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Design and Fabrication of a Robotic Arm for Material Handling

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ABSTRACT

The commercial robots are expensive for use in the educational institutions. The operation of them will not leave room for experimentation, which is necessary in an educational institution. Further a large number of components that can be used for building a robot are readily available in the market. Hence this project has been taken up to allow us to build a working robot using as many of the off the shelf components to provide the necessary flexibility. This would make it a low cost robot with enough flexibility for the students to experiment the various functions of the robot.

The mechanical component of the manipulator was built with three degrees of freedom, one revolute and two prismatic joints. This configuration is most common to be used as a material-handling device for machine tools. The revolute joint was achieved by making use of a pneumatic rotary table and one prismatic joint is realized by means of a pneumatic cylinder. The second prismatic joint in the Z-direction is achieved by the use of an AC servomotor with a ball screw and linear motion elements to provide for accurate positioning capability. The gripper had been designed for cylindrical components, since this robot was conceived as a material handling unit for a CNC turning center. All the necessary design calculations had been done and the finite element analysis was carried out for the main structure. The control system of the robot was one of the crucial elements. A PC is used as a controller. The motion control was

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carried out with the help of a motion control card DC2-PC100. It had the ability to control 2 servo and 2 stepper motors in addition to other digital and analogue controls. Several types of sensors and actuators were used for the robot to be fully automatic. The signal conditioning circuitry was designed in house for the interfacing between sensors, actuators and controllers. The control algorithm was developed with the necessary functioning to coordinate all the joint movement as well as gripper manipulation.

***Keywords**: Robot, manipulator, sensors, cost-effective, teaching tool*

Introduction

Robot is an automatically controlled material handling unit that is widely used in the manufacturing industry. It is generally used for high volume production and better quality. Implementation of robot technology with integration of automatic system can contribute in increasing of productivity of the company and enhances the profitability of the company [1].

The word 'robot' first appeared in 1921 in the Czech playwright Karel Capek's play 'Rossum's Universal Robots'. The word is linked to Czech words *Robota* (meaning work) and *Robotnik* (meaning slave) [2]. In 1942, the so called "three rules or laws of robotics" were presented the first time [3]:

- A robot may not injure a human being, or, through inaction, allow one to come to harm
- A robot must obey the orders given it by human beings except where such orders would conflict with the First Law
- A robot must protect its own existence as long as such protection does not conflict with the First and second laws

Webster dictionary defines a robot as: *An automatic apparatus or device that performs functions ordinarily ascribed to human or operates with what appears to be almost human intelligence.*

Robotic System for Teaching Environment

The requirements for ever-increasing high quality education and, perhaps more importantly, consistent learning outcomes have led to a number of research and development of project based learning kits worldwide aimed at increasing quality of teaching methodology [4]. The future implementation of outcome based education OBE also requires the teaching approach to be focused more on student-centered activities. In line with the requirement of OBE, the development of this robot offers an alternative teaching tool for mechanical students to embark especially at Universiti Teknologi MARA, Malaysia.

The development of robot in this project was to perform material handling tasks that are frequently required by the manufacturing industries. Material handling that may involve tasks like picking and placing the parts at desired locations or loading and unloading the parts of required machines. To suit the teaching environment that imitates real industrial application, a new approach of robotic system must be designed and developed. This needs new drastic concept of robot development by using as many of the off the shelf components to provide the necessary flexibility and modularity [5].

Design concept is very important in the early development of product design [6]. The design and development concept of robotic project in this paper was intended to be used in classroom for teaching environment. The main criteria in the development of this robot were to provide cost-effective, flexible configuration and ease of programming approach to students. Hence, the development of this robot focused on two main areas of design concept.

- Design concept of robot configuration
- Design concept of robot control system

Design Concept of Robot Configuration

In general, the design concept of robot configurations can be classified by type of motion provides such as Cartesian coordinates, Spherical or Polar co-ordinates, cylindrical co-ordinates motions and revolute or articulate coordinates [2]. In Cartesian coordinate motion, positioning may be done by linear motion along three principal axes. These axes known, respectively, as the Cartesian axes X, Y and Z. The work area or work envelope of Cartesian-co-ordinates robot's arm is a big box-shaped area. Spherical or Polar co-ordinates consist of two revolute and one prismatic joint. The axes for the spherical co-ordinates are θ, the rotational axis; R, the reach axis; and β, the bend-up-and-down axis. Cylindrical co-ordinates allow a rotary motion at the base followed by the two linear motions. The axes for the cylindrical co-ordinates are θ, the base rotational axis, R (reach) the in-and-out axis; and Z, the up-and down axis. Articulate co-ordinates motion permits the robotic arm that can rotate all three axes.

