MECHANICAL DESIGN OF ROBOTS

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Preface

The design of robots is an especially challenging task for mechanical design engineers. It's not because robots are differentiated by cleverness of design or analysis from other machines; rather it is their susceptibility to so many variations that makes their optimum design an illusive target. Furthermore, robots, by definition, are multiple-function machines. The variability of their function and the need for programmability makes it a challenge to define a unique set of specifications that the engineer can comfortably consider adequate for the final design. Even when well-defined specifications are available for a unique, single-process robot, the variability of configuration and programmability makes it difficult to find a reasonable combination of load conditions to base the design on.

Robot designers, having a prevailing background in the design of machine-tool and material-handling equipment, often attempt to design robots with comparable rigidity or use worst-case loading conditions. To their chagrin, they have often realized that such animals could become grossly overweight and highly inept!

While machine tools can accommodate heavier structures when required to attain rigidity, robot performance is usually penalized by the added weight. Similarly, material-handling equipment may have a well-defined configuration and its capacity defined by its worst-loading condition; on the other hand, such conditions occur only infrequently in robots, and, when encountered, their effect can often be fully circumvented by reprogramming or be reduced to a degraded dynamic performance or an emergency stop. In most robot design cases, there is hardly enough justification for adopting a worst-case design approach and paying the penalty with unwarrantedly heavier robots, slower performance, or more costly products. The robot design should be handled on the basis of statistics, with optimum conditions determined on the basis of the probability of the occurrence of combined loads during typical performance cycles.

Therefore, it should be obvious that the design of robots is highly specialized. It has its particulars, not only in determining optimum specifications or representative loading conditions but also in the selection of an appropriate configuration, component, material, or analysis technique and in the determination of their optimum characteristics.

Dr. Rivin's book addresses the latter requirements quite thoroughly. It brings together in one reference the information necessary for the expert design of robots, provided the specifications are given. The combination of basic information on the dynamics of mechanisms, mechanical design of robot components, and the characteristics of unique robotic elements makes it very convenient for robot designers to evaluate and make an informed selection among different options.

Of special interest to the reader should be the thorough treatment of the kinematics and dynamics of robot manipulators, the gravitational counterbalancing of robot mechanisms, and the inclusion of a special chapter on critical design components; the chapter on structural dynamic characteristics of robot manipulators also adds substance to this book.

Dr. Rivin's wide exposure to European and Russian literature, with their unique emphasis on the practical rather than the abstract, makes his book especially unique. This is reflected in the discussion of a collection of several directly applicable examples of wrist designs, robot configurations, and a host of other mechanisms.

There is much that this book offers to the robot design engineer and students of robot design. It should have an impact on future generations of robots by helping the engineers to make better design decisions and to apply better techniques to the design of future robots.

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Introduction

An industrial robot is defined by the U.S. Robot Industries Association (RIA) as a "reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks." Similar definitions are adopted by the British Robot Association, the Japanese Robot Association, etc.

There are several more or less clearly distinguished generations of industrial robots. The first-generation robots are fixed-sequence robots which can repeat a sequence of operations once they have been programmed to do so. To carry out a different job, they have to be reprogrammed, often by "training" or "education."

The second-generation robots are equipped with sensory devices which allow a robot to act in a not-completely defined environment, e.g., pick up a part which is misplaced from its ideal position, pick up a needed part from a batch of mixed parts, recognize a need to switch from one succession of motions to another etc.

The third-generation robots which are emerging now have the intelligence to allow them to make decisions, such as ones necessary in assembly operations (assembling a proper combination of parts; rejecting faulty parts; selecting necessary combinations of tolerances, etc.).

Robots of the first and so-called "1.5" generation (with some sensing devices) constitute the overwhelming majority of robots now in use and in production.

However, regardless of the generation, industrial robots are built of three basic systems:

- The "mechanical structure" consisting of mechanical linkages and joints capable of various movements. Additional movements are made possible by end effectors fitted at the arm end.
- The "control system," which can be of "fixed" or "servo" type. Robots with fixed control systems have fixed (but, possibly, adjustable) mechanical stops, limit switches, etc., for positioning and informing the controller. Servo-controlled robots can be either point to point (PTP),

where only specified point coordinates are under control and not the path between them, or continuous path (CP) controlled, thus achieving a smooth transition between the critical points.

