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Design and Development of a 3 axes Pneumatic Robotic Arm

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ABSTRACT: Pneumatic robots are essential for material handling in chemical industries where electric or hydraulic robots are unsuitable due to fire hazard. A 3 axes (3 Degrees of Freedom) articulated pneumatic robotic arm was designed and assembled in this project along with its control system. Pneumatic rod less linear actuators were used as the main drive system for the robotic arm and were controlled by pneumatic 5/3-way proportional directional control valve. The design of the arm for this project implements crank mechanism to convert linear actuation displacement to angular displacement about the joint. Two control systems were designed for the robotic arm: Programmable Logic Controller (PLC) and Arduino UNO microcontroller. It employed open loop control with PLC at first and closed loop PID control using Arduino UNO in the latter part of the study. MPU-6050 sensor was used for feedback signals to the Arduino UNO. Point to point motion control method was adopted for this robot arm and simple pick and place applications were carried out using a pneumatic gripper as the end effector. Mainly, the compressibility of air and the overall nonlinearity of the pneumatic servo system made it very difficult to achieve accurate positioning and control with PLC. Closed loop PID control with microcontroller and accelerometer and gyroscope enabled better control with joint angle accuracy of ±1 degrees. The force required by the pneumatic linear actuator to move the robot arm about its joint varied nonlinearly due to the design of the arm. Also, 5/3 directional control valve proved to be ineffective compared to 5/3 proportional valve in controlling the position of the actuators. The joint's angular displacement was found to be varying roughly linearly with the stroke of the linear actuator and the pressure required to move the arm without any load was found to be around 2.75 bars.

I.INTRODUCTION

Robotic arm (also referred to as robotic manipulator) are mainly used to carry out highly repetitive, material handling and precision tasks such as spot welding, assembling, cutting, palletizing, spray painting etc. in manufacturing industries. It is a programmable device with similar attributes to that of a human arm and is best suited to hazardous environments where human intervention is highly undesirable [1]. The main advantages include high quality of work, more repeatability, time saving, less material wastage and no fatigue. In recent years, major advancements in the field of robotics led its usage in numerous fields namely health care where it is used for executing complex surgical procedures, rehabilitation, prosthetics etc. [2]. Electromechanical robot arms were mainly dominant because they exhibit linear characteristics and hence easy to control. Despite of several advantages, electromechanical robot arms are still restricted to its work-cell because of its high stiffness and inability to work safely in a robot-human environment. Also it consumes a lot of power for its operation, has poor strength to weight ratio, bulky structure and requires high maintenance [3]. This demanded robots implementing different drive technologies and hence pneumatic robot arm emerged.

System that uses compressed air as its main source of energy is termed pneumatic systems. Pneumatic driven systems are of lower cost than hydraulic and electromechanical systems and perform well in carrying out arduous work. Advantages of pneumatically actuated systems are mainly increased level of safety, cleanliness, variable load carrying capacity, simple configuration, minimum pollution, reliable, storage capability, high strength to weight ratio, ease of maintenance, high speed and fast transmission. The system is better at working in hazardous environment where explosions are likely; industries where it is highly suitable are mining, chemical, petroleum and painting industries. It has been used extensively for many years in robotics and factory automation mostly to execute simple tasks using open loop control. Nonetheless, they are often avoided because they exhibit high nonlinearity and are hence difficult to control. But the advent of sophisticated control systems and algorithm for pneumatic servo system in the recent years shifted the paradigm in pneumatic technologies. It is now possible to control pneumatic servo system just like electro servo system [4,5,6-8]

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The study was carried out mainly to replace the robotic arms that utilize electric or hydraulic drive technologies which are unsuitable in industries such as chemical or petroleum industries. According to NFIRS/NFPA national statistical database, about 16% of the structural fires in the US are caused by electrical current from electrical and electronic equipment. In chemical and petroleum industries, fire and explosions are the most frequent potential hazards which may lead to loss of lives, exposure of hazardous chemicals to the environment, loss of resources etc. Hence, use of electrical prime movers for material handling in the chemical industry puts it in severe risk. Pneumatic systems thus prove to be a viable alternative. Although pneumatic systems are controlled by electronics (i.e. solenoid valves), it is possible to completely isolate the electronics to a safer place.

