Design and Control of an Automated SCARA Robotic Arm with a Pneumatic Soft Gripper

Pranav V K¹,², Nitheesh Kumar G¹, Yadukrishnan V¹, Krishnanand Anil¹, Ghanashyam S¹, Amal Prakash¹, Anikesh Rajendran¹ and Pramod Sreedharan¹

¹Department of mechanical engineering
Amrita Vishwa Vidyapeetham,
Amritapuri, India
²pranavvkumar21@gmail.com

Abstract. The paper focuses on the design, analysis and control of an automated 3 DOF SCARA robotic manipulator with an end effector made of asymmetric flexible pneumatic bellow actuator (AFPBA). The manipulator is made for use in the poultry industry and therefore tested in its ability to detect, pick and place eggs. The links of the manipulator are made using acrylonitrile butadiene styrene (ABS) and the end effector is made using nitrile rubber. A neural network derived from the VGG-16 and YOLO architecture is then implemented to detect and localize eggs. The predicted values were then used to calculate the inverse kinematics of the manipulator.

1. Introduction
Soft robotics is one of the most emerging subjects in the present world in the field of industrial robotics. Development of soft grippers has started in late 90s [1]. A soft robot is used to interact with environment and objects which is difficult for a hard robot to interact with [2]. The compliance of the soft robot makes it safe to interact with sensitive objects such as glass, eggs etc. The adaptability of a soft robot and its ability to interact with sensitive environment also shows its potential to be used for surgical assistance [3]. Due to their compliant nature, control of such robots becomes hard. Due to this reason, whenever possible, the softness of the robot is restricted to certain parts of the robot. An example of this would be the end effector of a soft robotic manipulator. Since the end effector is the only part of the manipulator that directly interacts with the environment, making the rest of the manipulator hard would make it easier to control with affecting its performance.

Engineers have designed robotic manipulators to do work that humans find dull, dangerous, difficult and dirty. Although these manipulators resemble human arm, they do not possess the mobility of a human arm. The simplest kind of robotic manipulator uses three prismatic joints to interact with its surroundings. These manipulators have limited work envelope. An articulated robotic manipulator uses three revolute joints to acquire a bigger work envelope compared to other manipulators. The most common kind of robotic manipulators used in industries for pick and place, welding tasks is Selective Compliance Assembly Robot Arm (SCARA). This project utilizes a SCARA robot for achieving high precision pick and place task [4].

In a market analysis we conducted in 2019 at Namakkal district of Tamil Nadu, also known as the “egg city of India”, we found that weighing and palletizing eggs is a time consuming and laborious task. During the study at RDS egg distributors, one of the biggest distributors in the district, we found that the process cost around $4585 every month. Using a SCARA robot with a soft gripper would be...
able to handle the careful handling of eggs at a faster rate than manual human labor. The robot uses inexpensive components and has low number of moving parts. This brings down the cost of production to around $2718. The paper discusses the design and control of a SCARA robot with a pneumatic gripper made from an AFPBA which is a type of pneumatically controlled soft actuator.

2. Related Works
In 2010, Ganesha Udupa et al designed an asymmetric flexible pneumatic actuator that works opposite to the way a bourdon tube works [5]. This actuator consists of a tube where the hole is slightly shifted from the centre. This creates a bending moment which causes the actuator to bend. This idea was originally developed by Joseph L McKibben and was known as pneumatic muscle actuator. Ganesh Udupa et al, in 2014, developed a soft gripper using AFPBA using silicon rubber which was able to pick and place light objects [6,7].

In 2017, Mata Amritandamayi et al designed an anti-bourdon tube pressure gauge [8] which proved to be reliable and economical. The study of the effect of changing material on the flexibility of the actuator [9] was studied by Rachkonda Praneeth et al and found that using nitrile rubber gave more deflection compared to using plastic AFPBA. In 2018, Mata Amritandamayi used AFPBA to develop robotic hand for prosthetic application [10]. In 2019, designed force control system for the pneumatic actuator [11]. In 2020, we analyzed different cross sections, corrugations of bellows and eccentricity to find the optimal values for an AFPBA [12]. We were also able to build and test a SCARA prototype using poly lactic acid (PLA) which employs a gripper made using AFPBA [13]. The manipulator used image processing to detect individual eggs. Proximity and force sensors were also used to detect slippage. The manipulator was able to safely pick up to 200 grams without slippage.

