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ROBOT ACCURACY AND STIFFNESS—AN EXPERIMENTAL STUDY

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Investigations in robotics have been mainly directed toward the design of robots with a significant degree of intelligence, capable of high adaptability. However, very little research has been done on the design of a robot manipulator as an executive mechanism of the intelligent control system, whose high quality design will allow the sophisticated functions imposed by the control system.

Experimental investigations of robot accuracy show unacceptable results which limit their future wider application. This is the reason why the off-line programming of robots has not been widely used, without which it is impossible to imagine a more significant integration of robots in the CIM environment.

The object of our study has been to find out the causes of the low degree of robot accuracy, emphasizing the non-corresponding choice of the robot coordinate system, algorithmic and computational errors and drive and transmission element design. Comparison with corresponding results gained from investigations of CNC machine tools cannot be avoided because of the fact that robots are also machines from which accuracy is required. What is missing in robotics today, but which inevitably is required, is the establishment of a standard methodology for testing robot accuracy and other performance.

1. INTRODUCTION

Investigations of robot accuracy and the discovery of methods for its improvement have been presented in robotics for quite a long time. This has been provoked not only by purely academic interest, but also by the fact that robots are characterized by a low position accuracy which by itself is the cause of their limited application, and represents a hindrance to their further development.

Numerous investigations, some of which are cited in this article,[3,4,10,14] are directed toward the improvement of the basic kinematic model with the inclusion of link geometry errors and joint angle errors. In that respect, the investigations given in Ref. 4 are all-inclusive. Experimental investigations of robots, details of which are very rarely given in the literature, show that such an approach cannot give an answer to the magnitude of the error in positioning the manipulator. Widening the circle of possible causes of error, with the inclusion of non-geometric errors,[1,7] supported by significant experimental investigations, has enabled the quantization of the influence of some errors upon the position accuracy of robots. Calibration has enabled the achievement of accuracies of the order of the robot's repeatability.

Experimental investigations, as well as most theory, relate to serial link manipulators with all rotary joints (Unimation PUMA-like robots). The experimental results are closely connected to the design of the robot investigated (PUMA 560) and can hardly be applied to others. This design has a d.c. motor drive system and multi-stage gear reduction with the possibility of checking and adjusting backlash. The manual does not publish data for transmission ratios and the number of pulses per revolution of the position encoders. The controller monitor does not show information about the joint angles at any given configuration of the robot. If, to this, we add that the authors did not know the deviation of the geometry of the manipulator links, then we can fully understand the problems with which the investigators were faced, as well as the complexity of the experiments that they have conducted. Having in mind that the necessary calibration procedure should primarily be made by the robot manufacturer, who is acquainted with all this information, we could expect simplification of the experimental procedure for robot calibration.

Our investigations[12,13] were directed toward finding the position accuracy and repeatability as well as the static stiffness of a robot with a parallel mechanism, which is substantially different from the PUMA 560, and, more important, with a computer that can show the joint angles. At the same time we were able to obtain data for transmission ratios and the resolution of the position encoders.

This approach enabled widening investigations toward the quantification of algorithmic and computational errors, as well as position encoder resolution errors. Within the static stiffness investigation the dominant sources of error in the robot manipulator were determined.

Before we discuss the results of our investigations, we will mention the influence of the chosen structure of the robot manipulator on its position accuracy and repeatability.

