Reliability and Quality Improvement of Robotic Manipulation Systems

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Abstract: - This paper reports the procedure of experimental evaluation and objective/quantitative comparison, among different performance parameters, of the Cartesian (3P) robots. Here, first by implementing the equations of motion, the mechanical model of this type of robot is simulated using Working Model software. Next, the initial model of robot is designed based on the results concluded from the simulated model and the robot structure including control unit, mechanical elements and operating procedure is described. Also, some tests are applied on the prototype robot in order to verify the analytical side of design procedure. The experiments consist of calibrating the robot motion along all three axes (prismatic joints) and validation of three performance indices, which are easy to measure via simple experimentations namely accuracy, repeatability and maximum allowable load carrying capacity. The acceptable values of the indices are predefined as input of design process. The data derived from the experimental tests showed that the robot satisfies the acceptable values. The main contribution of this paper is to improve the robot design by exerting the changes obtained from assessment of some defined statistical and mechanical indices.

Key-Words: - Design, Cartesian robot, Performance index, Experimental test, Design improvement.

1 Introduction

Industrial robots come in several forms. They are used to automate a wide range of tasks in manufacturing and assembly lines in virtually every industry. Based upon the required application, a full assortment of robot formats can be implemented such as SCARA, articulated arms and Cartesian configurations and installed depends upon the working area, accuracy and so on. Specifically, a growing trend is to simplify the automation process by utilizing Cartesian robots allowing for fewer controllers, enhancing instability and offering more integrated and unified software.

The Cartesian configuration provides three linear axes of movement at right angle to each other for robot. The modes of movement are similar to those of a milling machine, providing movement in X, Y and Z axes. It may also be termed a rectangular configuration since its working range sweeps out a three dimensional rectangular volume. Particular advantages of this configuration include easy programming movement, high accuracy, large pay load capacity, control system simplicity, large area

coverage, structural simplicity and easy to expand.

Considering the wide application of Cartesian robots and the need of good accuracy in various fields, proposing the reliable and easy to do methods to calibrate Cartesian robots is one of the most important stages in design and manufacturing processes. The calibration is the process of determining the actual values of kinematic and dynamic parameters of the industrial robots. Kinematic parameters describe the relative position and orientation of links and joints in the robot while the dynamic parameters are related to arm masses, moment of inertia and internal joint friction. Thus, in this paper, we present the procedure of calibration and working improvement of Cartesian robots in terms of some performance indices. These indices values are measured in order to evaluate how much they are close to the agreed values for a fabricated prototype robot as a case study.

Recently, interests in design, manufacturing, control and calibration of robots with prismatic joints have been increased with a various theoretical and practical contributions being made [1, 2].

Azhdari et al. [3] presented a modeling and simulation of a flexible 2 DOF robotic arm including prismatic and revolute joints. They fabricated the robot with flexible elements from either aluminum and laminated composite materials. Reynoso [4] investigated the design, kinematic and dynamic modeling and experimental tests of a Cartesian robot. In this study, the effect of disturbances such as friction were considered. Heinz et al. [5] used a Cartesian robot for capturing flying objects in laboratory environment. For this purpose, a camera system measured the object's position during a throw in subsequent periods of time and based on these measurements the processor of robot can predict the capturing point with an increasing accuracy. Ghorabi et al. [6] applied some experimental tests on a prototyped model of a robotic manipulator in order to improve the design of robot. Also, they employed the international certified standard requirements including ISO 9283 and IEC 31010 to reduce the robot errors and improved the end-effector movement. Callegari et al. [7] presented a high-speed Cartesian robot produced by Campetella Robotic Center. This robot was characterized by goo dynamic performance but was chosen by the producer for re-engineering. Cheng et al. [8] presented kinematic analysis of a robot designed for studying the feasibility of loading packages inside a flatbed trailer. This ten DOF robot provided a large workspace, which is achieved by operating three redundant prismatic joints in arm.

