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The Performance Parameter Analysis and Calibration Methodology for the Industrial Robot

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Abstract
The article's primary purpose is to present a new robot calibration system proposed to improve the positional accuracy and repeatability of the ABB IRB 1520ID industrial robot having six degrees of freedom. Various calibration methods of articulated industrial robots are discussed. A new calibration technique is proposed, using a five Linear Variable differential Transformer (LVDT) probe and a master tool designed for varying payload capacity during experimentation. Analysis of different robot parameters and internal or external factors affecting the performance ofthe robot was done. The planning, execution, and experimentation set up all the stages are mentioned in detail. Finally, after the experimental setup, statistical tools and formulae to evaluate the positional accuracy and repeatability are also described in detail.

Keywords: Robot Calibration, Robot's Accuracy, Robot's Repeatability, Parameter Identification, Statistical Analysis

1. Introduction

The recent advancements in automated production systems require highly accurate and repeatable industrial robots used as reprogrammable and multi-purpose devices. Remote-controlled experiments could operate the robot outsideand achieve the same results as onsite operation, thus fostering shortages of lab time, space, equipment, and teaching time. The primary motivation is reducing the production cycle of products and guarantees the required quality of both manipulating and technological operations performed by robots. Advancement in robotic applications such as robot assisted surgery, measurement based on the robot, demands highly accurate robots and better positioning performance. To fulfill these requirements, robots must undergo a calibration process. To fulfill these requirements, robots must undergo a calibration process.

Different performance criterias and related test methodologies for manipulation of industrial robots are mentioned in the ISO 9283:1998. The various performance characteristics are mentioned, such as distance accuracy and repeatability, pose accuracy and repeatability, variation in multidirectional pose accuracy, path velocity, path accuracy, repeatability characteristics, static compliance, etc. The significance of individual performance criteria is determined by the particular application of the test robot. Out of all requirements, accuracy and repeatability are mostly tested performance. Unidirectional position repeatability of the robot is defined as its ability of TCP (Tool Centre Point) returning at the same position repeatedly from the similar direction, hence minimizing the effects of backlashes in every individual joints on testing results. In comparison, multidirectional repeatability is determined as twice unidirectional repeatability.

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Accuracy is the robot's ability to attain a TCP's programmed position concerning the base reference frame of the robot. Various factors influence the accuracy and repeatability of the robot, causing errors, significantly geometric inaccuracies, and stiffness of the robot's arm are factors that influence position accuracy.

The norms in ISO 9283:1998 describe the information of conditions for testing, measurement methods, and calculation of individual performance criteria, but it does not specify the measuring equipment. Many works of literature have addressed a non-contact type complete position measurement of the robot using different visual systems such as in [1]and [2] two cameras used for capturing 3D images, but with low accuracy. Some systems have fixed cameras attached to end effectors for viewing targets closely without zooming, and this reduces the view of the camera's field [3]. The visual systems aforementioned are limited to measure the accurate position of the robot's end effectors. In [4] forfull pose measurement use of an optical device for better accuracy, and calibration [5] of a SCARA robot. A specialapparatus is attached to the robot's last link having intermediate point arrangements, and measurements are doneusing these points. It also has disadvantages as the manufacturing cost of special apparatus is high, pre-calibration ofa tool before using it, thus slow down the measuring process. However, from an economic view, devices range from digital indicators having low cost and optimal accuracy for measuring positioning performance as in ISO 9283:1998,through medium-cost laser interferometer to laser tracker, which is highly expensive. Primarily for robot calibration accuracy measurement, manufacturers use laser tracker commonly in [6]. Measure of position repeatability using FARO laser tracker given in [7], for IRB 1600 robot. However, one can select the measuring tool and calibration method that enlarge the measurement range, with high accuracy and low cost, elimination of pre-calibration of fixtures, and increased number of measurable cycles.