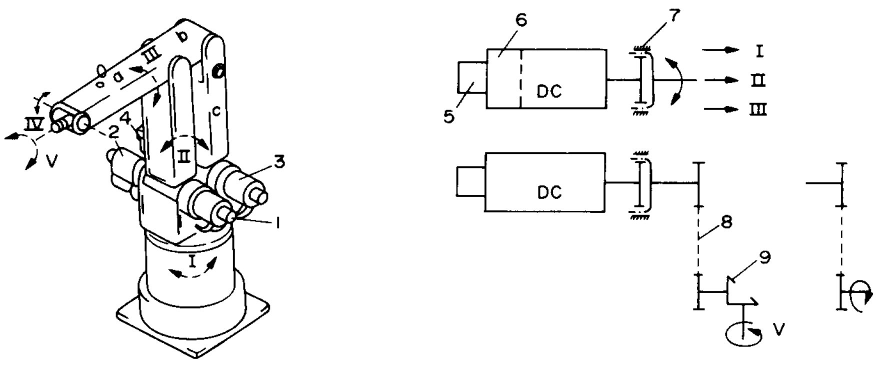
Position accuracy and robot repeatability directly depend on the chosen manipulator structure. From the aspect of achieving high accuracy the most suitable is the structure of Cartesian coordinate robots (CCR), while the least suitable is the structure of articulated robots (AR). This comes directly from the necessary mathematical transformations which determine the position of the end-effector depending on the joint angles. Errors in link geometry and joint angles cause significantly larger errors in an AR in comparison with a CCR.[11] In addition to this deficiency of the AR, it does not enable practical realization of a direct measuring system, which can easily be accomplished with a CCR. These advantages of the CCR are emphasized more in their application in cases where not only does better accuracy become apparent but also increased load capacity and speed, which reaches 120 m/min. Such an example is the loading of CNC machine tools, where gantry robots are used more often. In spite of all these advantages of the CCR, most investigations concern ARs. These can be justified by the challenge to the investigator faced by finding the solution to a large number of problems concerning this structure. Many problems in the practical use of robots could be avoided if, instead of AR, CCR was chosen. In that respect more attention should be paid to the choice of robot structure for particular applications, not neglecting the advantages of AR expressed in larger universality, flexibility and compactness.

2. EXPERIMENTAL INVESTIGATIONS OF POSITION ACCURACY AND REPEATABILITY

The GE-50 robot, whose general appearance and kinematic scheme are shown in Fig. 1, has been investigated. Measuring set-ups are shown in Fig. 2. Our objectives in studying algorithmic and computational errors are to quantify these errors and to compare the significance of these errors relative to others. In the experiments, the wrist center point of the P-50 was commanded to move in the x, y or z direction 300 mm from an initial configuration, as shown in Fig. 3.

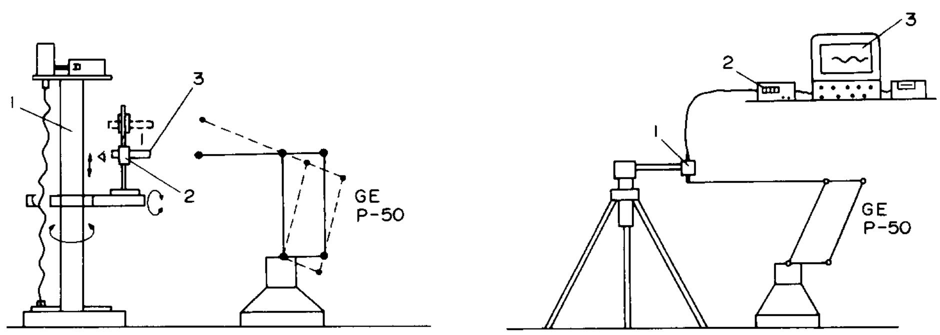
This can be done using the shifting function of the P-50 controller software. The vernier gauge was always made to move parallel to the line of movement of the robot wrist center point, which is essential for having an accurate measurement.

Two cases were tested for a robot moving in each of the x, y and z directions. The joint angles and the wrist center position errors generated by the P-50 controller together with those based on our inverse kinematics computations are compared in Table 1.



(a) (b)

Fig. 1. The GE-50 robot with a parallel mechanism (a) and kinematic scheme (b): 1, 2, 3, 4—d.c. motors, 5—encoder, 6—break, 7—harmonic drive, 8—chain, 9—gears.



(a) (b)

Fig. 2. Set-ups for measuring: (a) algorithmic and computational errors (1—structure, 2—vernier gauge, 3—microscope) and (b) digital quantization errors (1—LVTD probe, 2—digital display, 3—data acquisition system).

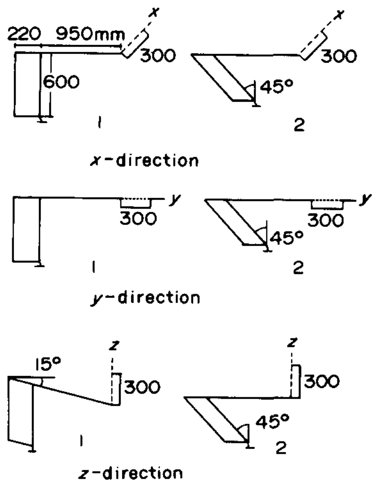


Fig. 3. Case tested in the investigation of algorithmic and computational errors.

