OPTIMIZATION OF REGULAR PICK AND PLACE TASKS VIA PARALLEL MANIPULATORS AND MODELLING

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ABSTRACT

Small-scale product handling industries are at the cusp of increasing their efficiency and effectiveness, where optimization is largely a considerable factor. Though regular pick and place tasks are nonvalue added steps, they can replace expensive manual labor and thereby increase efficiency by reducing idle times. Hence, this paper discusses the optimization of regular pick and place tasks using parallel manipulators. By evaluating alternative manipulators, the 3-link parallel manipulator which is the delta robot was taken for presenting the model given in this paper. A simulation and a real-time operation were conducted for comparison of 2 designs of the delta robot, in relation to the robot workspace and the component stress-strain analysis. The robot kinematics were derived to define the robot workspace and for the dimensions of the mechanical components which were equally designed and tested. Fabricating was done using lathe machining and 3D printing. The servo and visual systems were decided accordingly for the generalized pick and place application. Control and functionality with the input visual system and kinematics model were mapped and generated in a programming platform and were transferred to the controller in order to drive the motors of the manipulator. This makes the robot end effector activate and perform the picking and placing using the solenoid gripper. An accurate result in object detection, mapping, picking, and placing by the delta robot is thereby achieved which is presented in the paper. The presented model is feasible to be used in an industry which can accommodate regular pick and place tasks. An example application would be picking and placing screws as mentioned in the paper.

KEYWORDS: *Delta robot, Visual-servo system, Workspace, Pick and place, MATLAB®*

1. INTRODUCTION

The requirement for automation is in the verge of being an industrial necessity due to various challenges faced by modern day industries. Labor shortage, complex customer orders, cost of labor, idle times, inaccuracies, and compliance standards are a few instances that promote the need for automating various processes in a regular production flow. Automating the task of pick and place products from assembly lines shares a common interest in multiple industries mainly due to it being a nonvalue added task and with no direct effect to the quality standards of the production.

Different industrial manipulators with the required DOF are quite sufficient to handle the demanding tasks of the industry. The current automation solutions of utilizing robotic manipulators to achieve this task consist of major drawbacks such as space limitations, energy consumption, speed, and feasibility to cooperate with workers. However, the recent advancement of parallel robots has shown greater potential for finding better solutions to this problem.

Because parallel manipulators are of higher precision, stiffness, dynamic capacity (due to closed links), lower maintenance cost, efficiency in attaining higher accelerations (due to lower inertia), and lower space taken up in comparison to serial robots for pick and place applications. Some of these have also been discussed from comparisons in the review paper [1]. Furthermore, the trade-off as per the requirement for a series robot manipulator is mostly not viable for industries with small scale product categories mainly due to the aforementioned factors.

The above challenges were the main motivation for this study on optimizing general pick and place tasks commonly available in the small-scale product category industry. Pick and place objects on a moving conveyor, which is a commonly seen application, has been selected. The task was to detect the object via a web camera through image processing and to pick and place the item accurately with a considerable speed of operation. The proposed method with mathematical modeling also considers planning minimum cost paths.

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The main objective was the designing and development of a prototype of a parallel robot manipulator for optimizing a regular pick and place task with the implementation of a visual servo system for detecting and mapping the objects. Furthermore, testing and validating the proposed model for a generalized regular pick and place task was done using the developed prototype. Additionally, the comparison of the two designs was done to minimize the manipulator workspace for more compact and limited space requirements. These results and comparisons are presented in Section 5 of this paper.