There exists a variety of research work on determination of load capacity, Wang et al. [9] developed a technique to maximize the dynamic load capacity for an entire trajectory rather than in the neighbourhood of the robot configuration. Timar et al. [10] considered the problem of specifying the feed rate variation along a curved path, that yielded the minimum traversal time for a multi-axis CNC machine subject to given bounds on the feasible velocity and acceleration along each axis. Maddahi et al. [11] proposed an algorithm for determination of maximum allowable load carrying capacity of the robotic arms. In this approach, the maximum load is calculated by portioning the end-effector main trajectory to some sub-trajectories and calculating the required actuation torque of each motor.

In this paper, design, modeling and experimental study of Cartesian robots are presented. Here, after description of the related issues of Cartesian robots, the calibration method and performance indices are described and the proposed procedure is validated by implementing some experiments on a prototyped robot. Section 2 addresses the design procedure which starts by the derivation of robot equations. Section 3 presents the definitions implemented in this paper and is followed by explanation of the control algorithm and the program written to record the position of robot end-effector which is described in Section 4. In Section 5, the experimental analysis for the prototype robot is presented and the test results are analyzed (Section 6). The experiments are done on the prototype robot to increase the accuracy of robot as well as to improve the workability of prototyped model. Moreover, an algorithm for determination of load capacity of this type of robot is explained and finally, in order to verify the proposed algorithm, consequences of analytical, software simulation and experimental studies are performed for the manufactured robot as a case study.

2 Simulation and Modeling

The design process of robot includes some theoretical and practical stages. In this study, to design the initial model of 3P robot, the following algorithm is implemented. First, the kinematics and dynamics formulations of robot are derived considering the anticipated duties for robot. Next, based on the theoretical data, the robot elements are designed and then simulated using Working Model software in order to obtain the torque required for each actuator in some given trajectories. Then, the initial model is prototyped, after that some criteria to analyze the preliminary robot are presented.

2.1. Theoretical Modeling

The kinematics and dynamics modeling of robotics systems is the first stage in design of robots. This modeling concludes the formulations determine the posture (position and orientation) and torques of the robots, theoretically. In kinematic analysis, the study of the position, velocity and acceleration and all higher order derivatives of the position variables are investigated. The kinematic of robotic systems involves the study of the geometric and time-based properties of the motion and in particular how the various links move with respect to each other as time evolves. For the Cartesian robot with rigid link, the direct kinematic solution gives the coordinate of the tool attached to last link with respect to the reference coordinate (Fig. 1). In this figure, d_1 , d_2 and d_3 are prismatic joint displacements in x, y and z directions, respectively [12].

Furthermore, in order to obtain the amount of required torque for each actuator, the calculation of

equations of motion is necessary. The proposed model of robot must be accurate enough to give simple to use results which satisfactorily describe the operation of the actual system. The model simulates all the main existing forces/torques in the Cartesian robots such as the centrifugal term. The kinematics and dynamics formulation are presented in [12].



Fig.1. Generalized coordinates of Cartesian robot.

2.2. Simulation Study

Based on the robot equations of motion, the initial and approximate model of the Cartesian robot is designed (Fig. 2). using this model, the values for

position tracking and required torques are obtained using Working Model software. Then using the data exported from software, the model is initialized for fabrication. As a result, the creation of initial model seems to be essential in order to validate the derived mathematical formulations of prototype robot. This model is generated in Working Model software. This software helps the users to model and simulation the dynamical mechanisms and provides some analyses such as motion analysis, forward and inverse dynamic and finite element analysis (FEA).

As concluded from simulation output, there are some considerable errors between the analytical and simulation results. The maximum torques in analytical approach are about 100, 120 and 200 N.mm for motors 1, 2 and 3 while for simulation results, the obtained torques possess more fluctuations and their mean values are increased about 25%, 28% and 21% in x, y and z directions, respectively. The added amounts of torques are caused by some effects ignored in theoretical formulation and appeared in software modeling such as unsymmetrical geometry, friction force, joint misalignments and loss in motors.