These robots minimize the intrusion of the manipulator structure into the workspace, making them capable of reaching into confined space [7].

Besides development of manipulator arm, gripper is also an essential part of the robot development for material handling. The mechanical grippers are designed to grasp a part or work piece. Gripping force is very important in gripper design since the grippers must contact with the surface area of work piece. Adequate frictional force must be applied to the work piece to overcome the gravitational pull of the work piece. The gripper must also have enough contact force with the work piece so that when the manipulator rotates, the work piece will remain in the gripper [8].

Design Concept of Robot Control System

The overall design concept of robot control system is shown in Figure 1 [2]. The controller is used to control the robot manipulator's trajectory planning through forward and inverse kinematics. The controller optimizes the performance of the robot dynamic model of the robot arm and executes all program data for the robotic system. The sensor elements communicate to the robot controller about the status of the manipulator through the

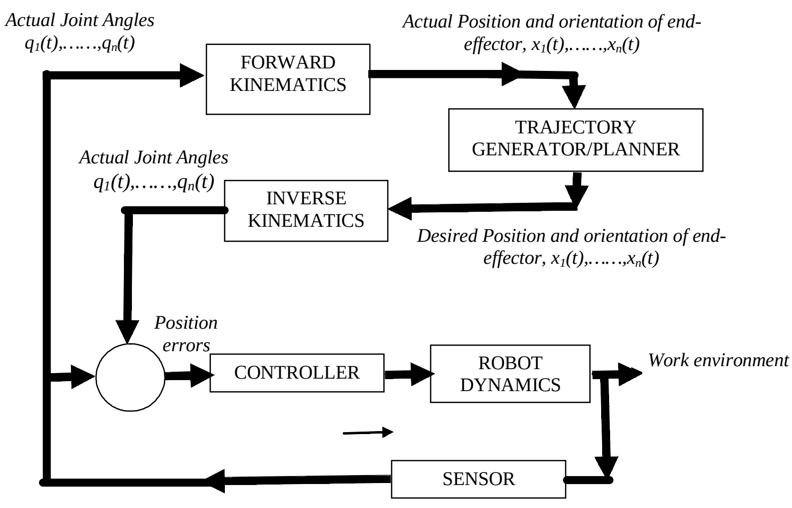


Figure 1: Overall Design Concept of Robot Control System

trajectory planning of the robot's end-effector. There are many researchers who are interested in robot control system of trajectory planning such as Huang H.P. *et al*. (1988), Li Y. *et al*. (1998) and Nakamura M., *et al*. (2000) [9-11].

Robot Manipulator Design

The design of this robot was based on three degree of freedom motions in such a way that the students can easily visualized the motion clearly. This is because robots can be classified by the type of motions provided. The three degree of freedom motions was realized by a mixture of one revolute joint coupled with two prismatic joints. This enabled students themselves to have hands-on experience to construct and program the robot. Besides that, students later on could study the effects of the required torque for each link joint due to inertia, centripetal, coriolis and gravitational forces. From the developed robotic system, students could also predict the expected dynamics behavior of the robot link for a given geometrical configuration and under certain working [12].

Robot Specification

The following specifications had been laid down for the design of the robot. The robot should be capable of picking a light and small component (1-kg payload and maximum diameter of 35 mm) for the CNC turning centre in the CNC Laboratory. The components were generally round with smaller weight (aluminium workpieces). The same design concept could be used to extend the mechanism for larger sizes, which would have the ability to pick heavy components. The robot was to be designed with 3 degrees of freedom. The basic movements were rotary movement, up-and-down movement (Z-axis) and Left-to-right movement (X-axis). The gripper should be able to grasp and hold the cylindrical parts used in the turning center.