2. LITERATURE REVIEW

A design has been proposed in [2] for a 4-DOF delta robot in SimMechanics environment of MATLAB software, by studying the performances of the Sliding Mode Control (SMC) mechanism and the PID control based on the Inverse Kinematic Problems (IKP). A simulation study of optimizing for delta robots is given in [3]. That is for the improvement of pick and place route based on lame curves to smooth the right angles of transitions. Thereby they have established the overall trajectory in the cartesian plane with good performance in comparison to the virtual prototype in ADAMS software and MATLAB. An algorithm for the forward kinematics method with one root for delta robots is given in [4] where the conventional method is to solve forward kinematics by 3 sphere method and find the intersection point out of which one is selected. But their calculation algorithm, only one solution is given. They have verified the method, by doing an analytical substantiation and a numerical experiment with the results obtained. The thesis [5] describes the modelling of the kinematics and forward dynamics for the IRB340 FlexPicker parallel robot and the implementation control through software and hardware by the B&R Automation company. A new approach has been utilized in [6] to design a delta robot with the desired workspace by using a technique known as inscribed workspace. Two kinematics calibration models have been proposed in [7] and it shows that the accuracy of the parallel robot can be improved by means of calibration. The mechanical development, kinematic analysis along with simulation for the training of the delta robot Caertec rk 2010 have been proposed in [8] using CATIA software. A vision servo-based delta robot was developed [9] to pick and place objects on a moving conveyor with a vacuum suction clamping method where Canny and Sobel edge detection methods was used for object recognition in a C++ based program. By the proposed algorithm, only when the object is fully present in the screen, the coordinates of the object is calculated and communicated to the delta robot via TCP/IP protocol. The fundamentals and mathematics for modelling series and parallel robots given in [10] and [11] describe the manipulator DOF, parallelogram theory for closed chains robots, and the manipulator forward inverse kinematics and dynamics.

3. EXPERIMENTAL DESIGNS

Through comparison of serial and parallel robots, another comparison was done to select 3-link parallel manipulators among 2-link and 4-link manipulators. The 3-link delta robot satisfied the minimum requirements to complete a regular pick and place task with 3-DOF for X,Y, and Z translation. Based on this, a further study was done to improve the optimization and workspace of delta robot.

To optimize in relation to workspace, conceptual designs were created with a new configuration by altering the motor orientation relative to the base plate. Motors were placed parallel to the tangent of the circumference of the base plate as shown in Figure 1 (a). The other design is where the motor is mounted so that the arm is perpendicular to the circumference of the circle, which is shown in Figure 1 (b). In both the designs, the motor shafts were placed at 120° apart. This is considered the standard configuration of the delta robot. Both configurations were fabricated to implement real-time kinematics along with manipulator workspace simulation for the end effector and for the 3 robot arms.

Figure 1: Design 1(a) Design 2(b)

The unique advantages and disadvantages of each design are presented in Section 5.

4. SYSTEM OVERVIEW

The specific application selected was, pick and place screws through a vision-based system which additionally requires an operation of sorting based on the color or size of the screw or both. The presented system uses a direct operating solenoid as the gripping mechanism. Sections mentioned under A, B, C, D, and E discuss the phases followed in developing the model.

A. Modeling of Parallel Manipulator

In pick and place, the delta robot changes its 3 motor parameters to move the end effector to the desired position where either the angles of the motors or the coordinates of the end position are to be decided. In inverse kinematics, if the desired position is known, the motor angles can be generated. In forward kinematics, if joint angles are known, the end effector position can be generated. One general observation is that for serial chains or open loop configuration robots, the forward kinematics is generally straightforward while inverse kinematics may be complex and for parallel mechanisms or closed loop configuration robots, the inverse kinematics is generally straightforward while forward kinematics may be complex.

The calculations required to determine the manipulator kinematics and motor torques were done based on the design criteria. A thorough calculation of the forward and inverse kinematic, and dynamics regarding parallel robots and series robots were studied and compared. The forward and inverse kinematic model given in [12] was referred in building up the inverse kinematics model. These kinematic model parameters and dimensions of the design were simultaneously taken into account when determining the most practical design parameters.

B. Design Specification and Simulation

Evaluation of alternative serial and parallel robots was done and conceptual designs were brought up prior to finalizing on design specifications. By designs 1 and 2, a calculation procedure was followed to arrive at the final machine designs. The calculations and the simulated material analysis acquired the final design parameters and verified if the design system can withstand all loads and deformations acting on the design parts. The material stress analysis, bending moment analysis, and twist analysis for components were done prior to selecting material and with the availability of materials, aluminum was selected as the most suitable material for almost all components. With the obtained designed values, 3D modeling and product simulation were done. The components were drawn partwise and assembled to form the required design which has given a visual representation of the system designed. A motion study was performed to depict the complete motion of all the components of the system.

