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Engaging Students' Creativity through Designing a Low-Cost Educational Robotic Arm

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Abstract

Robotic arms have been around for many years and are widely used within industries. In 2010, the availability of low-cost robotic arms increased substantially. These types of robots are ideal solutions with applications in automation, laboratory, and education because of their adaptability to various industries and tasks. The objective of this project is to design a low- cost/affordable industrial robot manipulator including base, arm, wrist, and end effector with similar functions to a human arm and fingers with educational applications. The mechanism of the manipulator is similar to the articulated robot so that the links of the manipulator are connected by joints allowing rotational motion. For the end effector, a two-finger gripper is designed that allows the robot to pick up and place down an object. The proposed robot has 5 degrees of freedom and operates with Dynamixel AX-12A and RX-24- F servo motors and mechanical components to perform a variety of tasks and operations. All the mechanical components, including links, gripper, connectors, spur, and bevel gears are designed by SolidWorks and Cero computer aided design (CAD) software. A 3D printer is used to manufacture the mechanical parts. The microcontroller and software are utilized to program servo motors so that the robot can do the desired tasks. The design of this robot will provide an opportunity to educators to explore the knowledge of mechatronics that will eventually open a whole new world of learning to them.

Introduction

Robots are much more likely to be used as learning tools for several subjects across the engineering curriculum. Designing a simple and low cost educational robot has become an increasingly popular project for engineering and technology programs [1-2]. Robots are currently used in engineering and technology classrooms and are being incorporated into education. Most of the schools use a robotics project in the Introduction to Engineering course to expose the freshmen students to assembling, programing, and integrating systems to perform the task.

The intent of this project is to design a low cost and lightweight electrical powered manipulator that can be used as a project to assess and validate student competencies. Overall, the proposed robot arm has five degrees of freedom including movements of base, shoulder, and elbow as well as pitch and roll movements of wrist. This project, which is geared towards addressing real-world problems, has been designed to excite and engage the interest of undergraduate students and exposes them to principles of robotics, mechanical design, and assembly.

Design Methodology

This project involves designing and prototyping mechanical components, selecting appropriate servo motors and programming them. Design of each component requires an understanding of its function within the system, as well as limitations caused by other components within the manipulator. The project starts with an initial design that can provide guidelines to design all the components precisely. The initial design of the manipulator and gripper are given in figures 1 and 2.

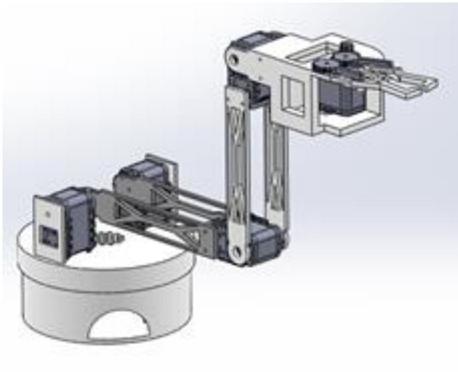

Fig 1. Initial design of robot

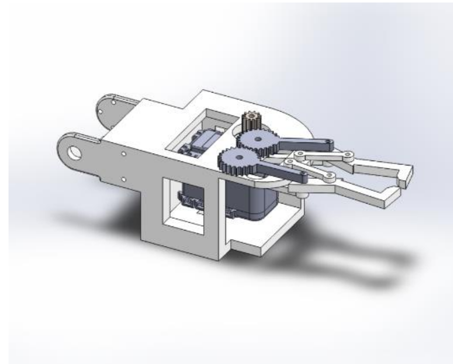

Fig 2. Initial design of gripper

<u>Motor Placement and Calculation:</u> As depicted in figure 1, movement of the proposed robot manipulator requires six servo motors to control and generate rotational motions. To move the arm easily and efficiently, three high torque servo motors that rotate the base, shoulder, and elbow are required. All three servo motors are placed in the base of the manipulator in order to design lighter links. Also, the two smaller serve motors are designated to create pitch and roll rotational motions for the wrist and another servo motor opens and closes the gripper. All three smaller servo motors are attached to the wrist of the robot. The selections of adequate servo motors require some calculations that are detailed as follows:

a. Servo motors that generate adequate torque/force to hold and rotate an object with 0.5 kg mass:
These three servo motors are attached to the wrist of the robot. One of them should be able to open and close the gripper as well as hold the object. The rotation of the servo motor transmits the torque/force to the gripper through a worm gear that allows the gripper to pick up the object and drop it at its destination.