Design Considerations

One of the main criteria used in the development process was to make use of as many components as available in the market. This helped in reducing the development time as well as making the system more robust and accurate than was possible by the individual fabrication of the

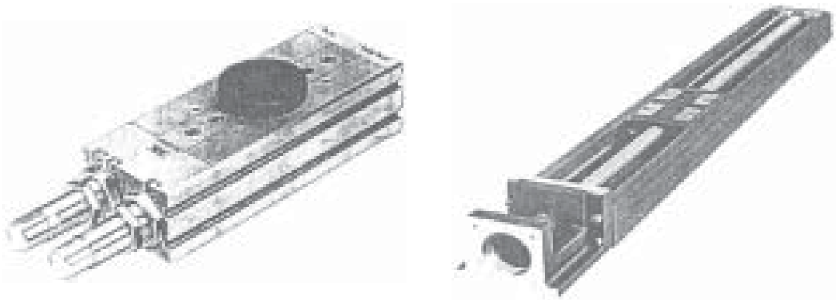


Figure 2: Festo Rotary Table and LM Guide Actuator
[Festo &THK Company Catalogue]

elements. The off-the-shelf available components had better specifications at lower cost because of the mass manufacture techniques employed. The following components were therefore selected from those available in the market.

In order to achieve the 180° motion in the horizontal plane the pneumatic rotary table a shown in Figure 2 was used. The specifications of the rotary table are completely provided by the supplier. In the initial design concept, this table has only two positions possible at 0° and 180°.

The LM guide actuator, as shown Figure 2, was available from THK in the form of complete assembly. This actuator was chosen because it suited the requirements as well as available at low cost.

FEM Analysis

Finite Element (FEM) analysis was applied to the bracket of the robot body to determine the stress levels at the critical points. The critical points were the joining part of the bracket 2 with bracket 4 as shown in Figure 3 (point A & B). In this case, LUSAS Modeler had been used to make the analysis. First step of the analysis, the model of the bracket need to be simplify into 2D modeling as in Figure 3 to reduce the number of elements. This was because the imitation of the element in this modeler only up to 250 elements (for the Evaluation version).

Use width of the bracket as the thickness of the model (34.08 mm). Then apply the load (total weight of the gripper, workpiece and safety factor) 29.43 N as in Figure 4. Meshing applied to the surface of the model before analysis can be done. Analysis becomes more accurate if the resolution is high. Figure 5 shows the model after applying the mesh.

Then apply all necessary parameter to the model.

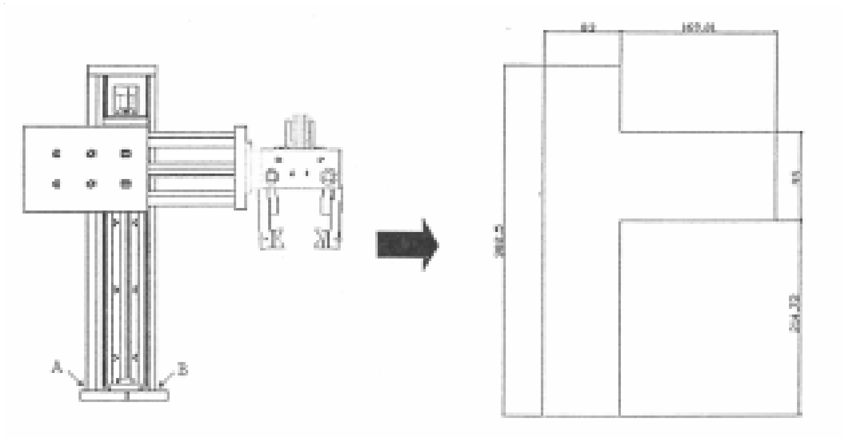


Figure 3: Simplify the Model into 2D Modeling

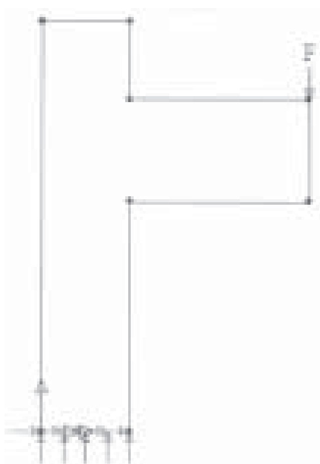


Figure 4: Applying Force and Support

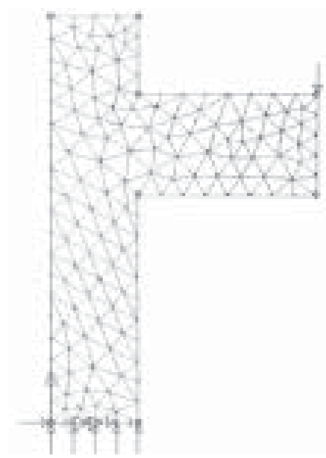


Figure 5: Applying Shell Mesh

Figure 6 shows the result of the analysis. From the result, we get the stress level at point A (tensile) is 0.129686 N/mm^2 (130 kPa) and point B (compression) is 0.144096 N/mm^2 (144 kPa). In this project, we use stainless steel screw (property class 4.8) as the joining members for this bracket. This analysis shows that the bracket is safe enough to hold the existing load. The screw proof strength is 310 MPa.