Industrial pneumatic arms are commonly Cartesian (gantry robots) and rarely articulated. Articulated robots arms are useful because it is the most versatile configuration of robot arm and is also anthropomorphic, i.e., it closely resembles the human arm [9]. In this study, a new and improved pneumatic robotic arm was designed and assembled and two different control systems were developed. The design of the robot arm employs crank mechanism using double acting pneumatic actuators controlled by 5/3 proportional valves which are in turn controlled by OMRON Programmable Logic Controller (PLC) at first and then Arduino UNO microcontroller. PLC employed an open loop control system to carry out sequential tasks in material handling whereas Arduino employed closed loop control system to improve control using feedback from MPU-6050 (MEMS accelerometer and MEMS gyroscope) sensor.

II. METHODOLOGY

2.1. Main Pneumatic Components

2.1.1. Linear Rod less Actuator: It is the main actuating mechanism of the pneumatic system and it contains a cylinder with a movable piston in it. The cylinder has two ports from which pressurized air can enter at any one port in a given time and can drive the piston either in the forward or in backward direction. It is called rodless because unlike other cylinder actuators, it does not have a rod attached to its piston. The model of the linear actuator used in the project is SRL2-G-LB-16B200 and has a bore diameter of 16mm with a stroke of 200mm.

2.1.2. Control Valve: It is analogous to an electrical switch which directs the flow of fluid (air in this case) and in special cases, regulate the flow of air (proportional valves). A spool valve (5/3-way proportional directional control) is used in this study which moves horizontally inside the valve casing and it opens and closes or controls the flow of fluid from the pressure supply to the working lines and the exhaust. It falls under the category of infinite position valves because the spool can be displaced anywhere within the range of space available inside the valve's housing. A solenoid is used to control the position of the spool from one control position to another using control signals and proportional valves contains internal microcontroller to control the position of the spool. In this study, 5/3 directional control valve was used at first and then 5/3 proportional valve was used all manufactured by FESTO.

2.2. Mechanical design

In this design, the robot arm has 3 axis of rotation and hence it has three degrees of freedom; axis-2 and axis-3 is pneumatically driven whereas axis-1 is electrically driven using an induction motor. The entire design of the pneumatic robotic arm revolves around the implementation of the rodless linear actuator which was available at the beginning of the design process. Upper arm is made with the rodless linear actuator but lower arm used a normal cylinder due to the unavailability of a second rodless linear actuator. Rodless linear actuators have a number of advantages over commonly used pneumatic muscle actuators including large stroke length and are double acting, meaning, it can provide force in both directions. The design of the robot arm for this study enables efficient conversion of linear stroke of actuator to angular displacement of the joint and hence provides a wide workspace volume, making it suitable for handling and transferring materials in the industries. The anthropomorphic configuration of the arm also makes it ideal for prosthetics. The design is however not limited to pneumatics actuators only, any linear actuators either driven by hydraulic or electricity can access its functionality.

Crank mechanism depicted in figure-1 is commonly found in car engines where the linear movement of the piston is converted to rotational motion of the crank. Here when 'x' varies to complete one stroke, 'r' (crank) is rotated 180° and the crank completes full revolution in the next stroke. Hence two strokes are needed for a full revolution (360°) and one stroke for half a revolution (180°). Please be noted that sliding axis and the centre of the crank are aligned.