3. Design and Material Selection of the Manipulator

3.1. Material Selection
3.1.1. Material of the Manipulator. For the purpose of making the links of the prototype of the manipulator, the idea was to select a material that was cheap and easily available but also light, strong and durable enough to serve the purpose of the project. Different materials such as steel, Aluminium, PLA (polylactic acid) and ABS (Acrylonitrile Butadiene Styrene) were good candidates for making the prototype. ABS ‘Table 1’ was then selected as it was tougher and heat resistant compared to PLA. Manufacturing was also easier compared to Aluminium and steel making it a good choice for building the manipulator. The drawback of using ABS is that it is less stiff compared to other materials but the deflection under load negligible according to the analysis performed.

3.1.2. Material of the End Effector. Nitrile butadiene rubber (NBR) ‘Table 2’ was used for molding the bellow actuator. The advantage of using this particular choice of rubber was that it was economical, easily available, durable, strong yet flexible enough to give a good amount of bending.

| Property       | Value          |
|----------------|----------------|
| Density        | 1000 Kg/m³     |
| Tensile Strength | 6.89-24.1 MPa |
| Elongation     | 650%           |
| Young’s Modulus| 4 MPa          |

| Property       | Value          |
|----------------|----------------|
| Density        | 1040 Kg/m³     |
| Tensile Strength | 41.4 MPa     |
| Elongation     | 0.15-100%      |
3.2. Design of SCARA

3.2.1. Base of the Manipulator. The design of the SCARA was modified to reduce the weight of the manipulator near the end effector. A SCARA robot typically has its prismatic joint near the end effector. The modified design features the prismatic joint at the base of the robot. The prismatic joint is actuated by a lead screw attached to the base flange bearings. Guide rods were employed to maintain stable motion ‘Figure 1’.

The lock nut of the lead screw attaches onto the 2nd link. The third link and the second are connected by a thrust bearing. The second link houses a stationary gear and the third link houses the motor with the pinion. Since the gear on link 2 is stationary, when the motor rotates, it causes link 3 to rotate. The 4th link is attached to the 3nd link by a bearing placed below the shaft of the gear in link 4 used for actuating the link.

![Figure 1. Design of the SCARA robot.](image)

3.3. Design of the End Effector

From previous studies [12] on the effectiveness of asymmetric flexible pneumatic actuator we have been able to conclude that the semicircular cross-section combined with semicircular corrugation provided the maximum stable bending at an eccentricity of 0.87 ‘Figure 2’ parameters of the end effector has been provided below ‘Table 3’. The operating pressure of the actuator 5 bar and provided a deflection angle of 32 degrees. Further testing of the gripper after manufacture showed that it was capable of lifting up to 200grams without slippage.

![Figure 2. Design of the end effector.](image)

| Parameters                              | Value  |
|-----------------------------------------|--------|
| Total length                            | 115 mm |
| Diameter of actuator chamber            | 4.5 mm |
| Total height                            | 12 mm  |
| Length of actuator                      | 100 mm |
| Number of corrugations                  | 12     |
| Corrugation Diameter                    | 4 mm   |
| Width                                   | 12 mm  |
4. Analysis

4.1. Structural Analysis

The structural analysis of the SCARA and its end effector was done using Ansys ‘Figure 2, 3 and 4’. The analysis was done with the meshing parameter set to fine to provide smaller nodes. The analysis was done separately for each body and was given a load of 2kg at the end of link 4, which is 10 times the weight of the object that the actuator can grip without slippage. At this weight the max deformation occurred in link 4 which had a maximum stress exceeding its yield strength ‘Table 4’. Since the deformation had a value of 5mm given the factor of safety of 10, the design can be approved for manufacture.

| Component Name | Max stress in component | Max deformation in component | Yield strength of component |
|----------------|------------------------|-----------------------------|-----------------------------|
| LINK2          | 2.494×10⁵              | 1.129×10⁻⁷                  | 4.14×10⁷                    |
| LINK3          | 1.837×10⁵              | 2.346×10⁻⁷                  | 4.14×10⁷                    |
| LINK4          | 6.686×10⁷              | 5.300×10⁻³                  | 4.14×10⁷                    |

4.2. Kinematic Analysis of SCARA

Kinematic analysis was employed by using Adams and roboanalyzer. The model designed in Solidworks was exported to Adams to verify the links and constraints provide and to verify the motion of the manipulator. We have employed the Denavit-Hartenberg method for assigning the coordinate frame to obtain the homogenous transformation matrix for forward kinematics ‘Table 5’. Trigonometry was employed to perform the inverse kinematics of the manipulator.