Figure 3 illustrates the result of simulation study while robot travels a straight path from point (40,40,40) to (235,235,235). As shown, there exist some errors in position of end-effector due to the existence of noted sources.



Linear bush 20 mm

Fig.2. Model simulated in Working Model software.



Fig.3. Results of simulation study in straight trajectory.

2.3. Design Improvement

The design algorithm usually accompanies some changes in the robot which are determined according to the performance characteristics such as the risk analysis in safety side of design, accordance with the predefined accuracy and repeatability as well as the amount of load carried by end-effector. This approach can be also widely used in manufacturing industries.

This algorithm starts with the analysis of changes in design, error estimation stages and effect of changes on values of agreed indices and it's followed by evaluation of the errors and the related sources. The main part of this assessment process is the evaluation of needed changes in the values of indices as well as the residual error in the system after applying the required changes. As explained in [12], some components of robot had high effect in error incrementing which must be improved in order to reduce the inaccuracy for the system. Thus, some corrective actions were needed for these critical items to improve the performance indices. The considered variables to evaluate the design quality were a) potential risks (R) which are many recognizable errors or defects in the design process in order to be reduced, especially those that affect the work quality and user safety and can be potentially or actually and b) performance indices including accuracy and repeatability of robot for given trajectory. Thus, the performance index (PI) was calculated. The allocated values of these variables are between 0.1 and 1, which the number represents the importance of the related variable in required changes. For instance, one denotes the most importance effect of the related variable in design change. The value of PI was used to rank the change effects in the robot design which PI=0.01 shows the condition that the action applied on design has no effect on the working improvement. The amount of each effect was numberized based on the criteria pre-defined and is similar to the criteria defined in failure modes and effects analysis (FMEA) method [13].

3 Definition of Indices

To investigate the performance of the robot, based on the defined indices, some experimental tests are performed for Cartesian prototype robot. These agreed values are considered equal to 5mm, 10mm and 15mm for accuracy and 5 time and 10 time repeatability. Also, the maximum amount of dynamic load capacity for given path (Section 5.3) is predefined equal to 5 kg. These indices are measured for straight trajectory with the length of 250 mm in diagonal direction of cube *XYZ* (Fig. 1). All indices must satisfy the above agreed values, otherwise, the robot design must be changed to achieve desired values.

3.1. Accuracy

The accuracy of this robot is defined as the degree of closeness of end-effector position to its actual value. Accuracy indicates proximity of measurement results to the true value (Fig. 4). The accuracy of actual robot is under the effect of the following factors such as accuracy of manufacturing mechanical parts of the robot, accuracy of assembling the constituting parts of robot, accuracy during the robot operation that is influenced by external forces, electronics system accuracy, motors operations, existing clearance in the system, wear behaviors (change in accuracy of the robot in long duration), change in accuracy of system after assembling and change in the system accuracy during the preventive maintenance periodic program.

3.2. Repeatability

The repeatability or test-retest reliability of robot position is the variation in measurements of endeffector position taken by a single user or instrument on the same item and under the same conditions (Fig. 4). A measurement is said to be repeatable when this variation is smaller than the agreed values defined before. The repeatability conditions include same measurement procedure, same observer, and same measuring instrument used under the same conditions as well as same location and repetition over a certain period of time.



Fig.4. Defined path and related variables for accuracy and repeatability tests.

3.3. Load Capacity

Determination of load capacity of robot leads to select and attach the proper tool in end-effector. In order to determine load capacity of the robot, proper modeling of robot is a pre-requisite. Here, the computational procedure to determine the maximum allowable load capacity is outlined. To calculate the dynamic load carrying capacity of robot, after discretizing the given trajectory into *m* points, joint motion constraints, Jacobian singularity conditions and joint velocity constraints are checked [11]. In cases in which each of the constraints is violated, the given trajectory is unrealizable and a new trajectory should be selected. At next step, acceleration of each joint is found and then the dynamic equations are employed to compute the load and end-effector dynamic effects. Once the below conditions are satisfied, the value of mass carried by end-effector and related coordinate are recorded.