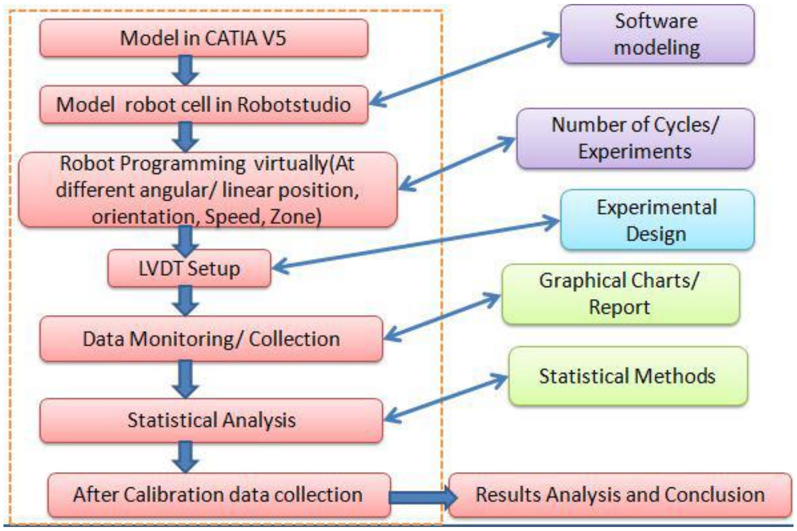


Figure 1: Step by step execution of Calibration Process

In this paper, a mechanical setup of five Linear Variable Differential Transformer (LVDT) probe is used as a measurement tool for the purpose of robot calibration of a 6 degree of freedom ABB IRB 1520ID industrial robot.LVDT is a low-cost, high dynamic response, accurate and easy to set up the device. Also, a master tool is designed particularly for varying payload capacity while experimenting with CATIA software. After experimental setup, analysis is done to determine the different robot parameters like manipulator velocity, robot's reach and payload, and other internal or external factors affecting robot performance. Further testing of robot positional accuracy and position repeatability can be performed using the method given in ISO 9283:1998 standard. Afterward, in statistical analysis, various formulae are mentioned to evaluate robot positional repeatability and accuracy.

The highlights and novelty of given paper are:

- For test of Robot calibration, the mechanical arrangement consists of 5 LVDTs, such as 2 in X-direction (X+X-), 2 in Y- direction (Y+ Y-), and one in Z-direction.
- A master tool is manufactured for varying payload capacity during the experiment.
- The number of cycles are counted using the inductive proximity sensor.

The remaining paper is organized as Section II has explained the robot calibration system and methodology for itin detail. The experimental setup details are mentioned in brief in Section III. Finally, the planning of the experiment is described in Section IV. Further statistical analysis for robot positional accuracy and repeatability given in SectionV and conclusion in VI.

2. Robot calibration system

The process to improve robot accuracy by modification in control software is called robot calibration. There are two main types of calibration systems: static and dynamic calibration. Generally, static calibration is to identify the parameters that affect the remarkably static positioning performance of the robot. In contrast, for specifying parameters that influence the primary motion performances like velocity or forces, dynamic calibration is used. Static characteristics mainly involve the position and orientation of the end effector. The main focus of a static calibration system is to correct geometrical parameters like offsets in joint angle and geometries of the joint axis. Non-geometrical characteristics mainly involve compliance, i.e., the elasticity of joint and link, gear form errors like eccentricity error and transmission error, backlash, and other expansions due to temperature. The static robot calibration model considers both the geometrical and non-geometrical parameters as parameters are measured from the robot's pose. After the completion of the identification of static parameters, dynamic calibration is performed. This calibration is committed explicitly to analyzing related dynamic parameters of the robot such as frictional effect in actuators and joints, stiffness, distribution of mass in the links, and many more. The paramount importance of dynamic robot calibration is in giant robots as they are subjected to very high velocity and high acceleration. Therefore a cumbersome experimental procedure is required. [8]