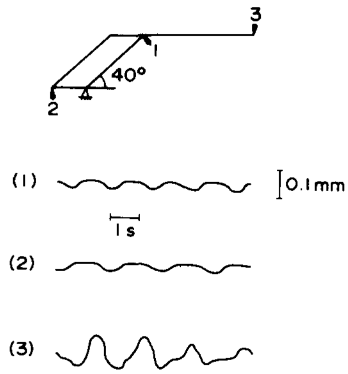


Fig. 4. Time histories of positions measured at three points on the robot body.

Table 1 shows that our position errors are significantly less than those generated by the P-50 controller. Since we calculated the joint angles using inverse kinematics equations, we had essentially bypassed the trajectory interpolation algorithm used by the robot controller. Therefore, the differences between the position errors generated by the P-50 controller and those based on our computations are algorithmic and computational errors. Our errors should then account for all of the position errors due to other sources (mainly geometry errors because harmonic drive transmissions are characterized by zero backlash and minimum tooth-to-tooth errors[8]). Apparently the inaccuracy of this robot is caused mainly by algorithmic and computational errors.

The optical encoders used in the P-50 have a resolution of 500 bits/rev. The gear transmission ratios of the shoulder joint and the elbow joint are 128 and 131, respectively. Based on these values, one encoder bit corresponds to 0.005625 ° for the shoulder joint rotation and 0.005496 ° for the elbow joint rotation. These finite encoder resolutions cause angular position errors in the shoulder and elbow rotations. These errors propagate to generate errors in the positioning of the robot wrist. It was observed from the P-50 controller display that the least significant bit of the encoder reading floats between 0 and 1 periodically. This fluctuation of the encoder reading can be regarded as an instability induced by digital quantization. Figure 4 shows the time histories of the positions measured at three points, in which the arrows indicate the probe orientations. The peak-to-peak displacements due to finite encoder resolution calculated at points 1, 2 and 3 are 0.05, 0.021 and 0.127 mm, respectively. These values agree fairly well with the peak-to-peak displacements shown in Fig. 4.

Note that the peak-to-peak displacement at the wrist center point is of the same order of magnitude as the repeatability error of the robot specified by its manufacturer.

When, during our investigation, we excluded the effect of digital quantization by taking the mean value of the signal, we obtained an extraordinary value of repeatability of from 0.003 to 0.008 mm, which is far below that given by the manufacturer (0.2 mm). It is obvious that this repeatability error is systematic in nature, caused by low encoder resolution. To reduce the effect of digital quantization, a high resolution encoder may be used. However, this will incur a higher cost and will require a faster computer to process the data.

3. AN INVESTIGATION OF STATIC STIFFNESS

Investigations of the static stiffness are different from those connected with position accuracy and repeatability because they are performed when the manipulator is loaded by an external force. These investigations should be carried out independently of the previous ones due to the fact that the errors which

Table 1. Joint angles and end-effector position errors generated by the P-50 vs. those based on our inverse kinematics computation

		P-50 data			Our data			Position error (mm)	
Director	Case	θ_1(deg)	θ_2	θ_3	θ_1	θ_2	θ_3	P-50	Ours
	1	19.299	85.174	0.158	19.440	85.087	0.149	3.05	0.68
X	2	34.858	33.159	5.238	35.171	32.846	5.388	4.37	0.48
	1	0.045	10.637	11.091	0	10.361	11.259	1.45	0.89
Y	2	0.034	30.611	5.755	0	30.446	5.586	1.55	0.58
	1	0	2.143	5.380	0	2.401	5.436	0.48	0.01
Z	2	0	39.642	17.970	0	39.398	17.885	0.20	0.08

appear in the positioning of the end-effector are caused by different sources.

The author was not able to find the results of large investigations concerning the static stiffness of robots in the available literature. Very often the known fact that robots are characterized by low stiffness is repeated, without quantification and presentation of the static model. In Ref. 7, some results from the investigations of a PUMA 560 are given, but only as a part of total experimental investigations, without paying more particular attention to them.

We dedicated a significant part of the complex investigations of the GE P-50 robot to the investigation of the static stiffness.[12] We will not describe the detailed procedure for the calculation of stiffness, nor give the complete results from the investigations, but we will show the manipulator model used for static stiffness analysis (Fig. 5) and experimental set-up (Fig. 6).