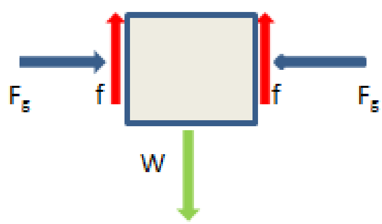

Fig 3. Free body diagram of the object

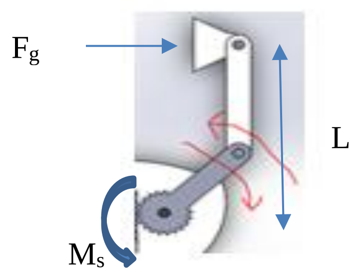

Fig 4. Part of gripper component

Calculation: Figure 3 shows the free body diagram of the object that is held by the gripper. Performing equilibrium condition in Y direction yields

$2f - W = 0$ Eq.1

Where f and W are friction force and weight of the object, respectively.
The gripper force F_g can be calculated by

$F_g = f/\mu$ Eq.2

Where μ is coefficient of static friction.
The value of weight is calculated by $W= m*g$=0.5 kg*9.81m/s^2= 4.9 N
From Eq.2 and assuming μ=0.4 for plastic materials, the gripper value is F_g= 6.12 N.
In figure 4, the equilibrium condition for moment is given by

$M_s - F_{g*} L$=0. Eq.3

Where M_s and L are moment at spur gear and length of gripper, respectively.
From Eq.3, the moment value is M_s=6.12*.08= 0.49 N. m.
The force exerts by worm gear, F_w, is given by

$F_w= M_s/R_s$ Eq.4

Where R_s=0.0112 m is radius of spur gear. Eq.4 gives the value of F_w= 43.7 N
The moment of worm gear M_w, lead angle Θ, angle of static friction between worm gear and spur gear Θ_s, lead l, and radius r of the worm gear have the following relations [3]:

$M_w=F_w*r*tan\ (\Theta+\Theta_s)$ Eq.5

$\Theta=tan^{-1}[l/(2*\pi*r)]$ Eq.6

$\Theta s=tan^{-1}(\mu)$ Eq.7

Substituting the values of r=5.3 mm, l=4 mm, μ, and F_w in equations yields the value of M_w= 0.126 N.m.

This is the minimum moment/torque required in order to hold 0.5 kg mass by the gripper.
The servo motor Dynamixel AX-12A is selected based on calculations. Overall, the three AX-12A servo motors that are attached to the wrist of the robot need to create pitch and roll rotational motions for the wrist which opens and closes the gripper.

b. Servo motors that generate adequate torque/force to rotate the base, shoulder, and elbow:
All three servo motors are placed in the base of the manipulator. The free body diagram of two links of the robot manipulator is given in figure 5.

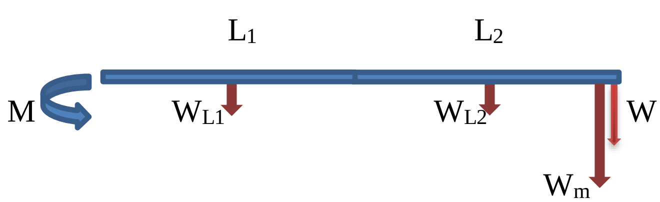

Fig 5. Free body diagram

The equilibrium condition for moment is given by

$(L_1+L_2)*(W_m+W) + W_{L2}*(L_1+L_2/2) +W_{L1}*L_1/2 – M =0$ Eq.8

Where L_1 and L_2 are length of links. Also, W_m is the total weight of the three servo motors attached to the gripper and M is moment at shoulder of the robot. Considering approximate 60 gr mass and 25 cm length for each L_1 and L_2 and 60 gr mass for each servo motor, the value of moment yields M= 0.35 N.m.

The servo motor Dynamixel RX-24F is selected based on calculation. All the three RX-24F servo motors are placed in the base of the manipulator.

<u>Base Design</u>: After sizing and identifying the location of the servo motors, the mechanical components of the manipulator are designed and prototyped with a 3D printer. The process starts with designing the base component of the robot that contains a stationary lower piece for mounting a RX-24F servo motor and an upper movable piece for allowing the rotational motion. Figure 6 shows the lower piece of the base component with an enclosure for a RX-24F servo motor and channeled wiring. The servo motor creates rotational movements for the base.