After finalizing the structure of the base plate and the type of rod end ball bearings, the length of the robot arms and links were decided according to the required workspace of the robot. The required workspace of the robot was decided upon the requirement of the application. Accordingly, it was decided to come up with the following workspace of the robot in the 3 axes to suit the requirement: X: -135 mm to 135 mm, Y: -135 mm to 135 mm, and Z: 600 mm to 300 mm. Using the kinematics models with the above values, the length of the arm and link (forearm) was designed: Length of the arm = 200 mm and length of the link (forearm) = 450 mm. The intermediate shaft used to join the arms with the links was designed to be 6 mm in diameter and a length of 70 mm, to suit the bearing shell. The base plate was decided according to the design proposed in the preliminary design and its diameter was chosen in a way that it can comfortably accommodate the 3 motors chosen. Finally, it was decided to design the base plate with a diameter of 300 mm and 6 mm thickness. 3 motor brackets to hold the motors were also designed. A structure was designed to hold the whole robot vertically.

C. Fabrication

After finalizing the design parameters and dimensions, the fabrication of the project was initiated part by part. The robot base plate, 3 robot-arms of 200 x 6 x 4 mm (l x b x h), 6 robot-links (forearm) of 6 mm diameter, motor brackets of 3 mm thickness, and 6 intermediate rods of 10 mm diameter and 70 mm length were fabricated in aluminum. The three arms were drilled with holes of 6 mm diameter for the intermediate shaft to pass through. The other end of the arm was drilled with 5 holes with a diameter of 3 mm to hold the motor coupling. Threads were made in robot-links (forearms) on both ends to a suitable length to attach the rod end ball bearings. For the base plate, a set of 4 holes each were drilled 120 degrees apart at the edge of the plate for smooth, fast, and error free operation of the robot. Finally, the end effector was 3D printed using Polylactic acid (PLA) polymer which is light weighted and even has high strength. The end effector holds the object and also performs the required task. The delta robot end effector, holds all the 3 links together at the ends or from the corners of the end effector as it is shaped similar to an equilateral triangle. The appropriate electromagnetic gripper for the end effector was selected for the application.

The mounting structure is used to hold the manipulator in place for its functioning. The main consideration of it was that the mounting structure needed to be designed to withstand the jerks and inertial effects caused by the movement of the links. As per the requirement, it needed to be portable and withstand the movements of the robot. It was designed and fabricated using 1.5 x 1.5 inch aluminum box bars. This cuboid structure comprised the dimensions of (65 x 65 x 70 cm) (l x b x h) and had extra two cross bars at the top to mount the robot. Finally, the fabricated components were assembled with the camera module mounted to the mounting structure and the solenoid gripper was attached to the middle of the end effector for the completion of the delta robot.

D. Image Processing

For the image processing task, a web camera with 720p resolution with 30 fps and as per the required specifications a minimum of 60° viewing angle was selected. The camera input is taken directly to MATLAB for image processing. Initially, surf features were used to detect the object. However, according to the experiments done, the surfing feature was not strong enough in identifying the same object among other objects and mixed up the relative points. Hence, the color of the object was taken as the next approach with the use of color thresholding tools. A lab color scheme was used for this, and it was successful in identifying the object based on its specific color.

To move the end effector, the system requires the location of the object. The robot was programmed to locate the center of mass based on the area of the image with the given color. The web camera connected to the system sends a 640 x 480 pixel frame from the video output to the model for detecting and locating the object. The model calls another function for processing the above-mentioned task and the output video stream is given from another function model. The frame was mapped to the physical dimension of the manipulator working area via a predefined scaling. The images were converted from RGB to Lab color scheme images for further processing. Locating this object was done through blob analysis technique for computing information for connected regions using computer vision system tools by creating a persistent variable. Hence initial steps were the trial sessions done for object detection.

For the application, to detect screws of varying lengths, morphological operations were used. The RGB image was first converted to binary. This image was then subjected to morphological erosion and dilation through the construction of a structuring element. The number of screws laid was correctly detected. All the object detections were done by capturing a snippet of the video stream. Finally, the center points of the screws and the length of each of the screws were obtained accurately from this procedure. The programmed model showed the exact x and y locations of the center of the object in pixels. The pixel coordinates were then mapped to the real x and y coordinates of the plane. With the increase in resolution of the image, a more accurate object locating can be done. The GUI (Graphical User Interface) shown in Figure 2 explains the centroid of the object in pixels as well as the converted value in meters via the mapping. These coordinates were then passed on to the kinematics model for generating the motor angles.

