PERFORMANCE DATA FOR EVALUATION OF INDUSTRIAL ROBOTS

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Abstract. *The objective of the achievement of performance tests in industrial robots is the checking of necessary data for comparison of the characteristics of different robots, as well as for an eventual maintenance of the equipment. In a standard test we determine the following data: geometrical values, kinematical values, values of power and noise, and dynamical values. The objective of the work presented here is evaluate these data, your characteristics and related problems. The problem of vibrations is one of the main problems that must be considered in the project and in an eventual analysis of defects too. Not only the problem of vibrations will be approached, but also some concepts related to tests and diagnosis of problems in robotics. One of the great obstacles in the evaluation of robots is the possible existence of distinct problems, some of them still unknown, who can occur for diverse causes. In the area of mechanical projects, and in particular in the development of robotic systems, we attempt to minimize the eventual problems that can appear after the final construction of the equipment, performing several improvements in the project. These improvements are only possible through the study of the data presented here.*

Keywords: *Performance tests, Industrial robots, Maintenance.*

1. INTRODUCTION

Industrial robots are programmable multifunctional mechanical devices designed to move material, parts, tools, or specialized devices through variable programmed motions to perform a variety of tasks. An industrial robot system includes not only industrial robots but also any devices and/or sensors required for the robot to perform its tasks as well as sequencing or monitoring communication interfaces (OSHA Technical Manual, http://www.osha.gov). Industrial robots are available commercially in a wide range of sizes, shapes, and configurations. They are designed and fabricated with different design configurations and a different number of axes or degrees of freedom. Diagrams of the different robot design configurations are shown in Fig. (1).

The objective of the achievement of performance tests in industrial robots is the checking of necessary data for comparison of the characteristics of different robots, as well as for an eventual maintenance of the equipment. According to Warnecke *et al.* (1985), a program of standardized tests can be used to evaluate the necessary characteristics to resolve a specific problem of a robot. It can also be determined the weak points in prototypes, to making possible a change of the control design and/or the project of structure. Moreover, it can be evaluated the robot in the course of a long period of operation, determining the behavior of the components, what is important for predictive maintenance. Parker and Draper (1999) present an excellent work about the maintenance and repair of industrial robots.