Fig 6: Lower piece of the base component including the base servo motor

Figure 7 shows top and bottom surfaces of the upper piece of the base component with two enclosures for mounting RX-24F motors and one central enclosure for fastening the top piece to the base's motor wheel. The slight clearance allows the upper piece to rotate freely around the stationary lower piece.

Fig 7: Top and bottom surfaces of the upper piece

Figure 8 shows the assembly of the base so that the servo motor is screwed to the upper piece and attached into the lower piece.

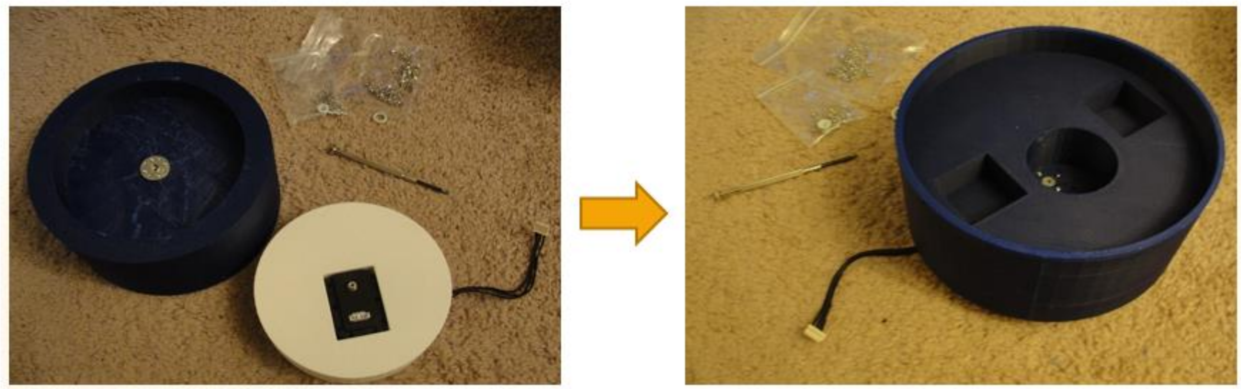

Fig 8: Combination of upper and lower pieces of base

Shoulder Design: The shoulder is designed via control from one of the RX-24F motors. Figure 9 shows the placement of the servo motor into one cavity of the top piece of the base that allows more structural stability. The mounted servo motor wheel is forced to fit into a slightly smaller hole on the shoulder to ensure rotational control from the motor.

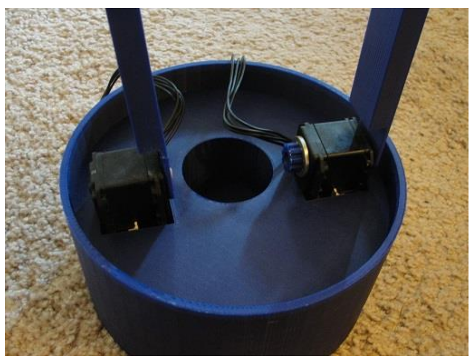

Fig 9: Shoulder and elbow servo motors inserted into base cavities

Elbow Movements: As shown in figure 9, a servo motor that rotates the elbow is mounted in the base of the robot as well. The torque induced by the servo motor needs to be transmitted through the timing belt and sprockets to the elbow. A timing belt and sprockets assembly is selected due to the absence of slip and due to the overall efficiency of such transmission systems. Design of this system begins by estimating the size of sprockets based upon the diameter of the elbow shaft, selecting an appropriate belt, and refining sprocket calculations to ensure proper mesh between the sprockets and timing belt. The belt pitch and tooth depth of XL belt sizes, figure 10, are used to estimate the required tooth profile of the sprockets. Figure 11 shows a visual representation of the prototype sprockets.