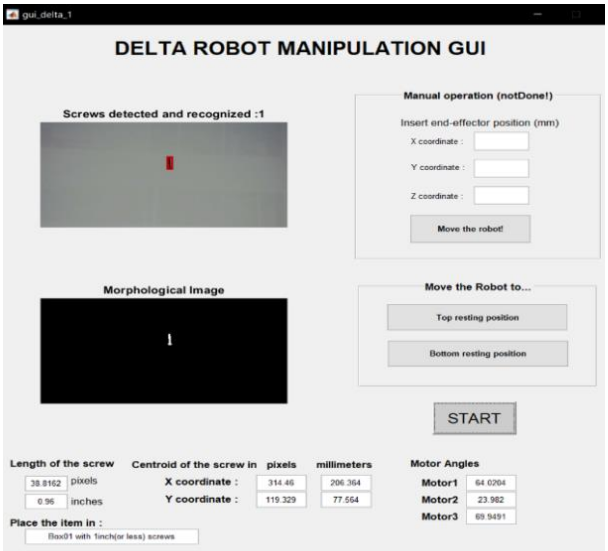

Figure 2: Graphical User Interface (GUI)

E. Control and Functionality

Position based and Model based control methods are the two available control strategies for robotic manipulations. In position-based control, each joint is separately considered in motor controlling whereas in model-based control the complete system dynamics are considered. Therefore, the model-based controller yields higher positional accuracy without the use of additional sensors. By considering the computational capacity of this process, the following physical components were required: PC, Microcontroller, Motor Driver, and software for programming and controlling. As initial testing, Robot Operating Software (ROS) was used as the communication medium for MATLAB and the Arduino controller. The image processing and kinematics are done by taking the input of the camera to the model and the generated motor angles are next passed on to the controller where the motors are connected via motor drivers.

The kinematics model given in [7], [13], and [14] was referred for controlling this robot as in our previous work [15]. The mathematical model for inverse kinematic computation utilized the robot dimensions and the characteristic features: robot arms (L) and base plate revolute joints relative to the fixed base plate, revolute joints relative to the end effector, and the end effector location relative to base plate {x,y,z} were taken to derive the vector loop closure equation for the delta robot. Eventually, the kinematic equations for the legs of the delta robot were derived.

These are the intersections of 3 spheres of radii of the length of links and arms in the geometrical aspect.

Where,

SB = radius of the base plate and, In an equilateral triangle of the end effector, where revolute joints are at the edges:

VE = distance from the reference point of the end effector to a vertex,

ES = side length of the equilateral triangle,

SE = distance from reference point of the end effector to revolute joint, where

$a = SB - VE$ Equation 01

$b = (ES/2) - (\sqrt{3}/2)\,SB$ Equation 02

$c = SE - (1/2)\,SB$ Equation 03

$$2L(y + a)\cos\theta_1 + 2zL\sin\theta_1 + x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2 = 0 \quad \text{Equation 04}$$

$$-L(\sqrt{3}(x + b) + y + c)\cos\theta_2 + 2zL\sin\theta_2 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 + 2xb + 2y - l^2 = 0 \quad \text{Equation 05}$$

$$L(\sqrt{3}(x - b) - y - c)\cos\theta_3 + 2zL\sin\theta_3 + x^2 + y^2 + z^2 + b^2 + c^2 + L^2 - 2xb + 2yc - l^2 = 0 \quad \text{Equation 06}$$

Hence, the three independent scalar inverse position kinematics are of the form,

$E\cos\theta_i + F\sin\theta_i + G_i = 0$ Equation 07

Where,

$E = 2L(y + a)$ Equation 08

$F = 2zL$ Equation 09

$G = x^2 + y^2 + z^2 + a^2 + L^2 + 2ya - l^2 = 0$ Equation 10

$t_i = \tan(\theta_i/2)$ Equation 11

Thereby, using tangent half angle substitution, the 3 theta values can be obtained for the motor parameters. The prior measurements of extreme values for arm angles avoided singularities.

The weights were calculated through simulation software by giving the proposed material. The simulation was done to examine the motion study of the robot, with weights and gravitational force. This motion study was done for the modelling; the motor torques were calculated. Since servo motors are more precise and accurate compared to stepper motors, a DC servo motor of 20 kilograms per centimeter was selected as the motor for the delta robot.