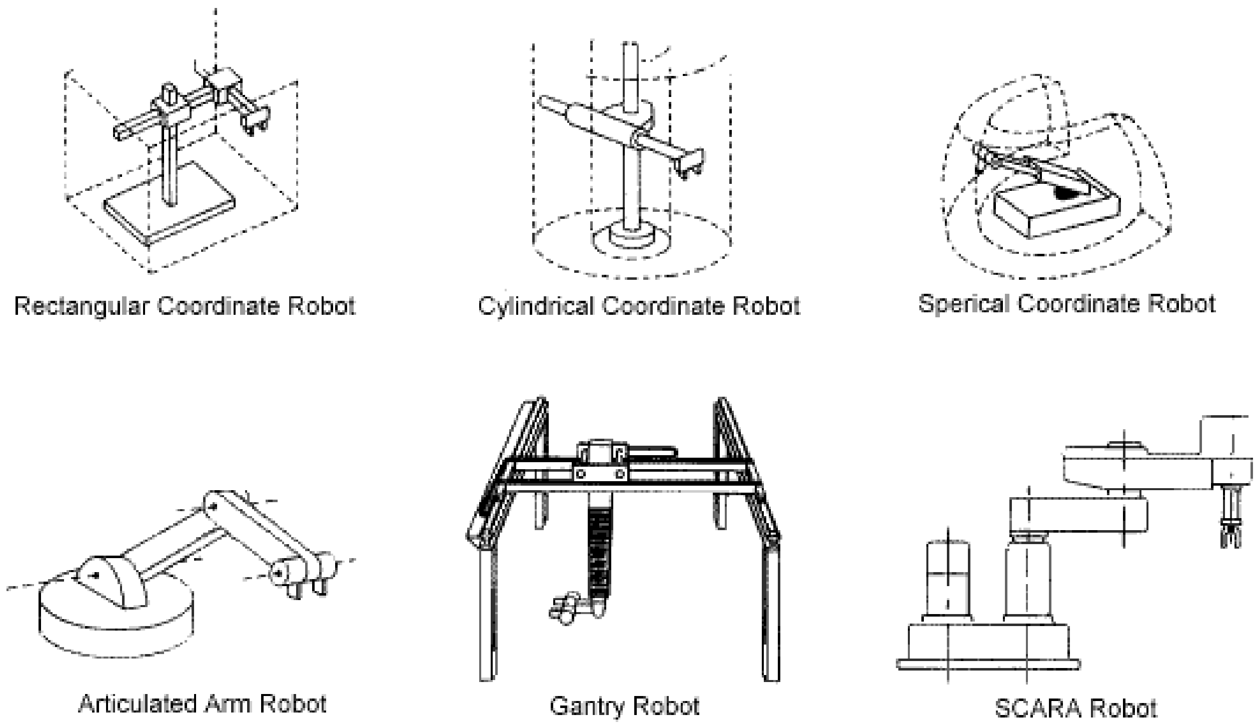

Figure 1. Industrial robots (OSHA Technical Manual, http://www.osha.gov).

An inspection program of robots should include, but not be limited to, the recommendations of the robot manufacturer and manufacturer of other associated robot system equipment such as conveyor mechanisms, parts feeders, tooling, gages, and sensors. A complete test of measurement includes recording devices with diverse channels for receive the signals. In a standard test sequence for industrial robots we determine the following data: geometrical values, kinematical values, values of power and noise, and dynamical values. The objective of the work presented here is evaluate these data, your characteristics and related problems.

2. EVALUATION OF THE GEOMETRICAL VALUES

The following geometrical values must be evaluated: workspace, static behavior, precision of the positioning (repeatability, errors of inversion), precision of the trajectory and the problem of “overshoot”, performing of very small steps, precision of the course synchronization and influence of the temperature on the components.

2.1. Workspace

The workspace is the covering reached for the center of the interface between the wrist and the tool using all the possible movements of the axles. It must be observed the clear separation of the axles of the arm, wrist and gripper, as shown in the Fig. (2). It must be prevented problems with the possible collision of the axles and expect the difference between the mechanical workspace and control workspace (structural tolerances and action radius of the systems of measurement of the trajectory).

