Optimization of Industrial Manipulation Tasks Using Parallel Manipulators

IM Akarawita#, BGMS Senadheera, HSG Samarasinghe and WSP Fernando

Department of Mechanical Engineering, Faculty of Engineering, General Sir John Kotelawala Defence University, Sri Lanka.

#iakarawita@gmail.com

Abstract— Small-scale product handling industries are at the cusp of increasing their efficiency and effectiveness, where optimization is a considerable factor. Though regular pick and place tasks are nonvalue added steps, it can replace expensive manual labour by increasing efficiency. Hence, this paper discusses the optimization of regular pick and place tasks using parallel manipulators. Out of the evaluations, on alternative manipulators, the 3-link parallel manipulator was of the focus. A simulation and a real-time operation were conducted for the comparison of the two designs in relation to robot workspace. The robot kinematics were derived to define the robot workspace, and for the dimensions of the mechanical components which were equally designed and tested using SOLIDWORKS. Fabricating was done using lathe machining and 3D-printing. The servo and visual systems were decided accordingly for the pick and place application. Control and functionality with the input visual system and kinematics model were mapped and generated in MATLAB, and then transferred to Arduino which drives the motors of the manipulator. This makes the robot end effector to actuate 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. The presented model is feasible to be used in the industry which can accommodate regular pick and place tasks in a facility.

Keywords: *pick and place, parallel manipulators, delta robot, kinematics, workspace, visual servo system, MATLAB*

I. INTRODUCTION

Requirement for automation is in the verge of being an industrial necessity due to various challenges faced by modern day industries. Labour shortage, complex customer orders, cost of labour, idle times, inaccuracy, and compliance standards are few instances which promotes the need for automating various processes in a regular production flow. Automating the task of pick and place products from assembly lines shares 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.

The current automation solutions of utilizing robotic manipulators to achieve this task consist of major draw backs. Recent advancement of parallel robots has shown greater potential towards finding solutions to this problem. Because, parallel manipulators are of higher precision, stiffness, and dynamic capacity due to closed links, lower maintenance cost, efficient in attaining higher accelerations due to lower inertia and lower space taken-up with comparison to serial robots for pick and place applications. Some of these have also been discussed from comparisons by Deshmukh and Patil (2015) in the review paper. Furthermore, the initial and implementation cost for a series robot manipulator is mostly not viable for industries with small scale product categories mainly due to afore mentioned factors.

Above challenges were the main motivation for this project 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 focus was more on the object identification, recognition, picking and placing accurately with a considerable speed of operation. The proposed method also considered optimization on the minimum cost paths.

This paper describes the designing, fabricating and testing of a visual servo based parallel manipulator, and these defined areas concurrently being the main objectives of the project. The application of the parallel robot, was to focus on a generaized pick and place task found commonly in industries, along with a design comparison in order to achieve a minimum manipulator workspace.

II. LITERATURE REVIEW

Azmoun et al. (2018) have proposed a similar design for a 4-DOF delta robot in SimMechanics environment of MATLAB software, by studying the performances of Sliding Mode Control (SMC) mechanism and the PID controlling based on the Inverse Kinematic Problems (IKP).

Chen et al. (2018) have presented a simulation study of optimizing for delta robots. 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 for the virtual prototype in ADAMS and MATLAB. Abduraimov et al. (2017) have proposed an algorithm for the forward kinematics method with one root for delta robots. Where the conventional method is to solve forward kinematics by 3 sphere method and finding the intersection point. Out of which one is selected. But in their calculation algorithm, the solution gives only one. They have verified the method, by doing an analytical substantiation and a numerical experiment with the results obtained. A thesis by Rosquist (2013) describes on the modelling of the kinematics and forward dynamics for the IRB340 FlexPicker parallel robot and the implementation control by software and hardware from B&R Automation. This was referred for the system, mathematical model in this paper. Peng et al. (2019) have studied 35 combinations of the same topology for a linear delta robot, on which they have obtained by changing the dimensional parameters. The kinematics model for all the combinations have been analysed, thereby revealing the coupling relationship between the output parameters of 2 parallel mechanisms. The article by Clavel (1998) have proposed 2 kinematics calibration models an 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 by Bulej et al. (2012) using CATIA software. A vision servo-based delta robot has been developed by Lin et al. (2016) to pick and place objects on a moving conveyor with a vacuum suction clamping method, where they have used Canny and Sobel edge detection methods 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 sent to the delta robot via TCP/IP protocol.