- The "power unit(s)," which can be hydraulic, pneumatic, electrical, or their combination, with or without mechanical transmissions.

Out of these basic systems constituting a robot, the highest degree of attention and development time in the United States has been given to the control system. Such an approach in this country resulted in the clear leadership by the United States in the robotic state of the art. However, the United States is certainly not a leader in robot use, and one of the reasons for this is the difficulty industrial managers have in accepting an extremely sophisticated robot without having had some previous experience with similar but simpler devices. Another reason is the very high cost of a robot which is substantially caused by a low technological level of its mechanical structure.

If we consider a human being as a manipulator, it would be a very effective and efficient one. With the total mass 68 to 90 kg (150 to 200 lb) and its "linkage" (lower and upper arm and wrist) mass 4.5 to 9.0 kg (10 to 20 lb), this manipulator can precisely handle, with a rather high speed, loads up to 4.5 to 9.0 kg (10 to 20 lb); with slightly lower speeds it can handle loads up to 15 to 25 kg (30 to 50 lb), or about one-fifth to one-quarter of its overall mass, far exceeding the "linkage" mass; and it can make simple movements with loads exceeding its overall mass, up to 90 to 135 kg (200 to 300 lb), and in cases of trained athletes, much more. On the other hand, industrial robots have payload limitations (and, in this case, the payload includes the mass of the gripper or end effector) which amount to one-twentieth to one-fiftieth of their total mass, more than 10 times less effective than a human being. And such massive structures cannot move with the required speeds. It was found that human operators can handle loads up to 1.5 kg (3 lb) faster than existing robots, in the 1.5 to 9 kg (3 to 20 lb) range they are very competitive, and only above 9 kg (20 lb) are robots technically more capable. If the mass of end effectors or grippers is considered, which the human operator has built in but which consumes up to half of the maximum payload mass in robots, then one can come to the conclusion that robots with maximum rated loads below 3 kg (6 lb) are mechanically inferior to human operators, in the 3 to 20 kg (6 to 40 lb) range they are comparable, and only at higher loads are they superior.

Since the cost of a control system, which includes sensors and computer hardware and software, does not depend significantly on the robot size, a robot's cost can be influenced to a great degree by the cost of its mechanical system. Also, the technical level of a robot can be greatly improved by perfecting the mechanical system.

For example, benefits which can be achieved by use of vision systems are frequently limited by arm dynamics. It is stated in [I.1] that, while simple scenes can be analyzed by vision control systems in 250 ms or less, it takes 500 ms for the arm of a Unimate 2000 B robot to respond to a small control input. While both time constants have definitely improved since publication time of [I.1], the former one seems to be improving faster than the latter.

In many cases, use of robots in assembly operations leads to reduced productivity because of their slow performance. For example, for a small-part assembly operation, which is performed by a human operator in 1.4 s, a PUMA robot requires 3.1 s, a SCARA robot 2.7 s, and a Nippondenso robot 1.9 s [I.2].

For a larger ASEA IRB60 robot (60-kg payload), positioning time was found to be as long as 6 s [I.3].

Recently, special efforts are being extended to develop universal offline programming techniques for robots. However, although the state-of-the-art CAD-CAM systems allow offline programming and computer simulation of robotized operations, unpredictable structural deformations, vibrations, and other dynamic effects that cause deviations from programmed trajectories prevent implementation of offline programming in critical applications.

Since modern robots are largely anthropomorphic (although they have not reached the sophistication and perfection of their divinely created prototypes), it would be reasonable to apply to them an old Roman saying, well proven in ages, "*Mens sana in corpora sano,*"—"Healthy spirit in a healthy body." If the anthropomorphic analogy is extended, the modern state-of-the-art robot can be compared with a bright but physically handicapped person.