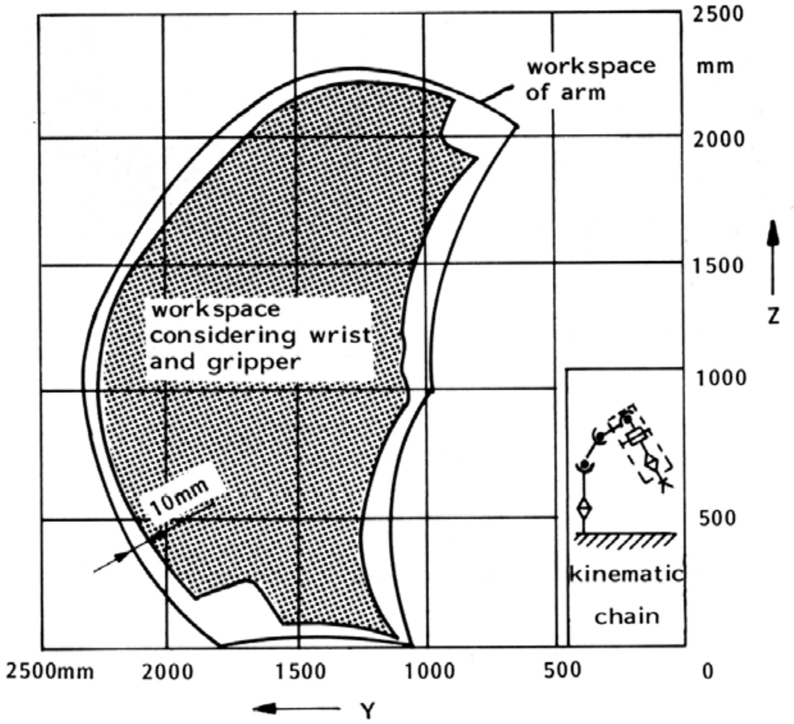

Figure 2. Workspace of arm versus workspace of wrist and gripper (Warnecke *et al.*, 1985).

2.2. Static Behavior

The static behavior supplies an indication of deformations of a fixed structure of the robot under different forms of loading. It must be evaluated the elastic behavior of the structure and axles to verify the necessity of compensation of errors of the regulator and to find potentially weak points in the axles. Figure (3) shows a typical example of some results of test. In this case the last axle demonstrates a nonlinear behavior and will be considered as weak point of the project.

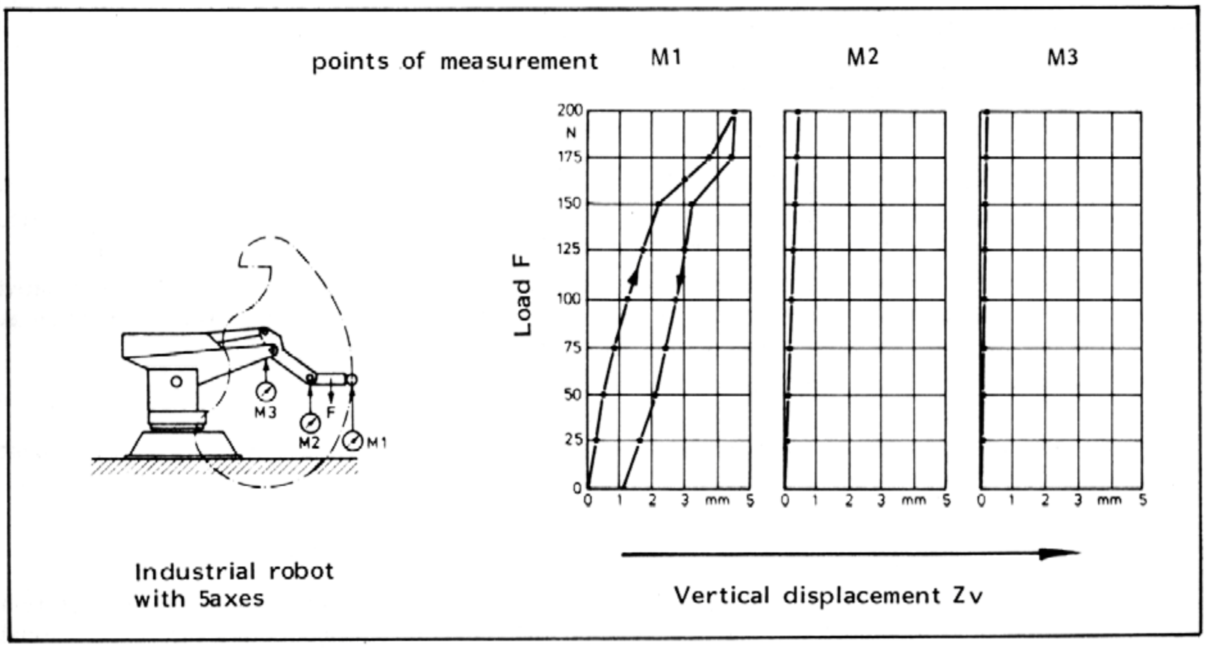

Figure 3. Static behavior of the different axles of a robot in function of the required loading (Warnecke *et al.*, 1985).