III. EXPERIMENTAL DESIGNS

Through comparison of serial and parallel robots, another comparison was done to select 3-link parallel manipulator 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.

Figure 1. Design 1

Figure 2. Design 2

Hence, conceptual designs were designed 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. The other design is where the motor is mounted so that the arm is in perpendicular to the circumference of the circle, which is shown in Figure 2. In both the designs, the motor shafts are placed at 120° apart. This is considered as the standard configuration of the delta robot. Both configurations were fabricated to implement real-time kinematics. Also, manipulator workspace simulation was done and the unique advantages and disadvantages of each design is presented in Section V.

IV. 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 colour or size of the screw or both. The presented system uses a direct operating solenoid as the gripping mechanism. Sectional headings A, B, C, D and E shows the phases followed in this working procedure.

A. *Mathematical Modelling*

In pick and placing, 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: for serial chains, the forward kinematics is generally straightforward while inverse kinematics may be complex and for parallel mechanisms, it is vice versa.

The calculations to determine the manipulator kinematics and motor torques were done based on the design criteria. A thorough calculation on forward kinematics inverse kinematics, and dynamics regarding parallel robots and series robots were studied and compared. The forward and inverse kinematic model given by Tsai et al. (2016) was referred for building up the inverse kinematics model. The kinematics and dimensions of the design were simultaneously taken into consideration for the simulation and the model, in determining the most practical parameters.

Robot-arms 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. Geometrically, these legs are considered as the intersection of 3 spheres of radii of the length of links and arms of the robot.

Eventually, the 3 contriant equations were obtained deriving the kinematic equations for the 3 legs of the delta robot. Mentioned below is the generalized equation used for the independent scalar inverse position kinematics.

$$A_i \cos\theta_i + B_i \sin\theta_i + C_i = 0 \qquad \text{where } i=1,2,3$$

This equation is further solved by taking A_i, B_i, and C_i as of the results obtained from loop closure equation which also involves dimensions. Thus, deriving the arc tan angles for the 3 individual motor parameters. The singulairties were avoided at the final stage by eliminating the extreme and impossible values.

B. Design Specification and Simulation

Evaluation of alternative serial and parallel robots were done and conceptual designs were brought up prior to finalizing on design specifications. By Design 1 and 2, a calculational procedure was followed to arrive at the final machine designs. The calculations and the material analysis were done to obtain 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 a material and with the availability of materials, aluminium was selected as the most suitable material for almost all components. The analysis done for the robot arm and the robot base plate is shown in Figure 3 and Figure 4. With the obtained designed values, software based 3D modelling was done. The components were drawn partwise and assembled to form the required design, which gave 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 our application. Accordingly, it was decided to come up with the following workspace of the robot in the 3 axes to suite the requirement: X: -135mm to 135mm, Y: -135mm to 135mm and Z: 600mm to 300mm. Using the kinematics models with the above values, the length of the arm and link (forearm) was derived: Length of the arm = 200mm and Length of the link (forearm) = 450 mm. The intermediate shaft used to join the arms with the links was designed to be of 6mm diameter to suite the bearing shell and a length of 70mm. 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 three motors chosen. Finally, it was decided to design the base plate with a diameter of 300mm and 6mm thickness. 3 Motor brackets to hold the motors were also designed. A structure was designed to hold the whole robot vertically.