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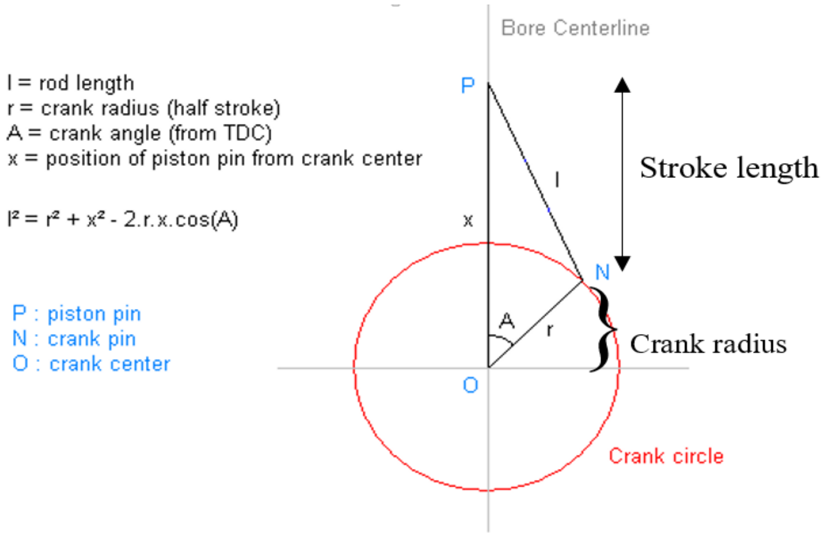

Figure 1: Crank Mechanism.

The crank mechanism can be described using equation-1 and the parameters of the equation labelled in figure 1 must satisfy equation-1.

$$x = r\cos A + \sqrt{l^2 - r^2 \sin^2 A} \quad (1)$$

A 3D CAD model was generated using CREO parametric which utilized the crank mechanism on the pneumatic linear actuator so that the actuator can rotate about axis-2 when the slider joint on the actuator is displaced by pneumatic actuation. This movement formed the upper arm of the robot and similarly, another actuator was used to form the lower arm using the same mechanism as shown in figure -2.

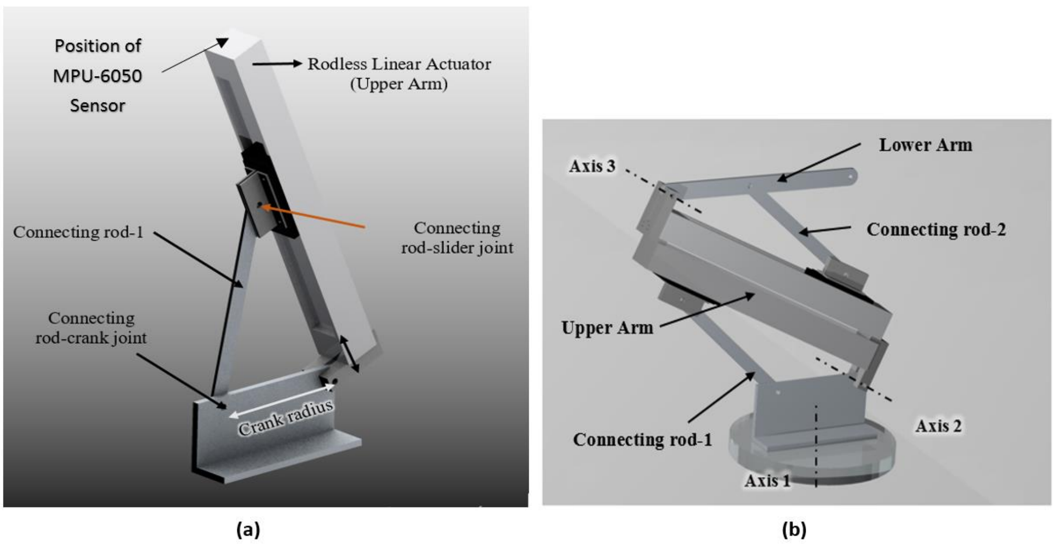

Figure2: 3D CAD model of crank mechanism of an arm (a) Upper Arm assembly of the robot arm (b) fully assembled robot arm with 3 axes

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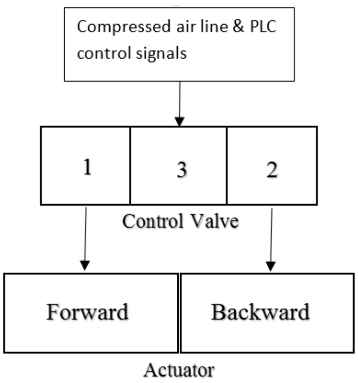
The mechanism provides 360°rotation but it is not required for the robotic arm and hence the angle of rotation was constrained for it to be useful. By analysing the 3D CAD model, it was found that increasing the crank radius (keeping other parameters constant) constrains the angle of rotation of crank. The ideal crank radius and connecting rod length was found by iteration on this 3D CAD model. The mechanism modelled in equation-1 is nonlinear but after constraining the angle of rotation, the linear displacement was found to be almost linear with angular displacement.
The robot arm was controlled using two separate control methods described below:

2.2.1. Control Hardware Development (PLC): The open loop control system for the pneumatic robotic arm was developed by integrating pneumatic control system (5/3 directional control valves) with OMRON PLC CP1L. The 5/3 directional control valve was directly controlled by PLC by applying control signals which determined the direction of air flow through the valve and hence the direction of actuation. The system is represented by a block diagram in figure 3. The three positions of the valve can be seen from the block diagram where the positions are numbered. Position-1 actuates the linear actuator in the forward direction whereas position-2 actuates the linear actuator in the opposite direction. Position-3 cuts the air flow to the actuator acting as a brake. The direction is controlled by applying appropriate control signals to the valve by the PLC. PLC controlled the overall sequential tasks by using timers and counters but was unable to control the angular position of the joints.



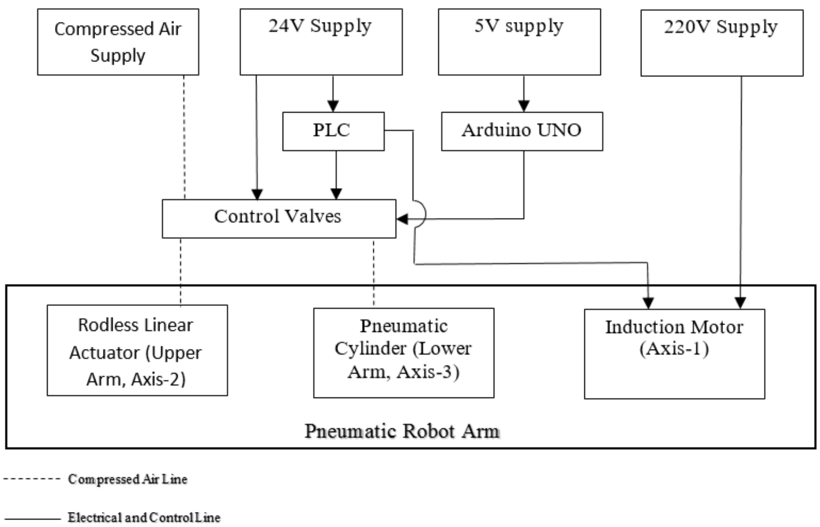


Figure 3: Block diagram of the (a) control valve and linear actuator section and (b) overall system.

The overall system is summarized crudely in the block diagram shown in figure 3. PLC and Arduino never controlled the arm simultaneously and are not interdependent. Notice that apart from the base axis, the whole arm is totally isolated from the electronics. This is important when the arm needs to work in a hazardous environment where using electronics is dangerous. The base motor can be easily replaced by a pneumatic motor in this case; the induction motor was used to exhibit rotation about axis-1 of the arm.

2.2.2. Control Hardware Development (Arduino): A closed loop control system was also developed for the pneumatic robot arm which used Arduino UNO microcontroller instead of PLC. It used feedback signals from MPU-6050 accelerometer and gyroscope sensors to determine the angular position of the arm. A 5/3 proportional control valve is used in this control system where the compressed air flow rate was also controlled by the Arduino microcontroller. The control system is represented using block diagrams in the figure 4.

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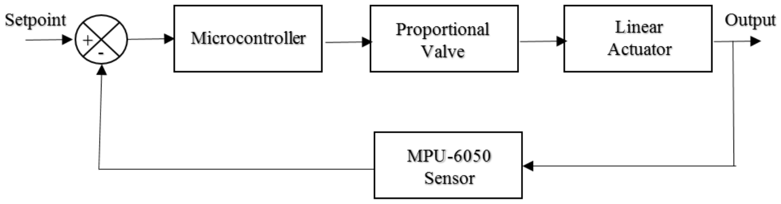

Figure 4: Block diagram of the closed loop system.