2.3. Precision of the Positioning

The precision of the positioning is defined as the precision in the repetition that can be reached with nominal loading and normal operating temperature. In this case, two distinct phenomena must be considered: the repeatability and the error of inversion.

The repeatability is related with the divergence between the positions and orientations reached to the end of some similar cycles, and the errors of inversion are characterized by divergence between the positions and orientations reached to the end of some different trajectories. The evaluation of these phenomena is important for robots with point to point control (PTP) or with control for continuous path (CP) and tasks PTP.

2.4. Precision of the Trajectory

The precision of the trajectory of a robot indicates the precision level that the programmed curves of course can be performed with a nominal loading. The following test methods are common:

- photogrammetry – the movement is registered by the use of two or more cameras. It is a method that supplies correct results, being able to be used for some ends, however the evaluation of data is very complicated;
- external measurement for laser system – it can be used with some objectives, however the cost is increased;
- scale in the space with measurement system for induction – restricted to trajectory with straight movements.

In despite of the restriction, this last method is more used, therefore it presents the best conditions: it is economic, very accurate, easily evaluated, and the majority of tasks CP have trajectories with straight lines.

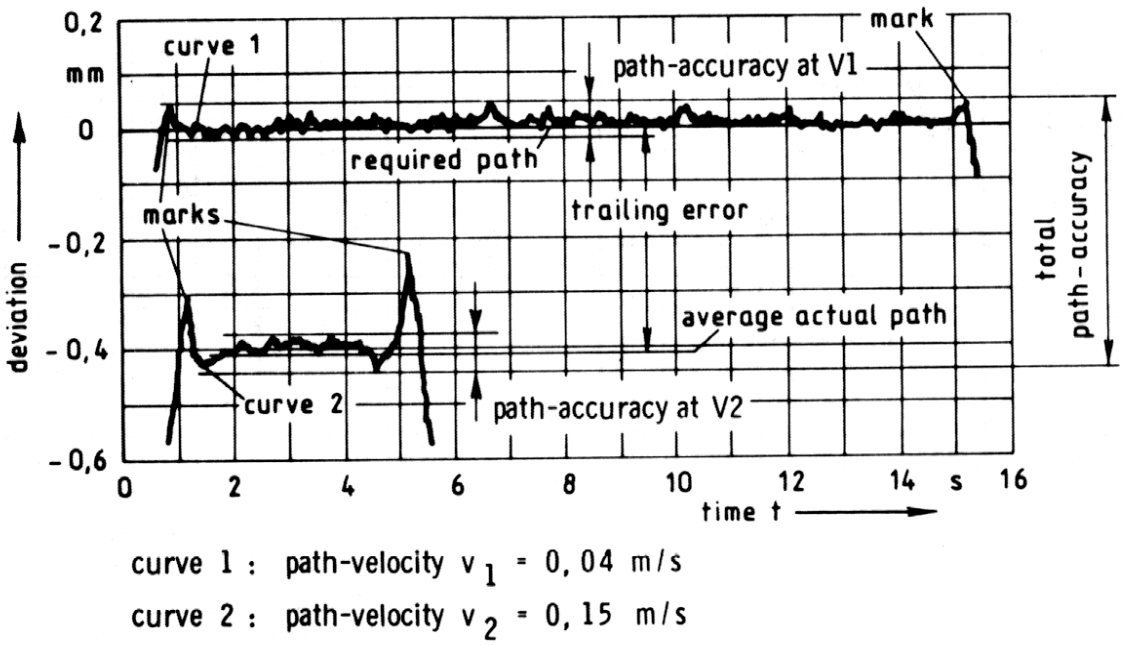

Figure 4. Precision of the trajectory – typical errors (Warnecke *et al.*, 1985).

Figure (4) shows the following typical errors in the precision of the trajectory for a robot:

- average dispersion error of the trajectory described for the effect of randomic deviations from the straight line of reference;

- trailing error or average deviation of the trajectory, whose value represents the difference between the current average trajectory and the straight line of reference;
- "overshoot" – one of the main problems that can occur in the course of a determined trajectory. The robot exceeds a predetermined point to stop. This occurs due to violent changes in the direction and mass, and during the acceleration and deceleration.