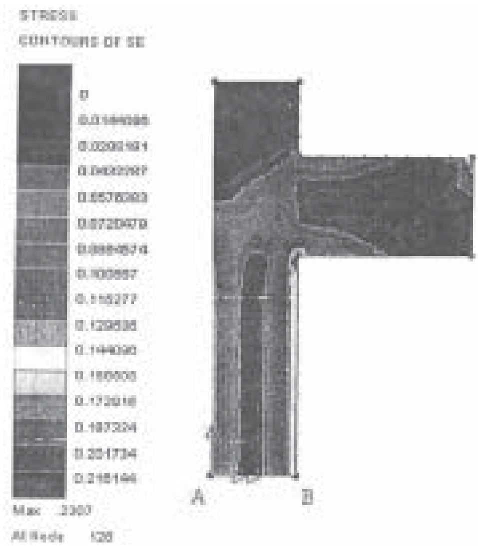


Figure 6: Stress Contour of the Bracket

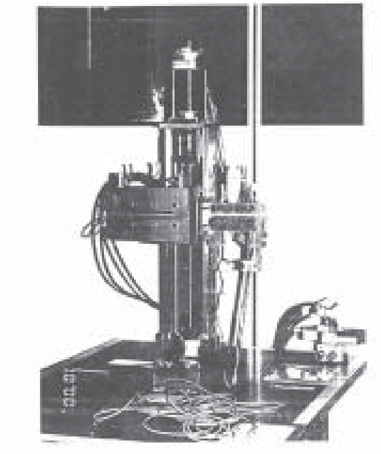
Table 1: Loads on the Various Components of the Robot

Item	Calculated value	Manufacturer value
Rotary tableStatic load (N)	29.43	1200
Horizontal armMax. working load (N)	29.43	117
Vertical arm Permission static moment (Nm)	6.20	84
Double acting cylinderGrasp force (N)	22.07	51

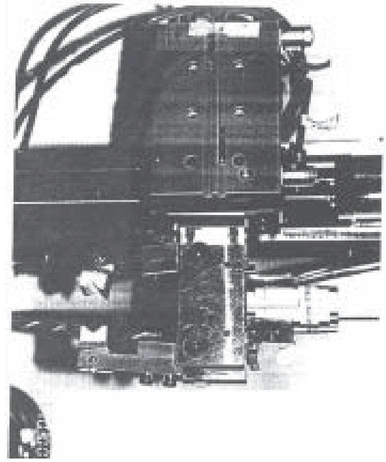
From the above Table 1 shows that the calculated value of the force analysis is less than compared with the manufacturer value. Therefore we can make the conclusion that the components are safe to use.

Fabrication of Final Robot Prototype

Based on this strength and dynamic analysis as well as control system investigation, the final prototype of the robot was fabricated and assembled as shown in Figure 7. The detailed construction and assembly of the robot components is shown in Figure 8 and Figure 9. The robot has a