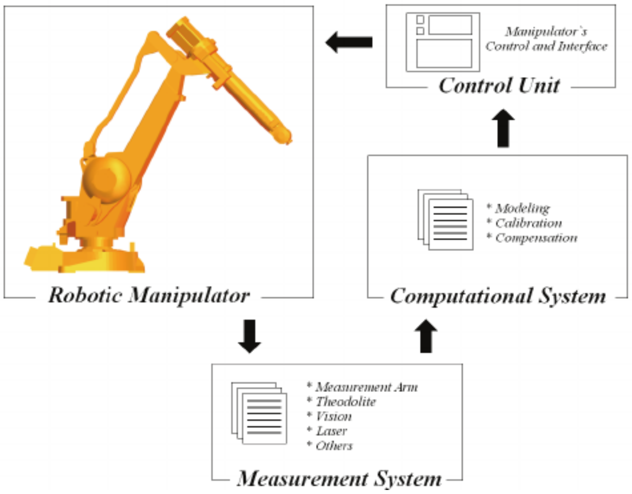


Figure 2: Setup of Calibration [5]

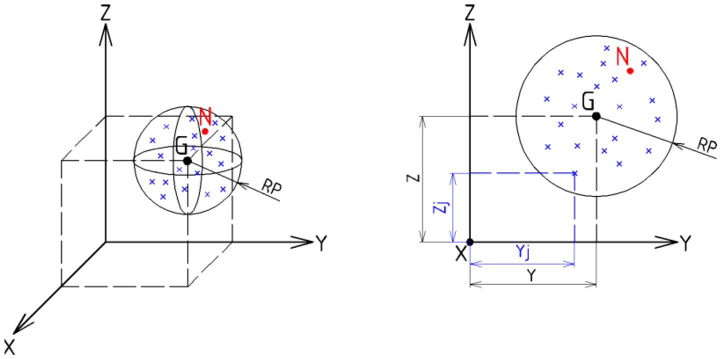


Figure 3: Graphical representation of position repeatability [9]

2.1. Methodology for robot calibration

The entire setup of calibration is the joint work of a measurement system using a measuring tool, an offline model of the robot, and the controller as shown in Fig. 2. The diagram has blocks of robot manipulators whose position is judged by a measurement device. Mainly we have used a Linear variable differential transformer (LVDT) that sends the coordinates of the robot end-effector to an offline computer that is present in any external coordinate frame. This system has all information regarding modeling error, parameter identity routines, and robot joint coordinate's compensation. After that, these new coordinates of the robot joint are sent to the robot controller for movement of the robot to the desired target as it is before the calibration, thus reduces errors. The procedures for robot calibration are divided into significant steps as shown in Fig. 1.Following is the execution methodology of the project after the experimentation design has been set up. The programming of robots at various angular/linear positions, speeds, and the zones will be done for number of execution of a cycle. For each process, the monitoring is done of real-time data on DAT-SPC in the form of graphical charts. After every cycle, the collection of data in excel format is done for analysing statistically. To apply the statistical process control method, the calculation of repeatability of the robot must be performed.

3. Accuracy and repeatability of robot

Industrial robots have been used for enormous applications, replacing men's work in dangerous and repetitive tasks. However, robots have better repeatability but abysmal accuracy. The terms regarding one direction positional accuracy and repeatability are defined in ISO 9283:1998 [9]. ABB IRB 1520ID robot is used for automating the handling, pick and place, and welding operations within robot cell of automatic assembly. The works of literature state that precision of servo and sensor, gear backlashes, and manipulator speed are the parameters affecting repeatability, whereas kinematic modeling of the robot, part loading are very crucial factors for accuracy. Further we will be considering just two variables: positional accuracy (Ap) and positioning repeatability (Rp), as also described in [10] and [11].