2.5. Performing of Very Small Steps

With very low speeds the "stick-slip" effect (static friction in sliding friction) can become a serious problem. This phenomenon is difficult of being controlled, and the measurements can be made by the same methods used in the evaluation of precision of the trajectory.

2.6. Precision of the Course Synchronization and Influence of the Temperature

In some cases the robot must make tasks that are synchronized to the transporting movement, as for example, in the painting with spray and the assembly. In this case the precision of the course synchronization, considering the movement of the robot and the speed of the transporting belt, is very important.

In relation to the temperature, a test of long-term behavior supplies information about the required time to reach the thermal stability (deviations that depend on the temperature). Changes in the temperature produce deviations in the structure, what is always important in the project of hydraulic units. The temperature is measured in different points and the infrared cameras are used in the search of weak thermal points.

3. EVALUATION OF THE KINEMATICAL VALUES

In relation to the kinematical values, the following data must be determined:

- cycle times reached by a sequence defined in different areas of the workspace. In many cases the manufacturer of the robot supplies information about speed and acceleration of the axles;
- the acceleration in the performing of a trajectory and the maximum and average speeds measured by the integration of the acceleration. The measurement is made by three-dimensional devices with inductive and piezoresistives accelerometers.

4. EVALUATION OF THE VALUES OF POWER AND NOISE

For the case of powers, maximum and average values must be determined in continuous operation. With pneumatic robots, for example, the volumetric draining is an important cost factor.

The measurement of noise is made to one meter of distance from the workspace. The number of measurement points is equivalent to the difference between the intensity of maximum and minimum noise in decibels.

5. EVALUATION OF THE DYNAMICAL VALUES

Besides the measurement for squeeze force it is important to know the dynamical behavior of simple components and the all structure. Here the experimental modal analysis is the tool used for the project of the robot (Warnecke *et al.*, 1984, and Dagalakis, 1983). With this method is possible to insert response data to a determined loading and to extract the modes of vibration without any assumption about mass distribution and tensions. The result is a set of information including frequency, damping, amplitude, phase, and residues.

It is possible to extract the response of the robot structure through some methods of excitement, as for example, a hammer. With these data a mathematical model for future improvements of project can be created. Another method involves the measurement of data from systems of measurement of trajectories and some places in the hand of the robot. Both methods can also be used for tests during a long period and as tools for preventive and predictive maintenance. In relation to the predictive maintenance, the monitoring of the robot functioning is perform through the proper instruments for pick up of vibrations, that as will be seen to follow, can create a series of complications to the robot structure.

6. VIBRATION PROBLEMS

The effects of inertia and flexibility create mechanic resonance, which frequently has harmful effect, especially in low frequencies when the amplitude is generally significant. This doesn't only result in uncontrolled oscillations in the desired trajectories (particularly causing "overshoot") but also in the long times of stabilization, depreciating the advantages of these essentially fast systems. The robots operate under changeable conditions, and the probability of excitement for some vibratory modes during any movement of the mechanism is great (Lhôte, 1984). In this way, it can be made a series of tests with monitoring and diagnosis of problems, and the solutions can be found in a number of different forms.

6.1. The Control System

A method that can be considered to form an accurate dynamical model and execute calculations online is that one in which the movement and damping is made in some controllable modes. This can be complex in, for example, models with variable and nonlinear parameters that frequently are not known (as loading and friction). Exist other modes not influenced for the control systems, are transversal modes related to the articulated axles.