The deflection of the end-effector accounts for elasticity existing in the following mechanical components:

(1) the driving and transmission elements,
(2) the link structure, and
(3) the bearings.

For a given force, the deflection of each of these elements was derived, and the resultant deflection of the end-effector was obtained as the sum of the deflections transmitted from the deflections of individual elements.

The major objectives of the experiments were to:

(1) Determine the relative significance among deflections due to joint, link and bearing deformations.
(2) Obtain the stiffness coefficient of each joint.
(3) Verify the validity of the analytical model.

The calculations and the experiments have shown that, for the maximum permitted loading of 90 N, deflections of the link structure, reduced to the end-effector, are smaller than 0.001 mm, while those of bearings are within hundredths of millimeters. The total deflections are within 0.81–2.83 mm, which obviously confirms the domination of elasticity in the driving and transmission elements. This confirms the statements given in Ref. 7.

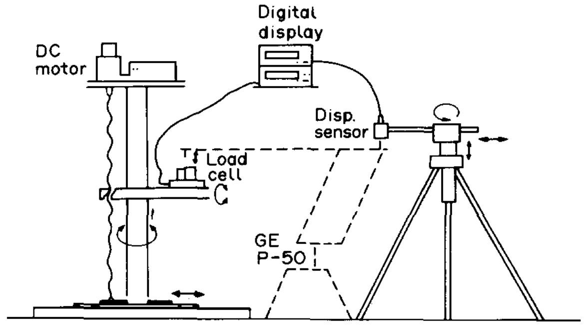


Fig. 6. Scheme of the experimental set-up for stiffness testing.

The coefficients of joint stiffness obtained by experiments are the following (for notation see Fig. 5):

K_1 (based rotation) = 37,580 Nm/rad
K_2 (upper arm) = 66,120 Nm/rad
K_3 (forearm) = 80,280 Nm/rad
K_4 (wrist bend) = 1420 Nm/rad.

The low stiffness of the wrist joint suggests that the chain drive between the shoulder and the wrist is much more compliant than the harmonic drive. In Ref. 7 for the PUMA 560 (classical gear drives are used), for both links the author gives coefficients of 77,000 Nm/rad and 16,000 Nm/rad (which would correspond to the joint stiffness K_2 and K_3), while for the wrist the results are not given. If for the P-50 the difference in joint stiffness is within 1:2 (for the compared links), for the PUMA 560 this difference is within 1:5, which is directly dependent on the type of the drive and quality of the design. The advantage of the harmonic drive is obvious.

We will also compare the results obtained from investigations of static stiffness carried out in machine tools. The minimum stiffness of the working spindles is recommended to be 200 N/μm, and usually that stiffness is much higher, within the limits of 500–900 N/μm. In robots, of course, deflection very much depends on the configuration in which the experiments were made. In our case the deflections were from 0.81 to 2.83 mm, which gives a stiffness within 0.03–0.1 N/μm, for a load of 90 N. If we compare that with the minimum accepted machine tool stiffness then it is from 200 to 667 times less, and in practice this difference is even much bigger and can be taken as real up to 2000 times less. According to Ref. 7, we can have a stiffness of 0.034 N/μm, which can be even much worse because it does not take into consideration the wrist deflections.

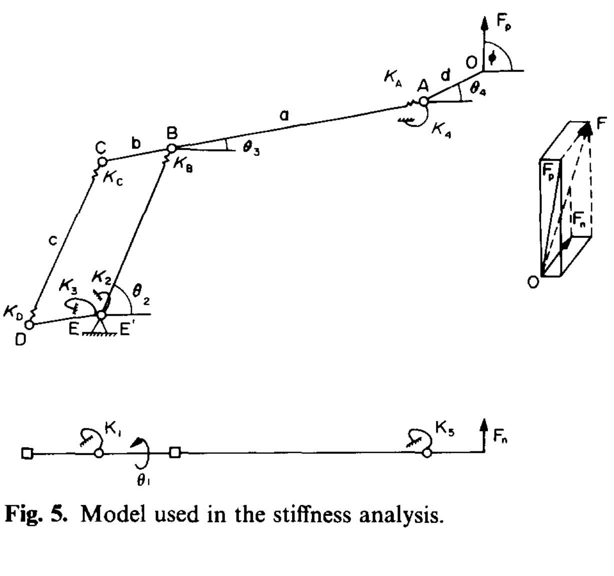


Fig. 5. Model used in the stiffness analysis.