Immaturity of mechanical design of robots can be illustrated with one more example. If one compares machine tools designed by various manufacturers, state-of-the-art designs with low-technology designs for developing countries, their similarity is striking. Paraphrasing the Gertrude Stein saying, a lathe is a lathe is a lathe. However, it is not always true for robots. Robots designed and built by machine tool companies look very much like machine tools—they are sturdy and heavy, just like any machine tool, and are usually made with the machine-tool precision. The author once encountered a robot with aluminum links all perforated by "weight-saving" holes; of course, it was designed by aerospace engineers. Many robots look like hoists, gantry cranes, and other traditional material-handling equipment—guess why?

However, robots are very different from any other structures and they have to be designed in a different way. And, as with any other product, an adequately designed robot would perform much better, would weigh much less, and would cost much less.

What are the specifics of the robot mechanical system? First, the robotic structure is a so-called active linkage, whereas each link has its individual power supply which differs from conventional passive linkages, such as a crank mechanism, where all the links receive motion from a single driving member. Thus, each link is performing motions not correlated with motions of other links. Second, the robotic system is in a large portion of its operational time an open chain, when the links are not properly supported and some of them are even cantilevered. Third, this is a servo-controlled system, with specific requirements to its power-transmission components regarding their backlash, stiffness, accuracy of movements, etc. Fourth, since the chain of links, whose configuration is constantly changing, is driven by a torque whose time history is very complex and depends on feedback either from the driven link or from the end of the chain, instability or excitation of some structural vibratory modes in the chain is highly likely.

What benefit can one receive from a better mechanical structure with a lower weight-to-payload ratio and higher stiffness and natural frequencies? A pick-and-place robot or a robot following the sample path can better follow the prescribed positions without (or with a reduced) overshoot at higher speeds. The second-generation robots can have more design flexibility since sensors can be located remotely from the execution point; better accuracy because of reduced static and/or dynamic deformations, which can be especially noticeable for offline programming; less need for very complex so-called "feed-forward" control systems; a faster settling time for a given deceleration and an additional productivity enhancement since deceleration (and acceleration) rates can be increased; and, of course, a more affordable robot because of its lower cost.

There is a substantial potential for designing lighter robotic structures with higher effective stiffness. These factors would result in smaller drive motors which lead to additional weight (and cost) savings.

This book is one of the few book addressing mechanical design of robots. Contrary to other publications, such as [I.4], which emphasize design configurations of typical units, it addresses the more basic topics of mechanical design that are frequently overlooked in the traditional design courses, such as contact stiffness, use of internal preload in mechanical systems, etc., as well as some specific issues of critical importance for optimization of the manipulator structures. Its aim is to help readers—practicing and/or future engineers—deal with specifics of robot manipulators. Since the book is aimed to reach, first of all, mechanical engineers, it addresses the basics of robotic systems with the purpose of developing an understanding of specific phenomena in such systems and specific requirements for their mechanical design.

The contents of the book is organized accordingly. A short Chapter 1 surveys basic parameters of robots in their interdependence and suggests ways to make their specification more beneficial. A critical survey of structural configurations is also given. Issues of kinematics and dynamics are analyzed in Chaps. 1 through 3 for two-degrees-of-freedom (planar) manipulators of all basic types (cartesian, cylindrical-spherical, jointed-SCARA, parallelogram). The two-dimensional approach makes equations less cumbersome and more transparent and allows clear conclusions to be made about ways of decoupling of the various motions; dynamic errors and oscillatory behavior of manipulator structures when their compliance is considered; advisable directions of dimensioning of mechanical structures, etc. The validity of such simplistic models is supported by a straightforward analysis of a three-dimensional jointed manipulator. One can find numerous publications on the comprehensive generalized mathematical treatment of three-dimensional robotic structures, but because of their complexity these publications are not used by "the real people"—mechanical engineers designing real robots. Also, because of a common use of high-level mathematical apparatus, such as matrix calculus, very efficient computational algorithms are generated at the expense of losing physical transparency which is always very important for mechanical designers. The author's hope is that after these designers understand basics as well as potential advantages of such analyses, they would be more willing to utilize available literature and software.