- *The joint kinematics variables* including the joint orientations and velocities should be bounded by two upper and lower limits:

$$\begin{cases} d_{\min,i} \leq d_i \leq d_{\max,i} \\ \dot{d}_{\min,i} \leq \dot{d}_i \leq \dot{d}_{\max,i} \end{cases}$$
(1)

Note that i=1,2,3 is the joint number of Cartesian robot.

- *Non-singularity condition of robot*: Non-zero condition of Jacobian matrix for given trajectory:

$$J(d_i, d_i, x_e, y_e, z_e) \neq 0$$
⁽²⁾

where (x_e, y_e, z_e) is the coordinate of end-effector along the specific trajectory which can be a function of time.

- *Calculated torques* should be bounded too using the following equation.

$$-T_0\left(1+\frac{\dot{q}_i}{\omega_i}\right) \le T_i \le T_0\left(1-\frac{\dot{q}_i}{\omega_i}\right) \tag{3}$$

In (3), T_0 is the stall torque of each motor and depends on the characteristic of actuator, \dot{q}_i denotes the full-loaded angular velocity of i^{th} motor for given path and ω_i represents the angular velocity of motor while carrying no load. Also, T_i is the torque of the i^{th} actuator.

4 Prototype Robot

Based on the process described before, a prototype model of the Cartesian robot is fabricated as shown in Fig. 5. This model is finalized after applying the changes concluded from design improvement. Also, this robot is designed on basis of the assumption in which each joint has an independent actuator with gear reduction and measuring angular joint position sensor. Mechanical elements of the robot are modelled using Solid Works software. In addition, the design of 3P robot is carried out using the design preliminary conditions (*i.e.* agreed values) and the proposed improvement algorithm to recognize and reduce the existing errors during the design and manufacturing stages [12].

4.1. Control Unit

The controller includes three drivers for three servo motors and used to drive the motors. Each motor has its own built-in reduction gears and incremental encoder. As compared to robot described in [12], the resolution of the encoders is increased from 270 p/rev to 900 p/rev. The commands are sent to the robot via the designed simulation software. This software is implemented because the manufactured robot should accomplish the given commands accurately and smoothly. This is possible in the case that the motion of the robot end-effector is accurate enough relative to the target-object that is the point that the end-effector of the manipulator has reached to. The robot works with a Pentium IV, 1600 MHz which is used for path detection algorithm processing.



Fig.5. Manufactured 3P robot.

4.2. Interfacing Program

To transform the robot coordinates to global reference coordinate (Fig. 1), the scale section of written program is implemented. With images from these two fixed cameras, the positions of objects are shown in image plane coordinate. As shown in Figs. 5 and 6, two cameras with a certain distance from

each other are looking at the end-effector. One of these two stationary cameras is fixed and zooms along Z axis (camera 1) and second one is located in Y axis direction (camera 2). Position of end-effector is determined in image plane and then is transferred to global coordinate using derived transformation matrices. Evaluation of the mentioned procedure is one of the most convenient approaches to assess the entire activity of industrial robots. Also, the measurement of described performance indices brings the opportunity of comparison the available robot with other existing robots. To make tests more applicable, the statistic analyzes are performed based on the definitions described before. As shown in Fig. 6, the cameras take the sequences of photo from object located at end-effector and the encoders read the amount of pulses of motors and the program scales the pictures and recognizes the endeffector and target situations among other objects. Then, based on the input desired path, the amount of error in X, Y and Z directions is calculated and the controller sends the compensated pulse to the motors in order to modify the motion of robot.

4.3. Mechanical Elements

The mechanical mechanism in manufactured base consists of three gearboxes and their own shafts to transmit the angular velocities of gearboxes to the axis shafts. On the bottom of the robot, covering platform is a wood plate that the work pieces are mounted on.



Fig.6. Position-based control structure of robot and stationary cameras (Modified from [12]).