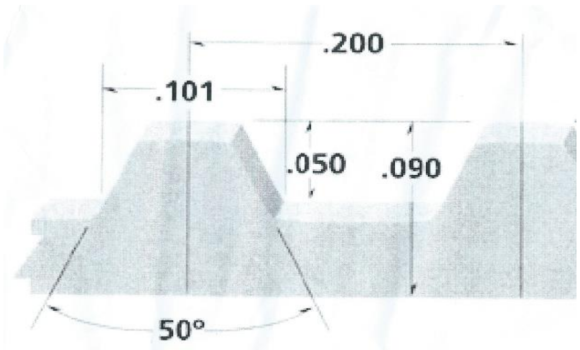

Fig 10: Common geometry for XL (0.200 in. Pitch) belts

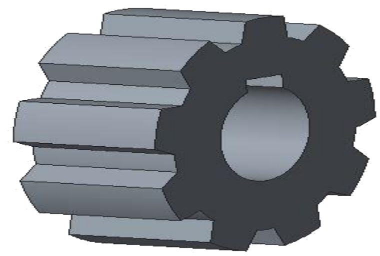
Fig11. Prototype sprockets

After completing the prototype design of the sprockets, the specific belt needs to be selected based upon the initial selection criteria and required total belt length. The Eq.9 provides the length of the belt.

$$L_b = [4C^2 - (D - d)^2]^{1/2} + \tfrac{1}{2}(\alpha D + \beta d) \qquad \text{Eq. 9}$$

Where L_b is the length of the belt, C is the center-to-center distance between sprockets, D and d are pitch diameters for sprockets, and α and β represent angles of wrap (contact) for the sprockets. In order to simplify the design, both sprockets are designed with the same dimensions and with a contact angle of 180 degrees. After substituting values of C = 10 and D= 0.75 inches in the equation, the value of the belt length yields 22.36 in. A Gates 220XL025 Power Grip Timing Belt is selected since it closely matches with calculated values with some tolerance in belt length (L_b = 22 in). After the timing belt selection, the initial model of the sprocket is modified in order to ensure an optimal mesh between the timing belt and sprockets. The new sprocket has a tooth width equal to the width of the available belt model. Two final versions of the sprockets are generated: one that is assembled by press fitting to the shaft of the elbow's servo motor, and another with a .10 in. * .15 in. keyway to allow it to join with the elbow link shaft. Keyway geometries were arbitrarily selected but matched to key dimensions with slight tolerance for fitting.

<u>Elbow Shaft Design</u>: The elbow link shaft has a key that uses as connection between sprockets and shaft. The detailed design of the elbow shaft is given in figure 12.

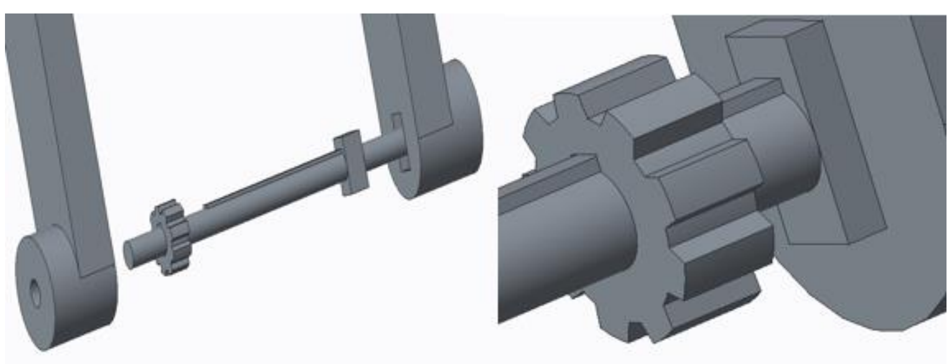
Fig 12: Elbow shaft connection to links

Wrist control: The design of the wrist involves using three bevel gears to control wrist roll and pitch movements, support for the servo motors, and links for smoothly transferring force and torque. The design of the wrist needs two side mounted servo motors that are connected to two side bevel gears. The third bevel gear is connected to the gripper. Figure 13 shows the movement of the third gear that has roll and pitch movements if two side bevel gears rotate in the same direction and opposite directions, respectively.

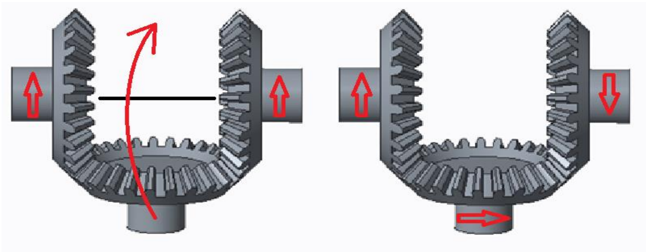

Fig 13: Pitch and roll motions using bevel gears

Additional design choices are assumed in order to simplify the gear train structure and resulting calculations. The size is assumed to have a 1:1 gear to pinion ratio, resulting in equivalent dimensions among individual gears. Also, a pitch cone angle of 45 degrees is selected, granting a 90-degree intersection between gear axes and further simplifying some calculations.