6.1.1. The Response Speed and Stability

The response speed and stability are two important characteristics of the dynamical performance related with the project of control systems. The response speed mentions the capacity of the robot to move itself for the next position in a short period to time. This time of response is obviously related with the speed of robot movement. The stability generally is defined as a measure of the oscillations that occur in the arm of the robot during the movement of a position for the next one. A robot with good stability will present little or no oscillation during or in the ending of the movement of the arm. In the project of control systems generally is desirable good stability and fast response time. Unfortunately these objectives are competitors.

The stability of a robot can be controlled, of certain form, by means of the incorporation of damping elements in the project of the robot, reducing the tendency for oscillation. However, the problem with the improved damping is that it reduces the response speed (Groover *et al.*, 1989). The concept of stability and its relation with the damping are illustrated in Fig. (5).

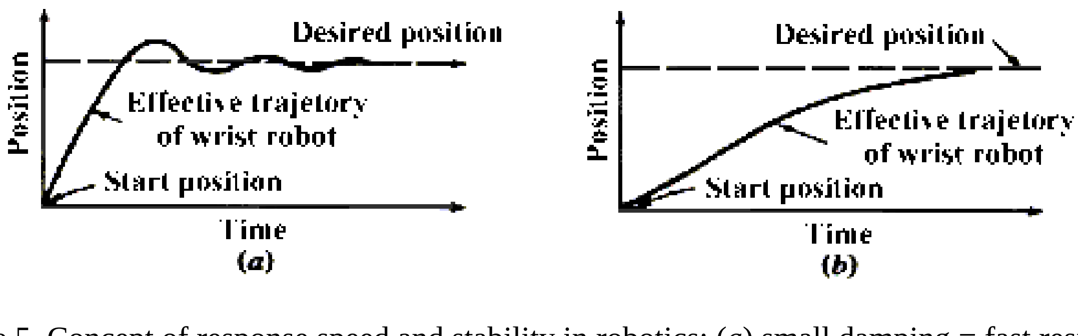

Figure 5. Concept of response speed and stability in robotics: (*a*) small damping = fast response, but instability; (*b*) great damping = stability, but slow response (Groover *et al.*, 1989).

In the two diagrams of the Fig. (5), the position of the robot wrist is shown in function of the time for the two cases: small e great damping. With a small damping, the robot arm is moved quickly for the programmed position, but presents considerable oscillation around the position. With a great damping, the movement of the arm for the desired position is very slow, but doesn't have oscillatory movement around the final position.axles.

6.2. The Robot Structure and Dynamical Balancing

In relation to the structure, a stiffness increase is frequently desirable because allows: good static precision and low vibrations – high frequencies and insignificant amplitudes reflect in the choice of the technological components, as well as in the construction, with a frequent increase of the weight and the size of the arm. The elasticity of the arm can be controlled by system acting on the workspace, but this would not give account the transversal modes.

Structures that are not balanced can have asymmetrical forces on the joints, what can lead to an oscillatory behavior. This can be eliminated by the study of weight compensation for all types of robotic systems.

6.3. The Damping of the Structure

The friction between the joints is a cause of damping. The dry friction is more common than the viscous friction. It results in moderate damping of great amplitude movements. Unfortunately the modeling in low speed is not sufficiently precise to be used in the determination of speed characteristics. These characteristics generally are introduced by a tachometric effect in the calculation of the necessary damping in the minimum favorable case (or either, minimum or insignificant dry friction). The increase of the friction between the segments is not recommendable, particularly in robots of changeable sequence (with servo-control system), in which it presents a notable loss in the precision (Lhôte, 1984).

The dry friction doesn't have to be confused with hysteresis caused for the movement in the transmission systems. It has a favorable effect in the stability, but he doesn't introduce any static error if included in the circuit of the servo-control system (sensor placed in the joint).

In relation to the small transversal movements (flexion or torsion of segments), the damping can be made by the introduction of a material in the outside of the desired parts (synthetic foam rubber).