In conclusion we can state that the dominant influence of stiffness in the driving and transmission elements is evident. The new transmissions, such as harmonic drive, represent a perspective solution which can enable an increased stiffness in the future.[8] Future investigations of this problem will also have to include those structures that have ball screws as a transmission element.

4. HOW WE REACH A HIGH ACCURACY WITH A CNC MACHINE TOOL

The results and methodology discussed below are not aimed to suggest their direct application in robots. It would be hard to establish an identity between these two kinds of machines because there is no such identity in their application.

In spite of the application of high-precision components and technology for manufacturing all parts of the NC machines, they still do not ensure the high precision which they should commonly have. This is supported by results gained from an investigation into the positioning accuracy of a CNC milling machine, along the X-axis (Fig. 7, curve 1). The position check was done using a Mitutoyo measuring comb, which guarantees deviation in length smaller than 0.001 mm (at 20 °C). As can be seen from the figure, significant deviations are present (up to 0.06 mm), with which the machine would virtually not be usable in practise. The machine is supplied with a modern CNC controller (Heidenhain 355B), which enables the inclusion of error correction in positioning. The software corrections of position deviations, as well as direct linear encoders, have enabled the achievement of an extraordinarily high accuracy, within 0.005 mm (line 2, Fig. 7).

It should be noted that temperature has a significant influence on position accuracy. Our experiments confirmed the data given in Ref. 7 that with a coefficient of thermal expansion of 10^{-5}/°C, a difference in temperature of 10 °C causes a 0.1 mm change of a 1 m length. The results were obtained by measuring the change in the length of a Mitutoyo measuring comb at different temperatures. Measurements were performed with a high precision coordinate measuring machine (CMM-Leitz Co.). The 355B CNC controller allows the connection of a temperature sensor and correction of temperature deviations.

All the above, together with careful design of all parts, enable ease of programming, with the application of the off-line method, which makes NC machines the basis of CIM systems. With their robustness and reliability, they are the necessary basis for the application of artificial intelligence methods to the control of standalone machines and integrated systems of machines. The high quality achieved, without doubt, is the result of the presence of standardized methods for machine tool testing, established at the beginning of this century.[15]

Certainly the experience gained in CNC machine tools should also be transferred more intensively into the design of robots, because many problems which researchers and manufacturers of robots encounter can be solved using the methods applied to CNC machine tools.

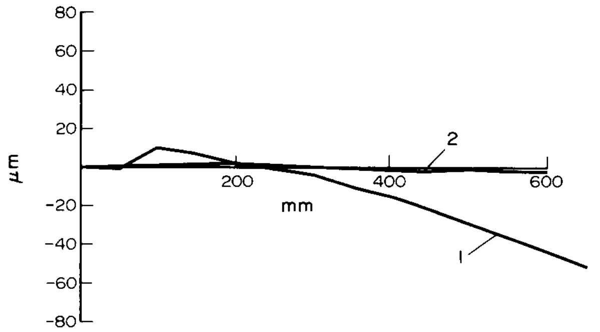


Fig. 7. Positioning error investigation of a CNC milling machine before (line 1) and after calibration (line 2).

5. CONCLUSION

The results of the investigations of robot accuracy discussed in this paper show that the essential source of bad position accuracy is to be found in algorithmic and computational errors. It is obvious that the problems connected with interpolation methods and algorithms have not been solved successfully, and this is a necessary condition for the implementation of off-line programming. Unfortunately, this problem has been very little dealt with in the literature. The application of on-line programming avoids this problem, however this cannot give spectacular results, either in manufacturing highly intelligent robots, or in their wide integration within the CIM environment. With on-line programming, robots remain hopelessly tied to programming by learning, which is slow, dependent on the operator and, more importantly, does not allow the same results with different samples of one type of robot. The common opinion that position accuracy is exclusively the result of the geometric and non-geometric errors should be corrected and should take into consideration the fact that algorithmic errors in interpolation methods can be the dominant sources of low accuracy.

The criteria for the design of robots have not been defined yet. Questions arise concerning their coordinate system, drive and transmission elements and encoders and their location. A deeper investigation of all these problems will remove the belief that robot accuracy should be sought exclusively through software, and that precise manufacturing of robot parts is an expensive solution.

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