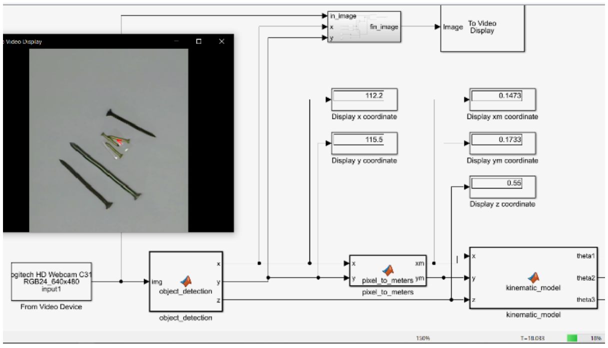

Figure 3: Image processing and kinematics model

F. Testing and Optimization

For testing the system with the mathematical model, the controller facilitated computational capacity and multi-sequential PWM signal generation for the 3 motors in the delta robot were used. Simulations and the fabrication of both designs 1 and 2 were conducted aiming at comparing and generating an accurate motion profile.

Ensuring the reachable area of the robot, the camera is mounted and pointed out to the area where the screws are located. The written program executes image processing and kinematics model to generate the coordinates. This data is then sent to the controller to actuate the motors thereby achieving the picking task by the delta robot as shown in Figure 3. Image processing and predefined locations determine the placement of the object by the delta robot.

The customized GUI created allows some basic operations for the user and to run the algorithm for sorting operations making it more user-friendly. However, this is a feature to which further improvements can be done. The real time captured image used for processing is also shown.

5. RESULTS

Workspace from the ground level of a parallel robot is less compared to a serial type of robot since a parallel robot is mounted from the top. When the system is running, unlike in serial robots, the positional error gets averaged without accumulating in the parallel robot. Parallel robots can achieve higher accelerations and is the ideal system for pick and place tasks when a quicker response is required and also when a limited workspace is available.

As the creation of kinematics code for Design 1 is complicated, workspace simulation was conducted in real time analysis for Design 1 and Design 2. This was due to the complexity of creating the kinematics code for Design 1. Both designs showed similar workspaces.

Table 1. Results from the mathematical model

Description of placement of screws (using 640x480 pixels video stream)	Location in pixels (x, y)	Location in mm (x, y, z)	Computed motor angles		
			ϑ_1	ϑ_2	ϑ_3
On a side of the delta robot	(362.0, 83.0)	(237.6, 53.9, -550)	66.9°	25.8°	78.2°
Underneath the delta robot	(282.6, 125.4)	(185.5, 81.5, -550)	60.9°	23.5°	64.7°
Underneath the delta robot	(314.5, 119.3)	(206.4, 77.6, -550)	64.0°	23.9°	70.0°
Underneath the delta robot	(283.6, 88.4)	(186.1, 61.8, -550)	71.2°	26.3°	81.6°

Design 1 has a better advantage over Design 2 when considering the robot arm workspace, which is the ideal solution for a system that has a limited area for tasks within a limited space, which will cut out lengthy conveyors and the time taken for a process to finish the entire task. But when the robot-end effector workspace is considered, Design 2 is more flexible since that orientation gives the minimum strain on bearings.

From the motion study simulation of both the designs, it was seen that the intermediate rod of Design 1 is affected by an additional force component when in motion. It is the twisting effect that occurs due to the tangential placement of the arms at the base plate as shown in Figure 4.

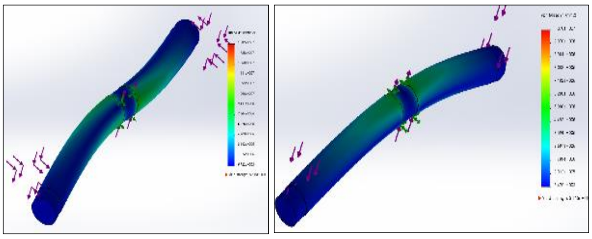

Figure 4: Stress strain analysis of intermediate rod

The amount, lengths, colors and coordinates of the screws and mapping were accurately done using the created image processing model, thereby generating the motor angles via the kinematics model. The results taken through computation of the model are given in Table I. The center of the detected object from the 640 x 480 resolution video stream were taken initially in pixel coordinates. Giving these coordinates to the kinematics model, the dimensions in real physical quantities were mapped in deriving the resulting motor angles given in Table I.