Figure 14 shows a revised design so that a supporting mount is added, and all bevel gears are modified to permit structural reinforcement of the gripper assembly. This structural unit would also allow the gripper's worm gear system to provide and receive additional support from other members of the manipulator. The servo motor unit that controls the worm gear will be mounted to the top of this support piece, and space has been assigned for the motor's wheel to rotate freely of the motor itself. This allows the worm gear to rotate somewhat independently of the bevel gear assembly.

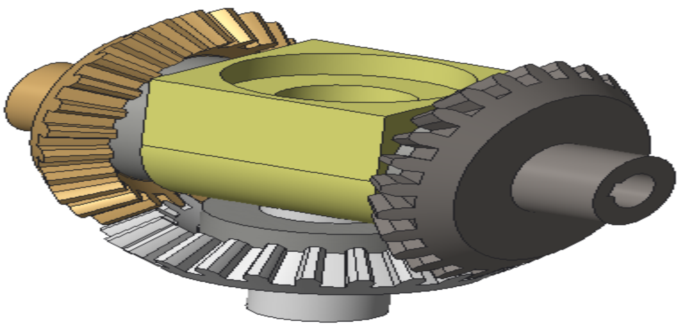

Fig 14: Bevel gear and bracket with spacers

The parts are further developed to allow structural support for the servo motor that controls the worm gear, restrict the physical rotation of the motor itself and allow all power transmission to the worm gear (Figure 15).

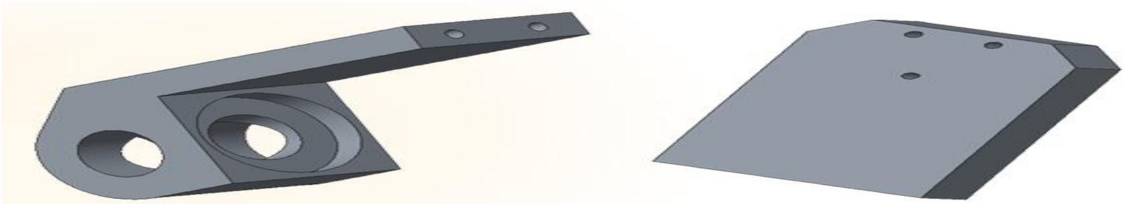

Fig 15: Bracket Structures

Gripper Design: Figures 16 shows the components of gripper and gear assembly.

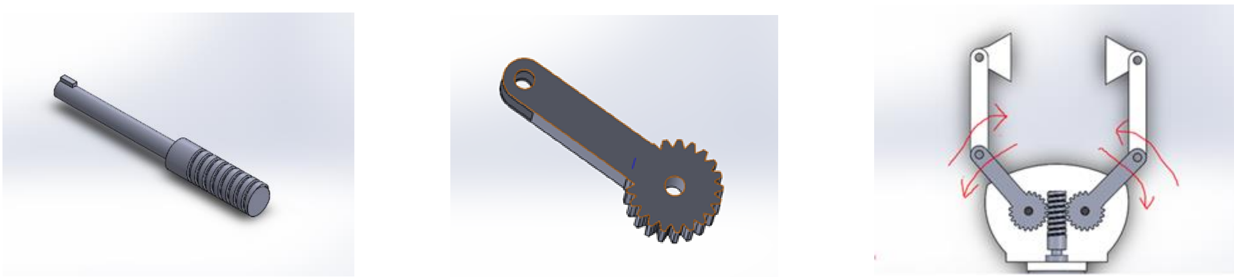

Fig 16: Gripper components

Many factors must be considered for the spur gear and worm to mesh properly, such as the diametrical pitch, pressure angle, and tooth profile. The diameter of the worm and spur gears cannot exceed two inches; therefore, the diametrical pitch is calculated based on these geometrical restraints. Mechanical fastening is required to ensure proper transmission of axial rotation between servo motor interfaces and various bevel gear trains. Shafts that are intended to provide such transmissions are modified with keys, while matching gears are fitted with keyways whose dimensions matched. Figure 17 demonstrates one of the simpler keyed joints, between the bevel gear train system and motor plate axes. Figure 18 shows the wrist and gripper with attached servo motors.