In addition to a comprehensive analysis of an itemized compliance breakdown for robotic structures in Chap. 4 and to rather simple (and well-proven) techniques that allow its analysis in a blueprint stage, substantial attention is given to design techniques (including some novel concepts) that significantly enhance the stiffness-to-weight ratio of a robotic structure. In Chap. 5 special attention is given to the description of specific characteristics of advanced components frequently used or having potential to be used in modern robots. These components are usually provided by specialized manufacturers without adequate and objective information on their positive and negative features. Such in-depth information is also not available in the traditional American courses on machine design. Also described are some novel developments which have a potential to significantly enhance performance of robots and manipulators. Chapter 6 covers some important issues of mechanical design of wrists.

Since Lagrange equations and the principle of virtual work, which are extensively used for dynamic analysis of manipulators in Chap. 3, are not included in many undergraduate engineering curricula, their derivation is described in App. A.

The author hopes that not only students and the established robot designers but also designers of general purpose machinery will benefit from the logical analysis of typical mechanical structures of manipulators and an infusion of some "high technology" information on critical mechanical components and units. Another group of engineers which is expected to benefit from the book are control system specialists. Only a profound understanding of both the behavior and potential for modification of the mechanical system to be controlled would allow the development of high-performance robots.

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Contents

Chapter

1

Basic Parameters and Structural Classification of Manipulators

Robot applications are continuously widening, their functions are becoming more and more complicated, and the optimal robot designs are not yet established. These are some of the reasons for the wide diversity of robot designs. Various basic coordinate frames and arms with different numbers of degrees of freedom are used for robotic manipulators. Their selection in the design stage is dictated by specifications on the basic parameters of a robot.

1.1 Basic Parameters of Robots

Before principal structural designs of robot manipulators are described, it is important to define the basic parameters of robots which are more or less closely associated with the mechanical structure. A list of such parameters includes:

- Payload
- Mobility, i.e., number and range of independent motions [*degrees of freedom* (DOF)]

- Workspace (its volume, shape, degree of redundancy)
- Agility (effective speeds of execution of prescribed motions)
- Accuracy and repeatability of positioning in various degrees of freedom
- Structural stiffnesses (compliances), masses, damping coefficients, and natural frequencies
- Economics (cost, reliability, maintainability, etc.)

Many of these parameters are closely interrelated (e.g., maximum payload, speeds, accelerations, and accuracy, depend on the point of the workspace at which they are being measured). As a result, standard definitions and test procedures are not yet fully developed.

The rated "payload" of a robot is the maximum mass which it can handle *in any configuration* of its linkage; of course, higher payloads can be handled in some configurations than they can in other ones. Since the load-carrying capacity of the system depends not only on the mass of the payload but also on its moments of inertia (depending on size and shape of the payload as well as its distance from the wrist flange), sometimes moments (torques) at the wrist flange are specified instead of or together with the payload mass. Also, sometimes qualified payload magnitudes are specified as functions of the distance from the flange, of the speed and acceleration, etc.

Figure 1.1*a* [1*a*] illustrates load-handling capabilities for various end-of-arm positions in the reachable workspace of a jointed robot as it is limited by maximum torques of joint actuators. The data are given for the arm moving in the x-z plane. Since the axis of the first joint ("waist," see Fig. 1.16) coincides with the z axis, the results also apply to a three-dimensional workspace. The numbers in the inset designate which joint has the limiting torque for the corresponding end-of-arm position (joint 2, "shoulder"; joint 3, "elbow"; see Fig. 1.16). One can see that the allowable payload can vary by 3.5 to 4.0 times across the workspace, and although the rated payload for this robot is about 150 units, it can handle loads above 600 units in some locations. If the designer knows how the manipulator he or she designs handles the payload across its workspace, he or she may find it beneficial to slightly limit the workspace and to substantially upgrade the rated payload characteristic of the robot.