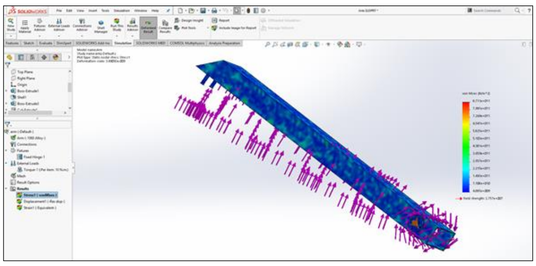

Figure 3. Stress and displacement analysis of magnitude 25N twisting moment on the robot arm

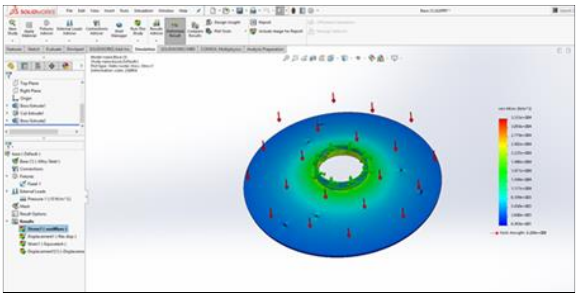

Figure 4. Stress and displacement analysis of magnitude 30N axial force on the robot base plate

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 200x6x4mm (lxbxh), 6 robot-links (forearm) of 6mm diameter, motor brackets of 3mm thickness and 6 intermediate rods of 10mm diameter and 70mm length were fabricated in aluminium. The three arms were drilled with holes of 6mm diameter for the intermediate shaft to pass through. The other end of the arm was drilled with 5 holes with a diameter of 3mm to hold the motor coupling. Threads were made in robot-links (forearms) in both ends to a suitable length to attach the rod end ball bearings. For the base plate, 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 PLA polymer which is light weighted and even has a high strength. 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. As per the requirement, it needed to be portable and withstand movements of the robot. It was designed and fabricated using 1.5x1.5inch aluminium box bars. This cuboid structure comprised the dimensions of 65x65x70cm (lxbxh) and had extra two crossed 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 delta robot.

D. Image Processing

Logitech C310 web camera was selected as per the required specifications of minimum of 60° viewing angle, coloured, a reasonable resolution and with a USB connection. The camera input is directly taken to model for image processing. Initially, surf feature was used to detect the object. However, the points of the image the function acquired was not strong enough in identifying the same object among other objects and mixed up the relative points. Hence, the colour of the object was taken as the next approach with the use of colour thresholding app in available with the software. Lab colour scheme was used for this, and it was successful in identifying the object based on its specific colour.

To move the end effector, the system requires the location of the object. The code was written to locate the centre of mass based on the area of the image with the given colour. The web camera connected to the system sends a 160 x 120-pixel frame from the video output to the mathematical model with the script file for detecting the object and for locating that object. The model calls another function for processing the above-mentioned task and the output video stream is given from another function model. Locating this object was done through the blob analysis technique with the computer vision systems toolbox, by creating a persistent variable.

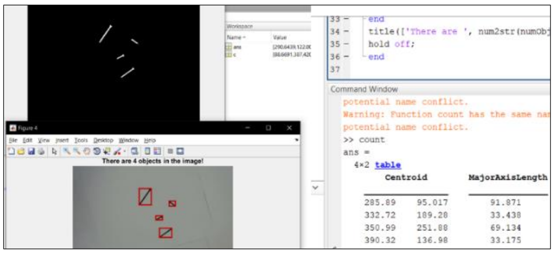

Figure 5. Image processing object detection

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 were correctly detected. Finally, the centre points of the screws and the length of each of the screws were obtained accurately because of this procedure. The programmed Simulink model shows the exact x and y location of the centre of the object in pixels. The pixel coordinates were then mapped to the real x and y coordinates of the plane. The GUI shows the centroid of the object in pixels as well as the converted value in meters. Depicted in Figure 6. These coordinates were then passed on to the kinematics model.