(a) The general view of the robot manipulator



(b) The view of the gripper

Figure 7: Final Prototype of the Robot

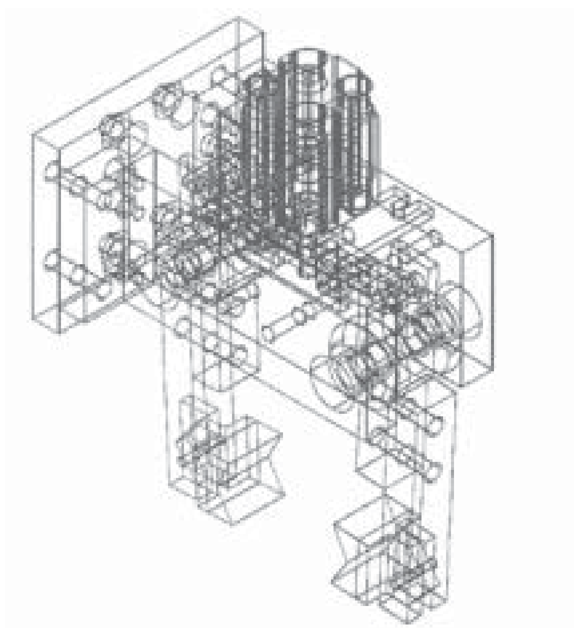


Figure 8: The Gripper Assembly

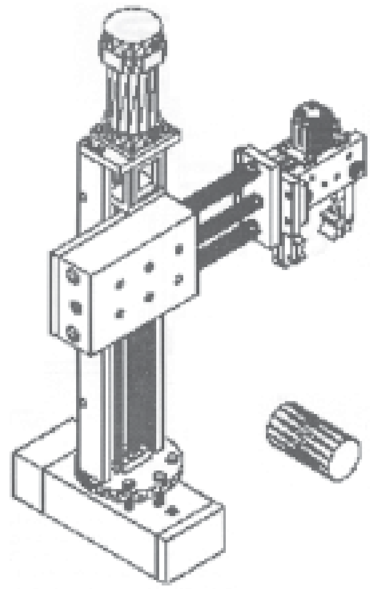


Figure 9: The Robot in Assembled Form

gripper that attached to its end-effector. The control system of the robot was interfaced to a PC-computer.

Motion Control System of the Robot Manipulator

The main job of the motion control system is to perform the time-intensive, high frequency tasks needed to keep each axis of the robot's end-effector moving along the desired path. The function is to plan each move, apply interpolation, close the servo loop, regulate motor commutation and maintain the current loop. A motion control system must perform all of its tasks at high speed, with extreme reliability and no jerk. Jerk is a phenomenon where there is a discontinuity in acceleration. Jerk of the desired trajectory planning adversely affects the performance of the tracking control algorithm for the laser cutting [13].

For proper control of the manipulator it is necessary to know the state of each joint, that is, its position, velocity and acceleration. To achieve this, a sensor is to be incorporated into the joint-link pair. Sensors may monitor position, speed, acceleration or torque. Safety features allow a motion control system to bring the robot to a safe condition in the event of an error, or if the PC “crashes” and stops functioning. The actual schematic of the robot controller as being planned is shown in Figure 10.