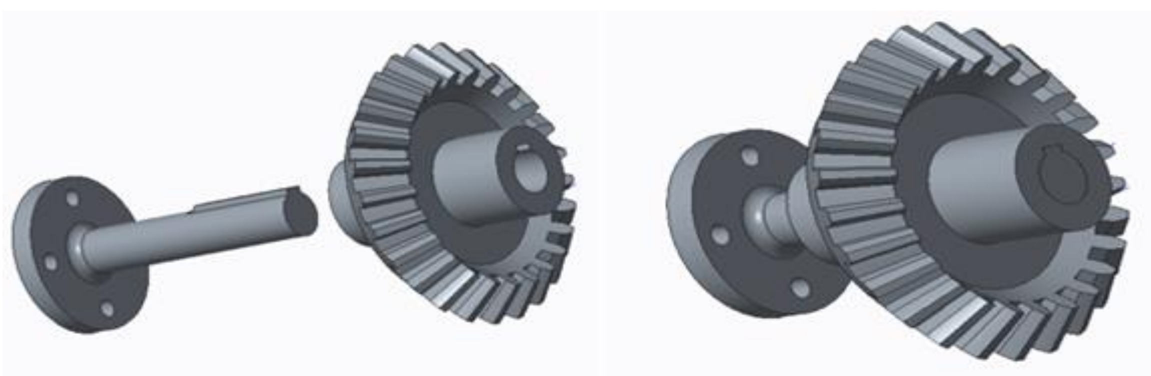

Fig 17: Keyed joints between bevel gear train and motor plates

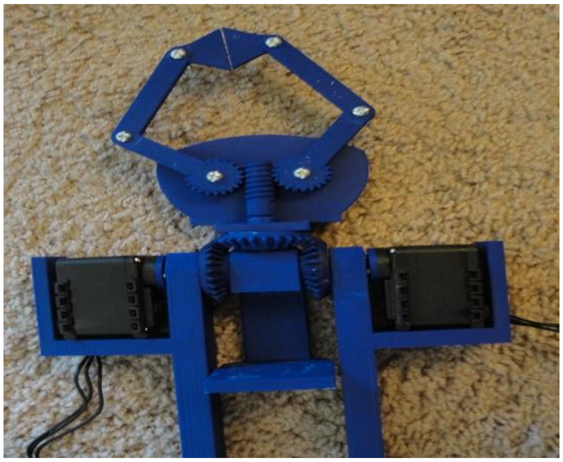

Fig 18: Final design of gripper

Figure 19 shows completed manipulator assembly that is tested to ensure proper rotation of all the parts, as well as the overall stability of the manipulator and its movement efficiency within its expected 3D working envelope.

Fig 19: Completed assembly (Unpowered)

<u>Programming the Servo Motors</u>: In order to communicate with computer and programs to be written into the memory, the Dynamixel servo motor needs CM-700 sub board and CM-700, a control module type with a CPU. The control board and program of the base servo motor are shown in figures 20 and 21.

Fig 20: Control board and servo motors

```
START PROGRAM
{
    ID[4]: Goal Position = 512
    ENDLESS LOOP
    {
        CALL Base
    }
}
FUNCTION Base
{
    Timer = 1.024sec
    WAIT WHILE ( Timer != 0.000sec )
    ID[4]: Goal Position = 1020
    Timer = 1.024sec
    WAIT WHILE ( Timer != 0.000sec )
    ID[4]: Goal Position = 520
    Timer = 1.024sec
    WAIT WHILE ( Timer != 0.000sec )
    ID[4]: Goal Position = 0
    Timer = 1.024sec
    WAIT WHILE ( Timer != 0.000sec )
    ID[4]: Goal Position = 516
}
```

Fig 21. A sample of programming the servo motors

Assessment of project

This project requires students to utilize their knowledge and skills as well as demonstrate the level of learning stated on the ABET-ETAC student learning outcomes. The project can be used as a direct assessment method to validate student outcomes and evidence of what students have learned from the curriculum. The students presented this project to faculty members in the Engineering Technology program. They used a rubric to assess how students performed each task and measured their competencies against students learning outcomes. The assessment results were reviewed by the faculty, who mentored the students.

Conclusion

This project provides step-by-step procedures to develop a relatively inexpensive educational robot manipulator that can be easily constructed using a 3D printer and simple programming interfaces. Analytical calculations for appropriate sizing of the belt, sprockets, gears, and other components as well as the power transmission led to an increased efficiency of the manipulator.

References

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