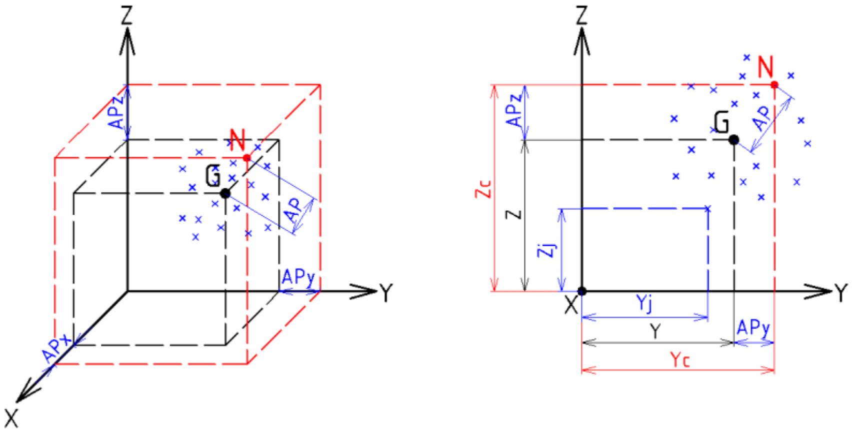


Figure 4: Graphical representation of positional accuracy [9]

3.1. The one direction positional performance variables

The one-directional Ap is the difference of commanded position (M) from the mean value i.e., barycenter-B which is obtained from the TCP’s positions reached repeatedly as given in Fig. 4. The dimensions are measured in (mm). Let i = 1, 2,...,m represents number of positions. In Fig.4, G is barycenter $[\bar{x}, \bar{y}, \bar{z}]$, commanded position given by N [xc; yc; zc], ith final reached position [xi; yi; zi]. The general formula for the representation of one direction position accuracy is:

$$A_p = \sqrt{(A_p)_x^2 + (A_p)_y^2 + (A_p)_z^2}, \tag{1}$$

Where,

$$(A_p)_x = \bar{x} - (x)_c, \tag{2}$$

$$(A_p)_y = \bar{y} - (y)_c, \tag{3}$$

$$(A_p)_z = \bar{z} - (z)_c, \tag{4}$$

where, mean values of repeatedly reached (programmed) points from the cluster is termed as co-ordinates of barycentre described by formulas:

$$\bar{x} = \frac{1}{m} \sum_{i=1}^{n} (x_i), \tag{5}$$

$$\bar{y} = \frac{1}{m} \sum_{i=1}^{n} (y_i), \tag{6}$$

$$\bar{z} = \frac{1}{m} \sum_{i=1}^{n} (z_i), \tag{7}$$

The ith position attained by TCP has coordinates given by variables xi, yi, zi.

Following are the calculations that are necessary for calculating one-directional positional repeatability Rp, which is ”the closeness of attained positions after m repetition of the robot to the similar commanded position in the same direction.” In Fig. 3 Rp shows radius of the sphere with barycentre G is the center. Lengths are given in (mm). Here Sl is the variable showing standard deviation for li, given by equation:

$$S_l = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}(l_i - \bar{l})^2}, \tag{8}$$

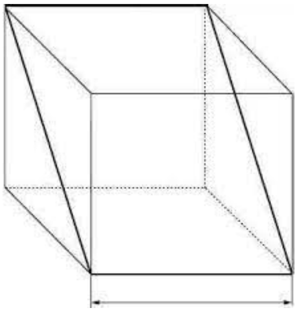


Figure 5: Imaginary ISO cube-ISO 9283:1998; Diagonal L(mm) [9]

where, m is the number of times robot attains the same position in the similar conditions, whereas _l(mm) is mean position repeatability as given in standard ANSI/RIA R15.05. It is the mean of the difference of ith attained positions (xi; yi; zi) and mean of attained position d i.e. $[\bar{x}, \bar{y}, \bar{z}]$ obtained in Eqs. 5, 6, 7,