E. Control and Functionality

Position based and Model based control methods are 2 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: Vision Sensor, PC, Microcontroller, Motor Driver and different softwares for the modelling and simulation. Initially, ROS (Robot Operating Software) was taken too for the implementation. The image processing and kinematics have been done in Simulink. The camera is taken as an input to the modeul and the generated motor angles are passed on to the controller where the motors are connected via motor drivers.

The weights were calculated via simulation 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 20kg/cm was selected as the three motors for the delta robot.

F. Testing and Optimizing

For testing the system, a raspberry pi with ROS as an interface was selected as the controller for its better performance. However, as this selected controller lacked both computational capacity and multi-sequential PWM signal generation for the 3 motors in the delta robot, an Arduino controller was used. Which is a more cost effective and a simpler version for the system.

Ensuring the reachable area of the robot, camera is mounted and pointed out to the area where the screws are located. The program written in Simulink, 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. Image processing and predefined locations determines 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 operation making it more user-friendly.

V. RESULTS

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

Table 1. Results obtained from the system

Placement of screws underneath the delta robot (using 640x480 pixels video stream)	Location in pixels (x, y)	Location in mm (x, y, z)	Computed motor angles		
			θ1	**θ2**	**θ3**
	(282.6, 125.4)	(185.5, 81.5, -550)	60.9°	23.5°	64.7°
	(314.5, 119.3)	(206.4, 77.6, -550)	64.0°	23.9°	70.0°

Design 1 and Design 2 were compared in real time analysis and mainly using workspace simulation. This was due to the complexity in creating the kinematics code for the Design 1. Both designs showed similar workspaces. 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 limited area for functioning. Thereby, more robots can be placed inline within the production system achieving more 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, the design 2 is more flexible since that orientation gives the minimum strain on bearings.

The quantity, lengths, colours and coordinates of the screws and mapping were accurately done by using the created image processing code. Thereby, generating the motor angles via the kinematics model. The results are tabulated in Table 1.

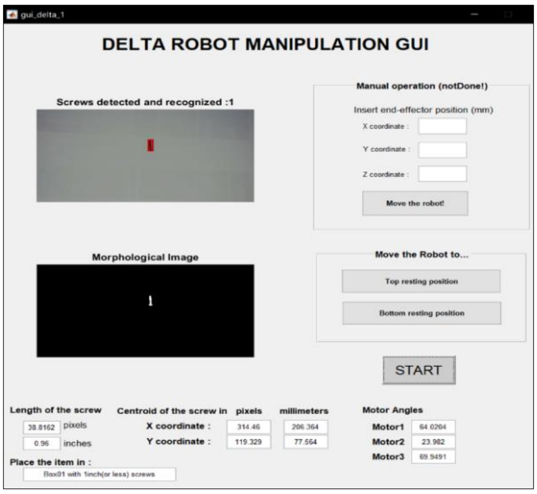

Figure 6. GUI

The fabrication and testing were done as of the method discussed in this paper. This produced accurate results in object detection, mapping, pick and placing by the robot as of the sequence of operation mentioned in Figure 7.

VI. DISCUSSION

The intermediate shafts 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 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.