The MPU-6050 was placed on top of the rodless linear actuator which formed the Upper arm as seen from figure-2 and only the Upper arm was tested using the closed loop system. The proportional valve (FESTO) requires 0-10V of input control signal and 24V DC power supply for operation. Arduino UNO is incapable of outputting a variable voltage output (true analog voltage) but can output variable PWM signals with power output of 0-5V. The PWM signal is used to vary the input control voltage of the proportional valve with the help of an intermediate electronic circuit which lies in the interface of the microcontroller and proportional valve. A low pass filter circuit filters the PWM to get the true analog DC voltage and the signal is then amplified from the range 0-5V to 0-10 V using a non-inverting Op amp amplifier with gain 2. Using this circuit, the Arduino can successfully control the voltage of the control signal of the proportional valve and hence control the valve.

2.2.3. Software Development:

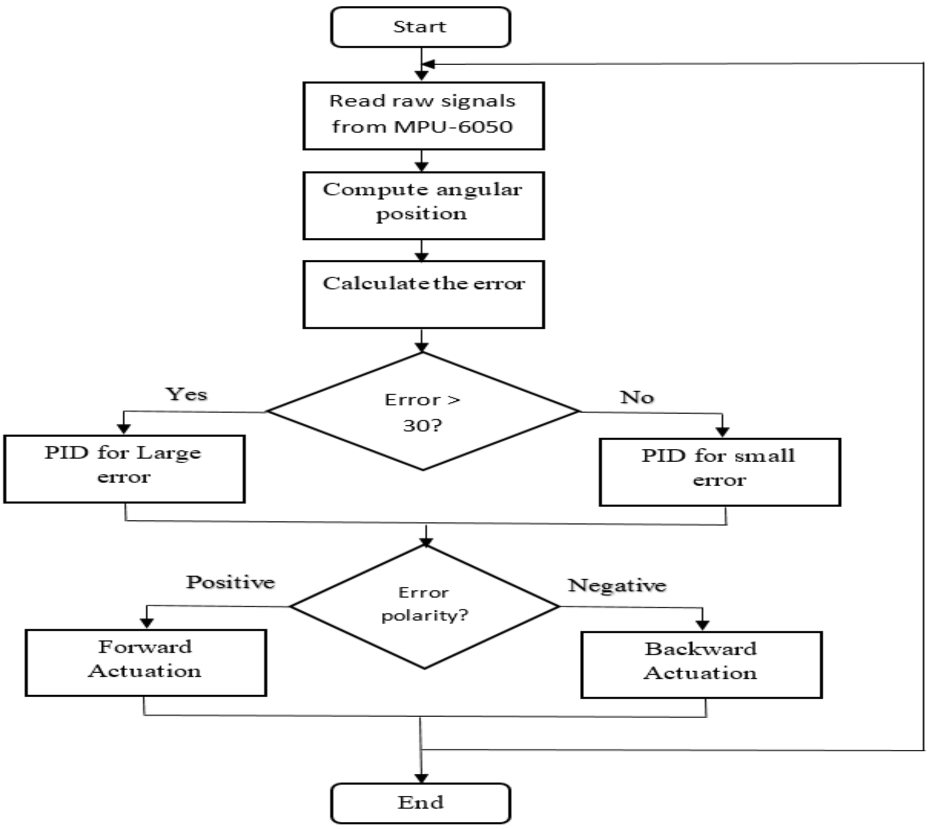

Figure 5: Flowchart of the control algorithm.

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PID control algorithm is used by the microcontroller to control the nonlinear robotic arm. The code developed uses the feedback signals from the accelerometer and gyroscope and computes the angular position and compares with the desired angular position. The error between the desired and current position is fed to the PID control algorithm which computes the output signal. This output signal is then fed to the proportional valve which regulates the flow and direction according to the control signal from the microcontroller. Two PID algorithms were used for better performance; one for large angle error and the other for small angle error which is summarized in the flowchart shown in figure-5.