$$l_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2}, \tag{9}$$

$$\bar{l} = \frac{1}{m}\sum_{i=1}^{m} l_i, \tag{10}$$

Using aforementioned equations, the calculation for positioning repeatability is termed as:

$$R_p = \bar{l} + 3S_l, \tag{11}$$

3.2. The Measurement method

Same conditions are used to measure both performance variables Ap and Rp. It means, same data is used for calculation of Ap and Rp, but procedure to calculate them is different as discussed in subsection III-A. ISO 9283:1998describes the measurement method, using an imaginary ISO cube, where corners have label from C1 to C8 shown in Fig. 5, with methods given in [12]. The cube is designated in the robot's working space, where the robot is maximumly used. Additionally, the selected cube should have the maximum possible volume. The edges of the cube must be parallel to the basic coordinate axes system of the robot, i.e., identified with the help of the World Coordinate System (WCS).The points that are measured are arranged in a plane that is present in the cube. In Fig.5 the vertices C1, C2, C7and C8 of cube, makes an inclined plane for 6-DOF robot.

The complete measurement procedure has 30 cycles of measurements in total, in which the movement of TCP point takes place to all individual points, which are P5 to P1 termed as tested positions. One direction approach of TCP's point considers each of these points. Measurement of coordinates of each point is done only after reaching its position, and further calculations of Ap and Rp is followed.

The testing of position performance has some conditions defined in norms of ISO 9283:1998. Some states are the loading effect of the robot's end-effector, ambient temperature, and speed of TCP point.

4. Planning of the experiments

In the planning phase of experimentation, the procedure given by authors in [13] was significantly followed step by step. This planning procedure was used to determine the control and constant variables and nuisance factors affecting the robot. Further robot's accuracy and repeatability were selected performance variables for analysis. The positional data is used to determine these performance variables.

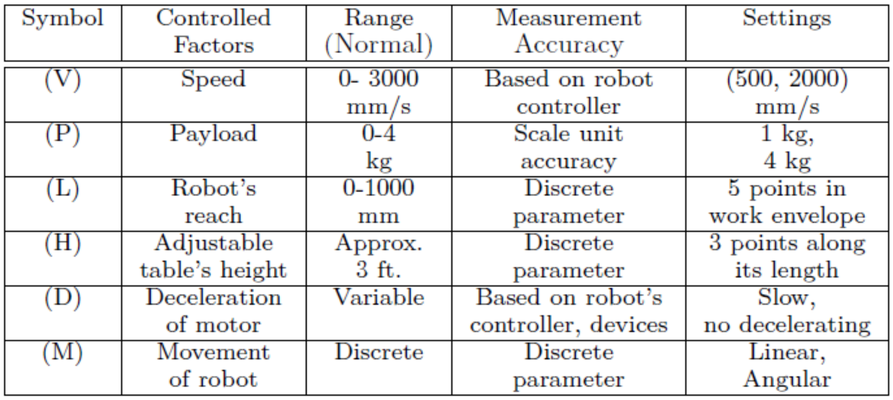
4.1. Controlled Variables

During the experiments, the control variables that need variation are chosen using different literature surveys and robots' practical working. The pertinent knowledge for each variable that can be controlled is mentioned in table I. In table I, the two factors, speed, and payload are continuous, whereas the remaining factors are discrete.