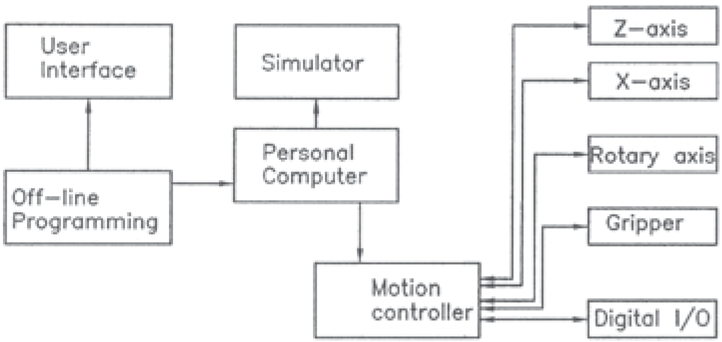


Figure 10: The Complete Architecture of Robot Motion Control System

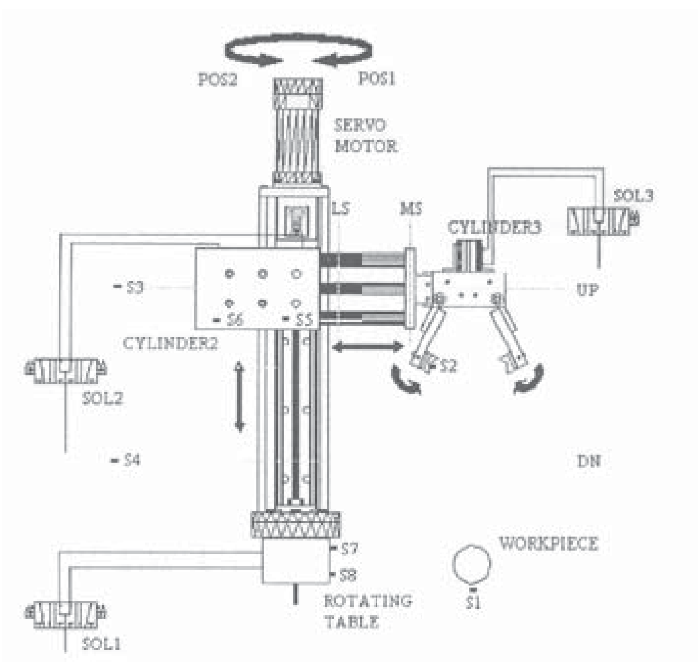


Figure 11: Robot with the Necessary Sensors and Actuator

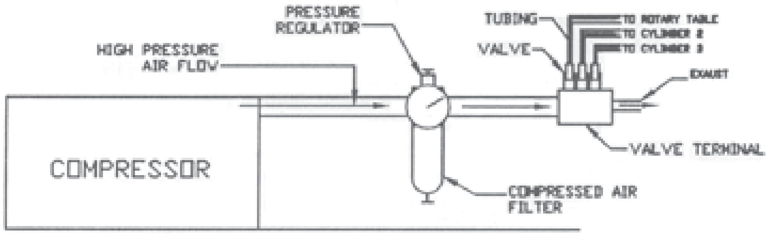


Figure 12: Schematic of the Pneumatic Connections from the Compressor

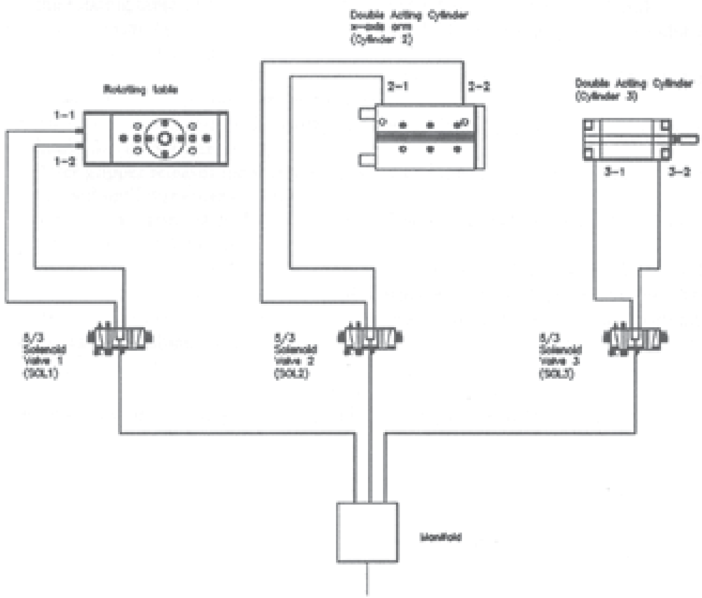


Figure 13: Schematic of the Pneumatic Connections to Control the Robot Functions

The purpose of the robot manipulator is to perform work. An end effector attached to the robot's arm must accomplish the work to be done by the robot. The end effector can be a gripper for work handling or end-of-arm tooling if a particular job is to be done such as welding or rivetting. The manipulator moves the end effector to the programmed locations. These moves of the end effector are controlled by a robot's program stored in the controller memory. The type of end effector depends upon the type of work holding to be done. These can be operated by mechanical means such as using a pneumatic or hydraulic cylinder, or use vacuum to lift and transfer the part, or use an electromagnet to lift and move the part. The robot's end effector may have sensors such as proximity switches, light sensors, pressure switches, magnetic-field sensor, vibration detectors or speed-of-motion sensors depending upon the application. The robot with all the necessary connections is shown in Figure 11. Figure 12 shows the schematic of the pneumatic connections from the compressor. The details of the pneumatic connections to control the robot functions are shown in schematic drawing of Figure 13. The various inputs and outputs used to control the robot actuators and sensors.

Operation Procedure

The operation procedure must be clearly stated before a program can be written. All the sequences must be debug and simulated before the program can be executed and tested with the robot. The safety of the user must be put at the highest level. The operation procedure and the ladder program is included in Appendix 1 and 2.

The robot system that is capable of pick-and-place job in the work are involves a CNC turning center and a conveyer system. The robotic system movement is in cylindrical coordinates that consists of translation movement in up-and-town and left-to-right and rotational movement at the base. The design makes use of as many of the shelf available components as possible with minimum amount of fabrication. It was possible to integrate the servo motor system and pneumatic system under 5 bar air pressure to generate the robot's movements. The components under pneumatic system, which we purchased are rotary table (180 degree – rotation), horizontal arm (100 mm stroke) and double acting cylinder (25 mm stroke). In order to move the arm up-and-down a recirculating ball lead screw system (200 mm traveling rail) powered by the servomotor.