5 Test Results

In experimental tests, first the prototype robot is tested and the performance indices are measured and compared with the agreed values. As the calculated indices in preliminary model cannot satisfy the design criteria firstly, thus, the improvement algorithm results (the required changes) are applied on robot in order to improve the design of the preliminary model. Also, the tests are repeated while some corrective actions are considered during the design and manufacturing process and the performance indices are calculated. Finally, the improvement factors are obtained and compared to the initial data. The performance tests are done using the two-camera measurement technique. As mentioned, the test parameters include accuracy, repeatability of end-effector position and load capacity of robot.

5.1. Accuracy and Repeatability: Results

Based on the described technique to posture measurement, the amount of accuracy and repeatability of robot are obtained in before and after design changes. In all experiments which are described in this section, the robot is programmed to move in a typical trajectory with l=250 mm in diagonal direction of XYZ cube which is shown in Fig. 1. In this experiment, the end-effector linear velocity is 0.12 m/s.

Figure 7 shows the mean values of experimental results obtained for accuracy and repeatability tests for given trajectory. The repeatability test is done when n=5 and n=10. The bars show the end-effector errors after and before applying the corrective actions. For each trial, this test is performed for 10 times and the end-effector error is defined as the mean value of the difference between the desired and actual positions by following equation:

$$RE = \frac{1}{10} \sum_{i=1}^{10} \sqrt{(\overline{X}_{a,i} - X_d)^2 + (\overline{Y}_{a,i} - Y_d)^2 + (\overline{Z}_{a,i} - Z_d)^2}$$
(5)

where $(\overline{X}_{a,i}, \overline{Y}_{a,i}, \overline{Z}_{a,i})$ and (X_d, Y_d, Z_d) are the actual and desired coordinates, respectively. The actual coordinates are calculated using the mentioned mapping algorithm.

As illustrated in Fig. 7, the accuracy 5 time and 10 time repeatability error were reduced by 63.5%, 29.3% and 29.8%, respectively.

5.2. Trajectory Test

In next experiment, desired position of endeffector is given to robot to reach. By computing



Fig.7. Error mean values of tool movement in accuracy and repeatability tests.

joint angles from inverse kinematics equations and rotation of joints, the end-effector will reach to the desired position. By taking photos with two fixed cameras, the robot equations and the counted pulses concludes the coordination of end-effector in global reference frame are determined. Also, by comparing the desired and actual amounts of end=effector position, the positioning errors are determined.

5.2.1. Quarter Circular Path

In this test, the accuracy of robot on the quarter circular continuous path is determined and the amount of error during the robot motion is calculated. The circle is in horizontal plane *i.e.* the height of robot end-effector is constant from earth level. The orientation of the end-effector doesn't vary, thus, the end-effector is always in horizontal plane and also, normal with respect to circular path and end-effector slides along perimeter of circle. During motion of end-effector on the path, 10 images have been taken from end-effector. Using mapping system, the image coordinates of points are transformed to the reference frame. The desired and actual paths are illustrated in Fig. 8. In this experiment, the mean value of end-effector linear velocity is 0.08 m/s.

5.2.2. Straight Line

To move end-effector along a direct line, its start and end points must be determined. Approach vector direction is normal with respect to direction of line path *i.e.* end-effector is always normal to its path. With pose of end-effector and inverse kinematics equations of robot, the joint angles are computed. Joints rotate and end-effector is positioned along its path. Coordinates of endeffector in global reference frame are determined by taking pictures with two fixed cameras. The positioning error is determined by comparing the desired pose and actual one. Error of tool in traversing direct line path, when they move along X axis are shown in Fig. 9. The start point is coordinated by (0, 0, 0) and the final point is located on (150, 150, 150). The linear velocity of end-effector is considered to be 0.3 m/s.



Fig.8. Desired and actual paths in quarter circular test.

5.3. Load Capacity

This section presents the calculation of the robot dynamic computations using three approaches

including analytical approach, simulation study and experimental test. In all approaches, the end-effector travels from point (0,0,0) toward point (120,120,120). All experiments and simulation studies in this section are performed for final model of robot after applying the corrective actions.