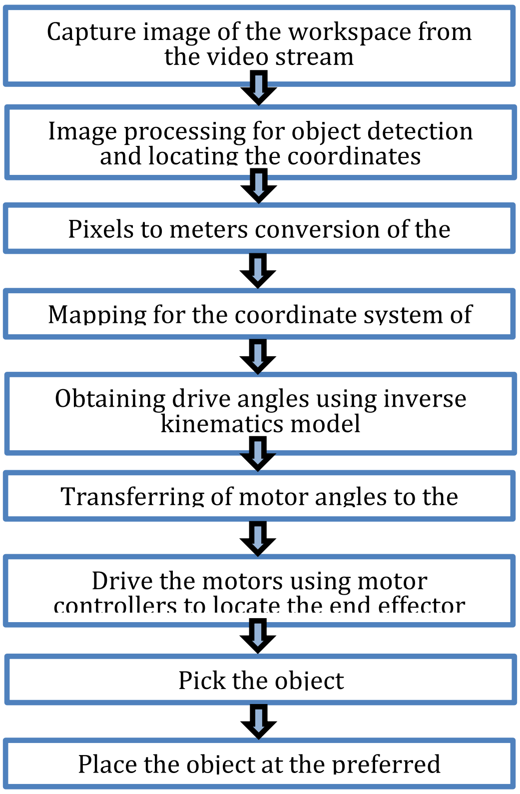

Figure 7. Control Flow

The initial decision was to undergo the manufacturing of links using carbon fibre due to its light weight and strength. Due to its fair of constraints of availability, cost, and fabrication, Aluminium was selected as the alternate material because of its lightweight and strength. However, the material stress analysis, bending moment analysis and twist analysis done for each component for both carbon fibre and aluminium yielded well above the required value.

Singularities were common at the initiation of the system.

The strength of the end effector solenoid should withstand the acceleration of the system.

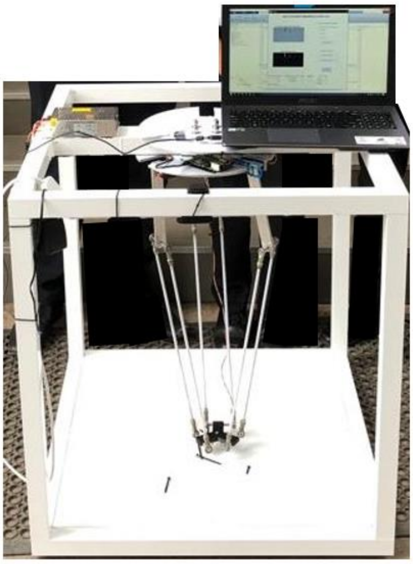

Figure 8. Fabricated, visual servo delta robot for sorting screws

VII. CONCLUSION

Since the functionality and the objectives of the prototype model were to its expected level, a scaled-up model is feasible to be used in the industry to accommodate regular pick and place tasks.

REFERENCES

Abduraimov, A. et al., 2017. Delta robot forward kinematics method with one root. s.l., IEEE.

Azmoun, M., Kalhor, A., Masouleh, M. T. & Rouhollahi, A., 2018. Kinematics and Control of a 4-DOF Delta Parallel Manipulator. s.l., IEEE.

Bulej , V., Poppeova, V., Rejda, R. & Uricek, J., 2012. THE DESIGN AND SIMULATION OF TRAINING DELTA ROBOT. Dubai, s.n.

Chen, Z., Geng, Y., Wu, J. & Xu, S., 2018. The simulation study of optimization of pick-and-place route for delta robot based on lame curves. s.l., IEEE.

Clavel, R. & Vischer, P., 1998. Kinematic calibration of the parallel Delta robot. Robotica, Volume 16, pp. 207 - 218.

Deshmukh, M. P. & Patil, M. J., 2015. A Review Paper on Introduction of Parallel Manipulator and Control System. International Journal of Engineering Research & Technology (IJERT), 4(2), pp. 959-963.

Kim, J., Liu, X.-J., Oh, K. & Wang, J., 2004. A New Approach to the Design of a DELTA Robot with a Desired Workspace. Journal of Intelligent and Robotic Systems, Volume 39, pp. 209-225.

Lin, C., Liu, C. C., Shaw, J. & Tsou, P. C., 2016. Vision servo based Delta robot to pick-and-place moving parts. s.l., IEEE.

Peng, B., Zhu, S., Khajepour, A. & Huang, Y., 2019. Kinematics and orientation capability of a family of 3-DOF parallel mechanisms. Mechanism and Machine Theory, Volume 142.

Rosquist, K., 2013. Modelling and Control of a Parallel Kinematic Robot, s.l.: s.n.

Tsai, C.-S.et al., 2016. Design and Simulation of a Delta Type Robot. s.l., IEEE