The fabrication and the testing were done according to the method discussed in this paper. This produced accurate results in object detection, mapping, picking, and placing by the delta robot following the sequence of operation mentioned in Figure 5.

6. DISCUSSION

The intermediate rods shown in Figure 4 are passed through the shell of the rod end ball bearings freely. Therefore, once the robot is in operation, the length of all the shafts will not be equal unless fixed. The intermediate shafts started to fall off the bearings and due to the shaft being passed into the bearings functioning. Thereby, more robots can be placed in line within the production system achieving more freely. Hence, intermediate shafts of 10mm diameter were taken and were threaded at the ends to a lesser diameter. By this, it was able to pass through the bearings freely and then they were tightened with a nut to achieve equal length.

The initial decision was to undergo the manufacturing of links using carbon fiber due to its light weight and strength. Due to availability, cost, and fabrication, Aluminum was selected as the alternate material because of its lightweight and strength as shown in Figure 6. However, the material stress analysis, bending moment analysis, and twist analysis done for each component for both carbon fiber and aluminum yielded well above the required value.

Singularities were common at the initiation of the system. Also, the strength of the end effector solenoid should withstand the acceleration of the system.

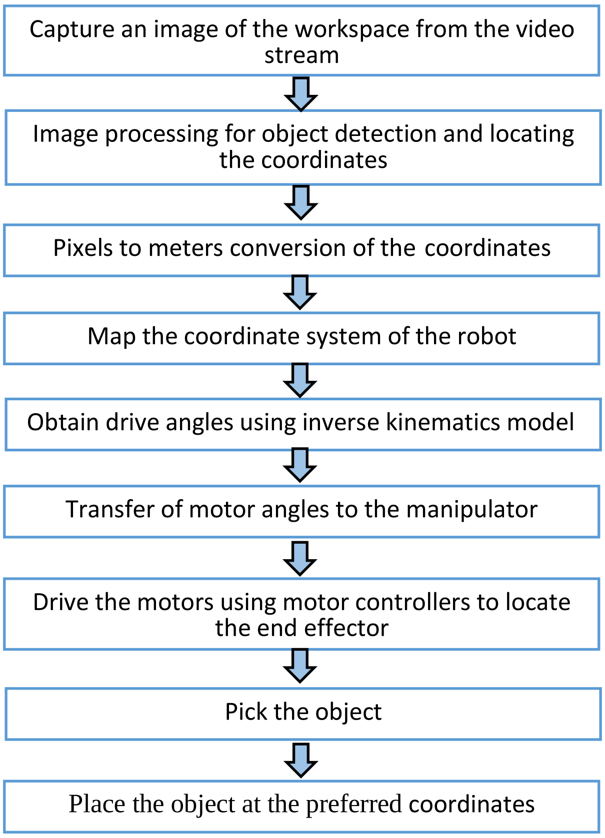

Figure 5: Control Flow

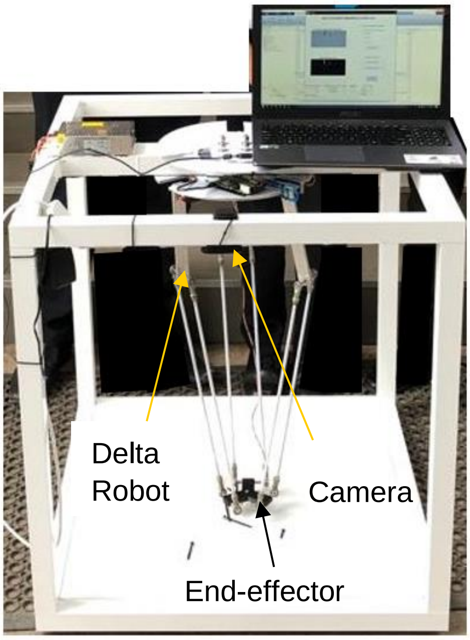

Figure 6: Fabricated, visual servo delta robot for sorting screws

7. CONCLUSION

As of the objective, a prototype was designed and developed by testing and validating to optimize regular pick and place tasks in the industry via parallel manipulators. Together with a comparison of two delta robot designs, with the aim of minimizing manipulator workspace for requirements on space constraints. Since the functionality and the objectives of the prototype model were to their expected level, a scaled-up model is feasible to be used in the industry to accommodate regular pick and place tasks such as stacking, sorting, packing, and palletizing.

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