4.2. Held-constant variables and Nuisance factors

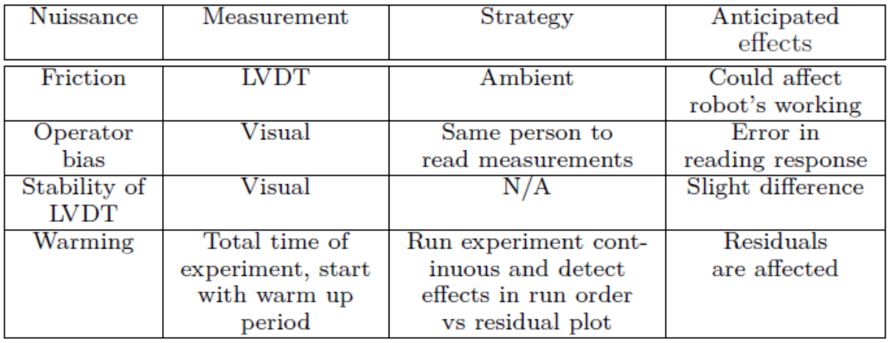
Next, to control variables were determined, we must pay attention to factors that must be held constant, so that there must not be any error in the results of experimentation. The elements decided to be constant are described in table III.

TABLE I
Controlled parameters after planning steps



Symbol	Controlled Factors	Range (Normal)	Measurement Accuracy	Settings
(V)	Speed	0- 3000 mm/s	Based on robot controller	(500, 2000) mm/s
(P)	Payload	0-4 kg	Scale unit accuracy	1 kg, 4 kg
(L)	Robot's reach	0-1000 mm	Discrete parameter	5 points in work envelope
(H)	Adjustable table's height	Approx. 3 ft.	Discrete parameter	3 points along its length
(D)	Deceleration of motor	Variable	Based on robot's controller, devices	Slow, no decelerating
(M)	Movement of robot	Discrete	Discrete parameter	Linear, Angular

TABLE II
Nuissance factors after planning steps



Nuissance	Measurement	Strategy	Anticipated effects
Friction	LVDT	Ambient	Could affect robot's working
Operator bias	Visual	Same person to read measurements	Error in reading response
Stability of LVDT	Visual	N/A	Slight difference
Warming	Total time of experiment, start with warm up period	Run experiment continuous and detect effects in run order vs residual plot	Residuals are affected

TABLE III
Held-constant variables after planning steps

Factors	Desired Experiment Level	Measurement (Accuracy)	Expected effects
Temperature	20-25 C	Ambient	Could affect robot's working
End effectors	Grippers, tool	N/A	Change in weight distribution
LVDT	Grippers, tool	N/A	Vibrations in surrounding affects

5. Experimentation details

5.1. The Measurement tools

A Linear variable differential transformer (LVDT) is used as a measuring tool that accurately performs measurements. For testing Ap and Rp the measurement used has linearity of 0.05 % and resolution of 1_m. Experimentation setup having 5 LVDT probes of Industrial robot is used for calibration method. The LVDT measurement principal test method for measuring four points located on the diagonal plane of an imaginary ISO cube given in standard ISO9283:1998 is used. The edge length of A=400 of an imaginary cube was selected in the active region of the IRB 1520IDrobot. The measuring points E1, E2, E4 must be placed along the diagonally opposite edges of the imaginary cube for each measured axis as shown in Fig. 5.The LVDT gives a very high output voltage that is practically linear and has 5mm displacement with infinite resolution. It also has a high sensitivity of 4V/mm. Therefore, care should be taken that no vibrations must be present in the surrounding during experimentation. It also has the added advantage of no sliding contacts hence less friction. In the experiment, the running of robot is done thirty-five times (n=35) for trials of controllable external/internal factors.

To perform calibration test of robot, mechanical arrangement was done consisting of 5 LVDT setups such as 2 inX-direction (X+ X-), 2 in Y- direction (Y+ Y-) and 1 in Z-direction.

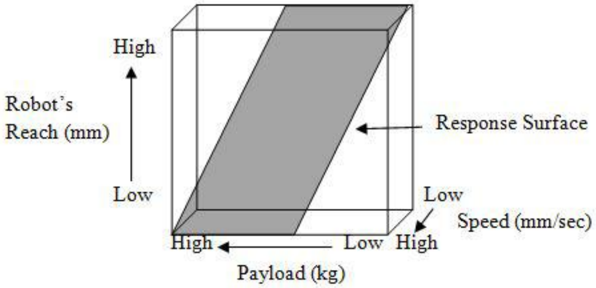


Figure 6: Design space for DOE

- The master tool designed for experiment must be in connection with the end-effector of robot.
- Inductive proximity sensor in the vicinity of robot is used to count the number of cycles.