| Joint no | Joint type | Joint offset | Joint angle (theta) degree | Link length (a) cm | Twist angle (alpha) degree |
|----------|------------|--------------|----------------------------|--------------------|---------------------------|
| 1        | Prismatic  | Variable     | 90                         | 0                  | 0                         |
4.3. Torque calculations

The torque required for raising and lowering of the second link using the lead screw was required for the selection of appropriate motor. The load to be lifted will not be more than 2 kg (the weight of links 2, 3 and 4 along with the weight of the payload). Providing a factor of safety of 5, the calculation was done on a load of 10 kg. The calculation was done using the formula –

\[
\text{Torque (raise)} = \frac{F \times Dm}{2} \times \frac{(L+u \times \pi \times Dm)}{(\pi \times Dm - u \times L)}
\]

\[
\text{Torque (lower)} = \frac{F \times Dm}{2} \times \frac{(L-u \times \pi \times Dm)}{(\pi \times Dm + u \times L)}
\]

Where,
- \(F\) = Load applied = 10000N
- \(Dm\) = mean diameter = 12mm
- \(L\) = lead = 5mm
- \(\pi\) = 3.14
- \(u\) = coefficient of friction = 0.1

Torque (raise) was determined to be 0.141Nm and torque (lower) was determined to be 0.0198Nm

From stepper motor NEMA17 whose torque ranges from 0.2Nm to 1Nm was chosen as the motor for the base using this calculation. Since NEMA17 occupies less space all the while provides a good amount of torque, it was used for the other revolute joints as well.

5. Control System

The robot utilizes a neural network for egg detection and localization. Python has been used to implement the network control system. The processed x and y coordinates of the egg in the image are used to calculate the joint angles. The predicted angles are then relayed to an Arduino mega which uses LN298N motor drivers for controlling the servos.

5.1. Network for Egg detection and localization

This network is derived from the VGG-16 network [14] and you only look once (YOLOv1) object detection algorithm [15]. The input consists of images of shape 400x400x3 and predicts an output of shape 13x13x5. Therefore, each image is split into a 13x13 grid and each cell outputs the following predictions – probability of the center of an egg being in the cell (Pc) ‘Figure 6’, the X and Y coordinates of the center as a fraction of the size of the cell and the width and height a fraction of the image. Since the network only classifies one object, anchor boxes are not used and only one prediction is made per cell. The output then goes through a filtering process which selects cells with high probability. Non max suppression is then used to further filter the output ‘Figure 7’. The x and y coordinates are then queued for calculation of joint angles. The training of this network utilized 1258 images split into a training and test of 1048 and 210 images. The algorithm is then run for 180 epochs till a stable test loss is obtained ‘Figure 8’.

![Figure 6. Probability matrix for same input.](image-url)
5.2. Calculation of joint angles
The maximum x and y distance in the scope of the image are measured and the distance covered by each pixel in an image is calculated. The pixel coordinates are then converted to actual coordinates of the egg where the centre is the centre of base of the manipulator. The formulae for calculating the joint angles are then used and the calculated values are sent to the microcontroller for actuation of the motors. Zero error should then be manually corrected for accurate motion. The following equations were used to calculate the joint angles –

$$D = - \frac{(x^2+y^2 - (L3^2 + L4^2))}{2 \times L3 \times L4}$$  \hspace{1cm} (3)

$$\Theta_2 = \arctan2(D, (1 \pm D^2))$$ \hspace{1cm} (4)

$$\Theta_1 = \arctan2(x, y) - \arctan2(L3 + L4 \times \cos(\Theta_2), L4 \times \sin(\Theta_2))$$ \hspace{1cm} (5)

Where,

- x, y – position of the egg on the conveyor
- L3, L4 – length of link 3 and link 4
- \(\Theta_1\) = angle between link 1 and link 2
- \(\Theta_2\) = angle between link 2 and link 3

6. Conclusion
The SCARA robot’s base was designed such that the load on the motor would be minimized thus improving its reliability as well as durability. By providing gears, the motor load is significantly reduced and yields greater accuracy. The analysis the design was done and the finalized design was selected after going through many designs for optimum output, and manufacturing ease. The SCARA robots’ base was designed such that the load on the motor would be minimized thus improving its reliability as well as durability. The designed network provided a test loss of 0.0011 and was very close to the train loss. The processed output gave accurate and reproducible results. The change in the control system also helped handle the task of multiple object detection.

7. References
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