7. TYPES OF ROBOTS AND APPLICATIONS

Industrial robots do jobs that are difficult, dangerous or dull. They perform the same job with precision and don't get tired, as well as don't make errors associated with fatigue and so are ideally suited to performing repetitive tasks. The robots if differentiate for the form that are controlled and are programmed, and its applications are related to the mechanical structure of each model. Among the recent works related to the study of the types of industrial robots and its applications they are distinguished Niku (2001), "Robots/Automation Devices" (2003) and "Types of Robots" (2003).

In relation to the form of control, all industrial robots are either servo or nonservo controlled (OSHA Technical Manual, http://www.osha.gov). Servo robots are controlled through the use of sensors that continually monitor the robot's axes and associated components for position and velocity. This feedback is compared to pre-taught information which has been programmed and stored in the robot's memory. Nonservo robots do not have the feedback capability, and their axes are controlled through a system of mechanical stops and limit switches.

Industrial robots can be programmed from a distance to perform their required and preprogrammed operations with different types of paths generated through different control techniques. Table (1) shows the three different types of paths generated and its characteristics (OSHA Technical Manual, http://www.osha.gov). Table (2) shows the main types of industrial robots and its applications ("Types of Robots", 2003).

Table 1. Types of paths generated and its characteristics.

Path	Characteristics
Point-to-Point	Robots are programmed to move from one discrete point to another within the robot’s working envelope. In the automatic mode of operation, the exact path taken by the robot will vary slightly due to variations in velocity, joint geometries, and point spatial locations.
Controlled	The path or mode of movement ensures that the end of the robot’s arm will follow a predictable (controlled) path and orientation as the robot travels from point to point. The coordinate transformations required for this hardware management are calculated by the robot’s control system computer.
Continuous	A robot whose path is controlled by storing a large number or close succession of spatial points in memory during a teaching sequence is a continuous path controlled robot. During this time, and while the robot is being moved, the coordinate points in space of each axis are continually monitored on a fixed time base, e.g., 60 or more times per second, and placed into the control system's computer memory. When the robot is placed in the automatic mode of operation, the program is replayed from memory and a duplicate path is generated.

Table 2. Types of industrial robots and its applications.

Robot	Applications
Cartesian/Gantry	Used for pick and place work, application of sealant, assembly operations, handling machine tools and arc welding.
Cylindrical	Used for assembly operations, handling at machine tools, spot welding, and handling at die-casting machines.
Spherical/Polar	Used for handling at machine tools, spot welding, die-casting, fettling machines, gas welding and arc welding.
SCARA	Used for pick and place work, application of sealant, assembly operations and handling machine tools.
Articulated	Used for assembly operations, die-casting, fettling machines, gas welding, arc welding and spray painting.
Parallel	One use is a mobile platform handling cockpit flight simulators.

8. FINAL CONSIDERATION

The work presented here consists of the analysis of performance data for evaluation of industrial robots, as well as the characteristics and problems related to these data. After this analysis becomes possible to evaluate the importance of some aspects related to the performance data and tests. Amongst them we can detach the following ones:

- From the presented and studied data and procedures is possible to evaluate the characteristics of diverse industrial robots, as well as using the tests as tool for monitoring and diagnosis of problems.
- The problem of vibrations is without a doubt one of the main problems that must be considered in the project and in an eventual analysis of defects too, not only of robots, but also of diverse other mechanisms. The monitoring of vibrations supplies a series of resources very used in the predictive maintenance.
- One of the great obstacles in the evaluation of robots is the possible existence of distinct problems (each problem is a problem), some of them still unknown, who can occur for diverse causes.
- In the area of mechanical projects, and in particular in the development of robotic systems, we attempt to minimize the eventual problems that can appear after the final construction of the equipment, performing several improvements in the project. These improvements are only possible through the study of the data presented here.
- Naturally, the data and tests presented here also can be used as tools for maintenance of the industrial robots.

9. ACKNOWLEDGMENTS

The authors would like to express their gratitude to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the financial support provided during the course of this present research.

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