5.3.1. Computational Method

In this section, the previous diagonal trajectory for the load is assumed using the algorithm presented in Section 3.3. Considering the modeling equations, the task space trajectory is descritized into equally spaced m=40 points. The allowable load carrying capacity for the mobile manipulator at every point of the trajectory is determined and maximum allowable load is found $m_{load}=8.16kg$ at point X(t)=62.5mm, Y(t)=62.5mm, Z(t)=120mm as shown in Fig. 10. As shown in this section, there are some differences in the results of analytical and simulation approaches in calculation of maximum allowable load carrying capacity. The effects of friction force, load and inertia distribution types are the major reasons of this difference.

5.3.2. Simulation Approach

In this approach, the load capacity value is calculated using simulation study. Also, to determine the maximum load capacity, the model is moved in given trajectory in Working Model software and the torques of motors are derived from



Fig. 9. Error diagram in x, y, z directions in straight line trajectory applied on final design of robot which are shown by e_x , e_y , e_z , respectively.



Fig. 10. Variation of allowable load along load trajectory and load capacity.

software output. In this estimation, the amount of plus load mass is increased in each trial and the torques are checked. When one of motors reaches to its critical torque, it means that robot is carrying its maximum load in given trajectory. For calculation of maximum allowable load, Cartesian robot is moved in given trajectory and the initial load is taken to zero, then the load is increased by steps of 0.1 kg. Figure 11 shows the maximum torques of motor 2 for given manipulator load in each trials.



Fig.11. Torque-load variations for 2nd actuator.

As a results, according to this figure, for $m_{load}=7.5kg$, motor 2 (Y axis motor) reaches its maximum value $\tau=1058$ Nmm. As shown in Fig. 11, the torque of motor 2 restricts the load capacity in end-effector and the maximum allowable load for given trajectory is determined as $m_{allowable}=7.5kg$. In

this estimation, some disturbances neglected in theoretical modeling take into account such as the effect of friction forces, unsymmetrical distribution of robot mass and probable misalignments in joints. This consideration makes the results more accurate as opposed to analytical approach.

5.3.3. Experimental Approach

In this approach, the amount of torque for each motor is derived using laboratory tests applied on this robot. The obtained data are perfectly experimental and all existing errors sources such as friction effects have been considered. The amount of maximum load capacity for this path is obtained about 5.64kg using three torque-meters installed on the actuators (Fig. 11). The implemented digital torque meters are made by Shenzhen Tony Electronics Company and named SHITO. They are the intellectualized instruments for measuring and setting torque which are mostly used for inspecting the torque of electric torque drivers and used to measure the torque produced during the actuators motions. These sensors are designed as easy-tooperate, accurate, functional and portable tools.

6 Statistical Analysis

In order to compare the obtained results with the agreed values in design stage, the calculated indices based on the data resulted from experiments are considered according to Table 1. As shown in this

	DLCC (kg)	Mean Accuracy (mm)	Mean Repeatability 5 times (mm)	Mean Repeatability 10 times (mm)
Agreed Values	5.00	5	10	15
Preliminary Design	3.21	10.70	12.75	19.80
Final Design	5.64	3.91	9.01	13.90

table, all derived data are acceptable and also, confirm the final design based on the agreed values. Thus, the changes applied during the design process are reasonable in the sense of defined and agreed indices.

7 Conclusions

This paper addressed the procedure of experimental evaluation and improvement of the design and application of Cartesian robots by implementing the experimental tests. This design was completed based on some predefined indices which can be obtained using experimental tests. These indices were specified during the design process as design inputs according to the anticipated workability of Cartesian robots. These performance indices consist of the accuracy, repeatability and load carrying capacity. In addition, in order to validate the described procedure, a prototype model of Cartesian robot was manufactured and tested. Then, after exerting changes during design process (mentioned in [12]), the experiments showed great improvement over the preliminary design of robot. For example, the accuracy, 5 time and 10 time repeatability errors were reduced by 63.5%, 29.3% and 29.8%, respectively.

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