5.2. The Master tools

The master tool was designed and manufactured for varying the payload capacity during experimentation. Various material that can be used for manufacturing includes Teflon (500 gm), steel

(4.5 kg), aluminum (3.2 kg), nylon (1.1kg). We have mainly used nylon due to its strength, lightweight, durability, and cost-effectiveness.

1)Plate thickness (t): The plate thickness (t) is calculated using the formula as given in Eq. (12) and (13).

$$\frac{M}{I} = \frac{\sigma_{yd}}{y_{max}} \tag{12}$$

$$I = w(\frac{t^3}{12}) \tag{13}$$

where, σ_{yd} is tensile strength, M is maximum plate load supporting weight of almost 5.1 kg, ymax is the yield strength,

w is the plate width and I represents ......

Substituting all values with safety factor of 1.5 in Eq. (12), we get plate thickness (t) as:

$$t = 0.33mm \tag{14}$$

The value signifies that the plate loading is insignificant but during experiment when robot will be in motion all the dynamic forces acting on the plate are significant

2) Cylinder outer diameter (Do): The outer diameter (Do) of the cylindrical part of the master tool is calculated. Here the inner diameter Di is constrained as Di = 75mm.

$$\sigma = \frac{F}{A} \tag{15}$$

where, _ is tensile stress and A is the area of cylinder, F is the maximum plate load with weight of 3 kg.

$$\sigma = \frac{F}{(\frac{\pi}{4})(D_o^2 - D_i^2)} \tag{16}$$

Substituting all the values in Eq. (16) we get,

$$D_o = 75.028mm \tag{17}$$

Since here also same nylon material is used with high tensile stress, the thickness of cylinder ((Do-Di)/2=0.014 mm)

is negligibly small, so any thickness can be selected that is easily available/manufactured.

3) Weight calculations: The weight calculations for the cylinder, plate, and probe are calculated using the formula mentioned in Eq.18. A detailed explanation of the material used for manufacturing, the density of the material, andthe calculated weight is shown in Table IV.

$$w = \frac{1}{2}\rho V \tag{18}$$

TABLE IV
Weight calculations

Weight Calculations	Material	Density	Weight
Cylinder	Cast Nylon	1.15×10^{-6} kg/mm^3	153.4 gm
Plate	Nylon 6	1.15×10^{-6} kg/mm^3	28.34 gm
Probe	EN8	7.48×10^{-6} kg/mm^3	165.23 gm

C. Design of Experiment

Critical process parameters are generally affected by multiple factors such as velocity of manipulator, payload, reach adopting a trial and error or one factor at a time approach, we prefer methodology termed as Design of Experiment (DOE).

It is a multivariate approach that finds relationship between the factors affecting the process and output of the same process by varying the potentially influential factors, simultaneously.

As mentioned in Fig. (6), there are three parameters like payload, speed and robot's reach having two levels either high or low. So ultimately 23 test conditions are possible, i.e. 8 test conditions. For this the experiments are performed in systematic way within accurately controlled framework under reproducible conditions. Designs are particularly independent of the process.

6. Conclusion

The paper presents the study of the most influential performance parameters of a robot. The significant attention is to focus on one-directional Ap and Rp testing of ABB IRB 1520ID industrial robot with the help of measuring device like LVDT, which is mainly used for contact type of measurement. LVDT is a low cost, accurate, high dynamic response, and easy to set up, which is not addressed in any literature before, being the novelty of the work. Also, a master tool is designed for varying payloads. Finally, the most significant factors affecting both the accuracy and repeatability of an industrial robot are found.

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