Our design concept is based on the operating load of 1 kg mild steel cylindrical workpiece. The gripper was designed to help in orienting the workpiece where when the two-dimensional. The gripper work depends upon the double acting cylinder where when the cylinder shaft retract the gripper to grasp the object and it will open when the shaft is in extended position.

The operation of this robot starts when it senses the workpiece that came from the CNC lathe machine. When the robot receives the signal from controller then it will start operation by grasp the workpiece and transfer it into the other side of the CNC lathe machine. Then robot will return back to the home position again to do next same sequence. At every movement destination of the robot, it have sensor to control the operation. If the sensor does not activate, then the operation will be halt and the operator need to reset the robot manually to the home position.

Costing

The main consideration in designing and developing of this robot is to provide cost-effective solution for learning environment. Most of the robot components are available off-the self, easy to assembly and cheap. To keep the cost cheaper, students were ask to develop the computer algorithm to control the robot actuators and sensors. The complete list of components purchase under robot's project is illustrated in Table 2.

Table 2: Components Purchase under Robot's Project

	Description	Total amount (RM)
1.	Ball screw (vertical arm)Sensor attached to the vertical arm	2800.00 260.00
2.	Pneumatic system and accessories including horizontal arm, rotary actuator, double acting cylinder solenoid valve (5/3 & 3/2), tubing, fitting and manifold	4713.88
3.	Amplifier power supply and	700
4.	Motor and motion control card	8068.00
5.	Coupling	150.58
6.	Screw and bearing	168.90
7.	Bracket fabrication including UiTM technician cost	1035.00
	Total	17896.36

Conclusion and Suggestions for Future Work

Conclusions

The robot which can be used as a material handling unit had been successfully fabricated and assembled. It had one servo controlled axis, with complete flexibility, while the other axes (two) had limited positional control. The proved to make it one of the cheapest control unit had been achieved. The robot was electro-pneumatic controlled with sufficient flexibility. It has provided excellent opportunity to work in multi-discipline areas with appropriate understanding.

Suggestions for Future Work

Upgrade the robot drive system; changing the pneumatic system to servomotor actuator, which will lead to complete automatic control. It is also possible to develop the robot control with sufficient amount of programmability in all the axes. Implement vision system to detect and monitor the robot motion and sequence. Increase the gripper flexibility.

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Appendix 1 Operation Procedure

1. Robot will start operation at home position (POS1, UP, LS, GRO-gripper open).
2. When Sensor 1 (S1) detects workpiece, robot will start operation of Solenoid Valve 2 (SOL2) to supply air to the cylinder 2 at intake 2-1 to extend gripper to MS position.
3. The motor will rotate counter clockwise to move x-axis arm downward.
4. When x-axis arm reach DN position, motor stop.
5. When sensor 2 (S2) senses the workpiece, Solenoid Valve 3 (SOL3) will supply air to cylinder 3 at intake 3-2. This will make gripper grasp the workpiece (5s timer used to ensure that the workpiece has been completely grasped by the gripper).
6. After gripper grasps the workpiece, servo motor will rotate clockwise to send x-axis arm upward to UP position
7. When x-axis arm reaches UP position, motor stops.
8. Then gripper will retract to LS position (SOL 2 supply air at intake 2-2 in cylinder 2).
9. Then Solenoid Valve 1 (SOL1) will rotate the robot to the Position 2 (POS2).
10. When sensor 7 (S7) senses the robot at POS2, SOL2 will supply air to cylinder 2 at intake 2-1 to extend the gripper to MS position.
11. Then servo motor will rotate counter clockwise to send x-axis arm to DN position.
12. When it reaches DN position, motor stops.
13. Then gripper will release the workpiece into the ‘Handling Box” (SOL3 supply air at intake 3-1 in cylinder 3.
14. After gripper releases the workpiece, motor will rotate clockwise to move x-axis arm upward until it reaches UP position.
15. When x-axis arm reach UP position, SOL 2 will supply air to the intake 2-2 to retract the gripper to the LS position.
16. Then, SOL1 will supply air at intake 1-2 at the rotating table to rotate the robot 180 back to the home position, sensor 8 (S8) will sense the rotation of the robot to the POS1.
17. Robot operation is now completed (workpiece been transferred to the ‘Handling Box’).
18. Robot now waiting for the next sequence.

The above sequence as implemented in a ladder diagram is shown Appendix 2.

Appendix 2 Ladder Diagram to Control the Robot Functions