III. RESULTS AND DISCUSSION

3.1. Mechanical Design

The fabricated robotic arm is shown in figure-6 which was developed with the help of 3D CAD model shown in figure-2. The simulation of the mechanism carried out in CREO parametric matched with the actual behavior of the physical robot arm. A pneumatic gripper was attached to the wrist of the robot arm which plays the role of the end effector of the robot. It was noticed that the force that rodless pneumatic actuator needs to exert to move the robot arm about its joint does not stay constant for this particular design of the robot arm. The force varies nonlinearly with the angular displacement of the arm about its respective joint. The maximum angular displacement of the upper arm was measured to be 120°.

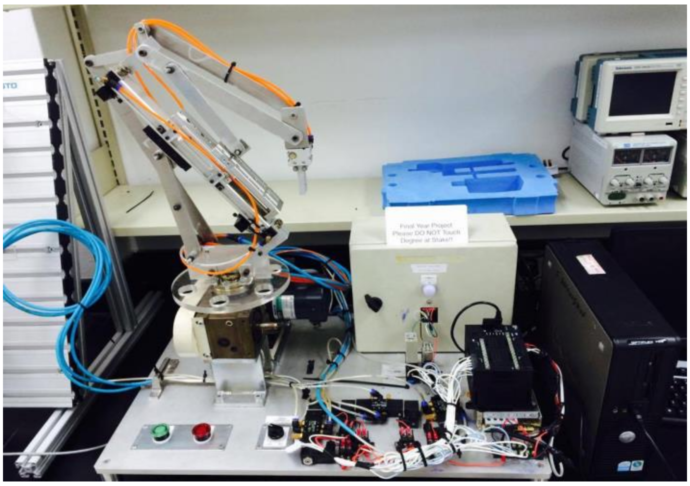

Figure 6: Fabricated Pneumatic Robotic Arm.

Measurements from the actual arm were carried out to determine the maximum and minimum reach of the arm both horizontally and vertically. All the measurements were taken by setting axis-2 as the reference point and is set to be zero position. Right and top directions are chosen to be positive with respect to axis-2 and any measurements to the left or bottom of axis 2 is hence negative. The measurements are tabulated in table-1.

Table 1: Robot specifications

Parameter	Value in mm
Maximum horizontal reach	600mm
Minimum horizontal reach	-300mm
Maximum vertical reach	500mm
Minimum vertical reach	-90mm

3.2. Relationship between Linear And Angular Displacement

The relationship of the linear displacement to the angular displacement is found out by measuring the linear displacement and the corresponding angular displacement and a graph was plotted using the values to visualize the relationship as shown in figure-7.

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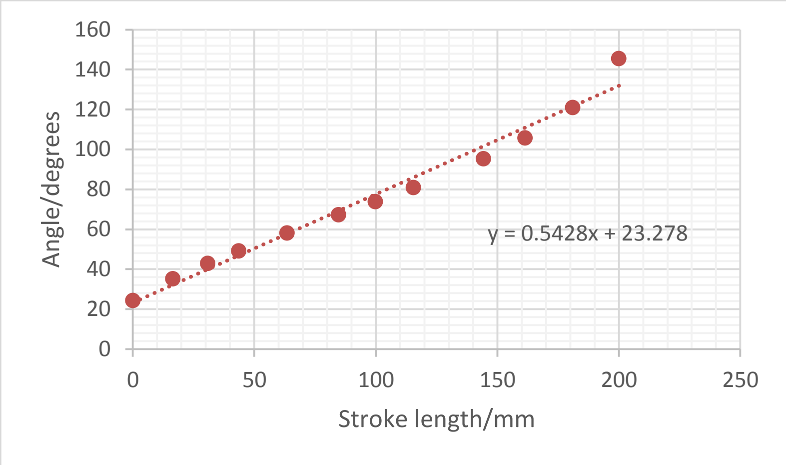

Figure 7: Angular displacement vs linear displacement.

3.3. Load Carrying Capacity

The arm was tested without any load at first to find out the minimum working pressure. Upper arm and lower arm was found to require at least 2.75 bars of compressed air when unloaded to function. This is because the arm needs to lift itself since it has its own mass. The total mass of the arm including all the links and gripper is roughly 2 kg. The arm was then tested with an iron block of dimension 30mm by 30mm by 45mm of mass 330 g and was found that upper arm needs 3.5 bars to move and lower arm requires 4 bars for full displacement.

