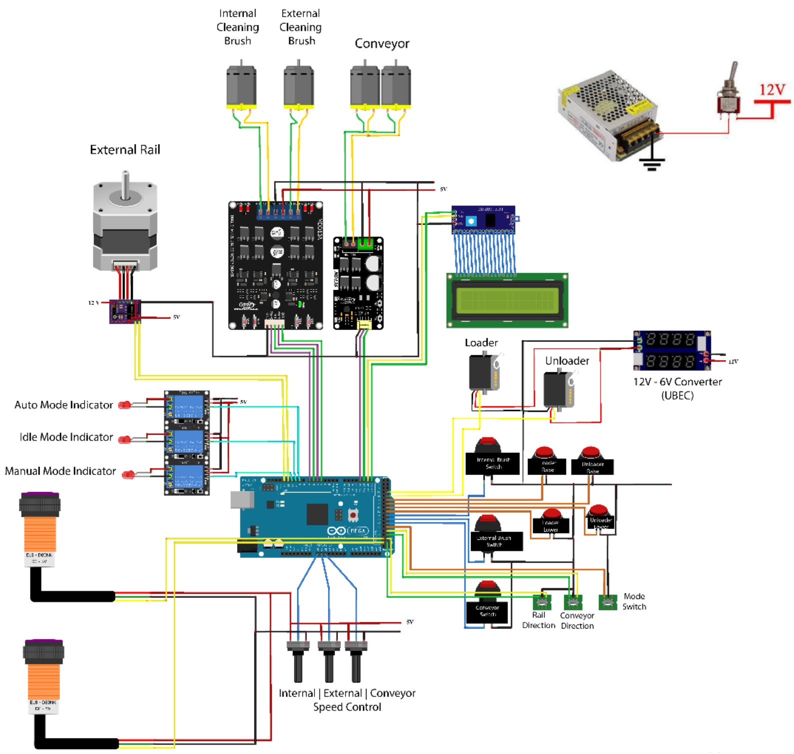

Figure 12: Comprehensive circuit diagram illustrating the complete electrical connections, component arrangement, and functionality of the system

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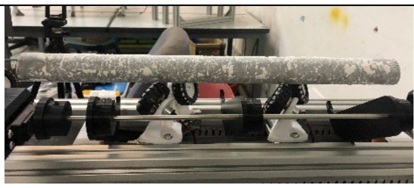
Figure 11 display the board diagram of the PCB. A board diagram is essential for understanding the physical layout and connections of components in a system, aiding in design, troubleshooting, and assembly. It ensures accurate placement, improves communication among teams, and serves as a reference for modifications, making it indispensable for efficient planning, implementation, and maintenance of electronic or mechanical systems. Figure 12 shows the full circuit diagram. The schematic diagram depicts an automated control system integrating an Arduino microcontroller to manage various components, including stepper motors, cleaning brushes, a conveyor, and mode indicators. It features a power supply, a UBEC for voltage regulation, and a relay module for switching modes. The system includes user interfaces like push buttons, speed control knobs, and an LCD for feedback, ensuring efficient coordination for tasks like loading, unloading, and cleaning operations.

3.0 RESULTS AND DISCUSSION

3.1 Effectiveness of Cleaning

An experiment was conducted to test the effectiveness of the cleaning at different speed. Table 1 shows the picture of the pipe before and after the cleaning process.

Table 1: Results of pipe cleaning at different speed

Conveyor PWM	Before	After
40		
60		
90		

It can be seen from the table that the machine managed to remove some of the powder (dirt) on the pipe. The images have been converted to grey scale and the brightness (powder/dirt) has been measured through histogram. A histogram illustrates how pixels in an image are distributed by graphing the number of pixels at each color intensity level. The mean values of 163.04 (PWM 30), 149.71 (PWM 60), and 140.89 (PWM 90) are shown in the histogram, indicating that PWM 30 produces the brightest intensity. Based on the results, it can be observed that the higher the PWM, the cleaner the pipe. The result came out as such due to the stronger brushing force applied on the dirt. Based on Newton's second law, the change in force is affected by the acceleration of the object. Thus, when the speed of the conveyor is increased, the pipe moves faster, and the momentum between the dirt on the pipe and the brush surface increases, resulting in a cleaner pipe.

3.2 Effect of Mass on the time taken to complete the operation

Another experiment was conducted to study the effect of mass on the time taken for a complete cycle of the conveyor. For this experiment, two pipes with the same diameter and length but different masses were used. Both pipes have a length of 45 cm and a diameter of 34 mm. The time for a complete cycle was measured from the moment the conveyor started moving when the infrared sensor detected the pipe's presence for the first time until it detected the pipe again for the second time. The experiment was conducted at eight different PWM values for each pipe, ranging from 30 to 160 PWM. The results were then tabulated and analyzed. Pipe A has a mass of 0.4 kg, while Pipe B has a mass of 1.2 kg.

Table 2: Result from effect of mass on time taken for completion

PWM/Pipes	Time Taken for a Complete Cycle (s)	
	PIPE A	**PIPE B**
30	44.26	-
40	34.16	-
60	24.42	37.45
80	15.00	28.37
100	11.00	14.37
120	9.26	12.67
140	7.25	10.03
160	-	8.95

From the results in Figure 13, a heavier mass results in a longer time to complete the cycle. Since the pipe is moved by multiple DC motors, an increased load affects the motor's load torque. The pipe's movement depends on the motor's load torque being able to overcome the weight of the applied load. PWM determines the motor's speed, while torque is the output produced by the motor, representing the amount of rotational force the motor generates. Theoretically, the motor's torque is inversely proportional to its speed. Thus, when the pipe's load increases, higher torque is produced, resulting in a lower speed. It can also be observed that when mass B is placed on the motor at a lower PWM, the conveyor is unable to move the pipe. This is because the torque produced by the motor is insufficient to overcome the weight of the pipe.

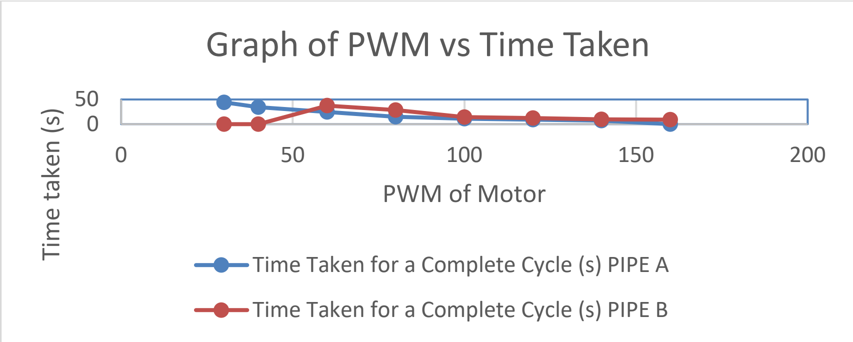


Figure 13: Graph of PWM vs time taken for different mass

4.0 CONCLUSION

Tubular cleaning prototype had been successfully built and tested. The design was made by choosing the optimized components which are suitable for the cleaning system. The chosen components also have been compared with other components which will bring the same function with lower cost. The electrical part of the prototype also has been successfully installed. Every input and output of the electrical components were tested and checked if they are still working and suitable for this project. The machine had been able to clean the dirt off the pipe, which has shown that PWM 30, 60 and 90 recorded means brightness values (powder/dirt) of 163.04, 149.71 and 140.89 respectively.

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