3.4. Arduino Control with 5/3 Proportional Control Valve

The proportional control valve allowed the microcontroller to control the flow of compressed air which resulted in a better and precise control compared to PLC. The proportional controller in the PID controller controlled the proportional valve and hence the air flow. The angular output from the MPU-6050 is used to calculate the error which is then used by the PID algorithm inside the code. At first, only one PID controller was used in the code and a trade off had to be made between the speed and accuracy of the robot arm. To solve this problem, two PID controllers were used simultaneously in the code; one for large angle differences and the other for small angle. Since the arm is nonlinear, more force/gain is required when the difference between the set angle and current angle is large. Two PID controller exhibited good control making the speed faster and also increased accuracy.
The PID parameters were tuned using Ziegler-Nichols tuning method while keeping the supply pressure constant at 4.5 bars and the following values shown in table-2 were assigned to Kp, Kd and Ki

Table 2: PID parameters.

	Kp	Ki	Kd
Small error PID	2.655	0.085	3.5
Large error PID	3.2	0.8	3.5

Gain is more for the large error PID to make the robot arm faster by applying more force. In general, Kp varies the force of the actuator by varying the flow rate at the valve. Ki determines the amount by which the force increases at regular time intervals if the error remains unchanged. Kd determines the time interval at which the force is adjusted by Ki. The double PID control algorithm was also successful in eliminating disturbances and parameter variations including changes in supply pressure and load. The accuracy of the controller in controlling the joint angle was found to be ±1 degrees. Also, double PID controllers reduces overshoot and settling time.

The arm requires voltage range of 5-10V for clockwise turning and 0-5V for Anticlockwise turning which is fed to the proportional valve. At 5V it will be at rest theoretically. Control parameters can also be varied physically by turning the

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knobs of the restriction check valves which are installed at the intakes of the linear actuators. The controller was tested with different input pressures and was found that at 3 bars, the arm is more accurate but slow. At 5 bars and above, the arm is very fast and provides more force but takes a bit more time to stabilize.

3.5. Further Improvements

The factors that contributed to the overall nonlinearity of the system includes leakage, compressibility of air, hysteresis, joint friction, backlash, force and parameter variation while carrying loads of different mass. The current design employs simple and single links that accounts for the bending observed in the structure. The mechanical design of the structure can be improved by analysing the forces, moment, shear, bending and torsion involved in the current design. Bearings should also be installed on the pin joints to reduce joint friction. The usage of stronger but light material such as carbon fibre, titanium alloys etc. is also recommended since the robotic arm needs to execute material handling tasks most of the time. Machining the parts of the arm using a CNC machine will increase the accuracy of the overall design. Linear actuators with larger bore diameter and strokes are particularly useful when heavy loads are involved. Diameter of the bore/piston greatly increases the load carrying capacity of the actuators. Also, actuators with built in braking mechanism and displacement encoders are available which is highly suitable for the design of robotic arm made for this study.

The usage of Microcontroller or microprocessor is highly recommended since the problems that arise from pneumatic systems can only be solved using advanced control algorithm such as PID which is obviously very difficult to implement in a PLC. Closed loop system with accelerometer and gyroscope sensors proved to be the best way to control the robotic arm. Sequential tasks are also easy to program in a microcontroller compared to that of a PLC. Usage of 5/3 proportional control valves is imperative in precise controlling of the robot arm. More PID controllers can be used to improve the control further and also, PID can be combined with neural networks to adaptively tune the PID parameters to improve performance.

IV. CONCLUSION

An articulated robot arm was developed using pneumatic linear actuators to carry out material handling tasks for industries where the usage of electric components can be hazardous. The design of the arm employed crank mechanism in which linear displacement from actuation was converted to angular displacement of the joint effectively. A 5/3-way proportional control valve proved to be very effective in controlling the highly nonlinear arm compared to normal 5/3-way directional control valve. Closed loop control using a microcontroller and feedback sensors provided precise and improved control of the joint angle with high accuracy which was previously unachievable by PLC. It was also found that the force changes with the position of the articulated arm dynamically.

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