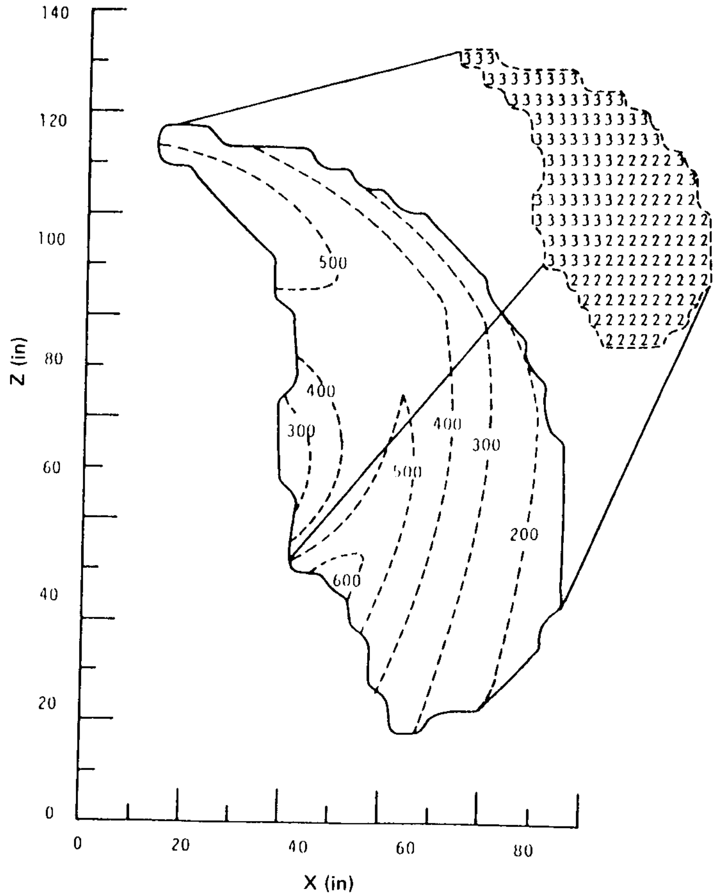
Since the payload is limited not only by joint motor torques but by stresses in the linkage, the payload may differ depending on the environment and on the parameters of motion (magnitudes and/or directions of velocities or accelerations). For example, the Remote Manipulator System (RMS) or Canadarm for the space shuttle (see Fig. 1.17) has the rated payload of 32,000 lb (14,500 kg), but it can handle

65,000 lb (29,500 kg) at lower rates of acceleration [1*b*]. However, both ratings are valid only for the outer space environment since in the earth environment the RMS cannot move even its own linkage [total mass 905 lb (410 kg)], without any payload, because of unacceptable gravity-caused deformations. Usually, the rated payload is given in the robot specifications inclusive with an end-effector (gripper) mass.

The "mobility" of a robot is determined by the total number of independent motions [degrees of freedom (DOF)] which can be performed by all its links. Since the motions can be either translational along a certain axis via a prismatic (P) joint or rotational around a certain axis via a revolute (R) joint, sometimes the "number of axes" term is used instead of "number of degrees of freedom," with a possible abbreviated characterization of joints in the structure (e.g., RPRR means revolute-prismatic-revolute-revolute). The degree of mobility of the end point of the arm is equal to the sum of independent degrees of freedom of all the intermediate links. However, because of the so-called "degeneracy" of both the major and minor (wrist) linkages (see Chaps. 2 and 6), some linkage configurations may have a reduced degree of mobility, thus a six-DOF manipulator may have only four DOF "guaranteed" in all points of its workspace.

For a comparison, the mobility of a human arm is characterized by about 50 DOF, mostly in the wrist. The bone structure of the human arm is shown in Fig. 1.2*a*. Collarbone I can be considered as its "stationary link"; the joint between it and shoulder blade II together with the shoulder joint provide for rotations around the x and y axes (DOF 1 and 2, Fig. 1.2*b*). Upper arm III provides for roll DOF 3; the elbow is associated with bending 4; funny bone IV and radius V provide for roll 5, wrist VI provides for bending DOF 6 and 7. These are regional 7 degrees of freedom of the human arm, while the other 43 DOF are allocated to the fingers. It can be seen from Fig. 1.2*b* that all the main joints in a human arm have at least two degrees of mobility each. As it was recently shown in [2], the introduction of a limited roll mobility in the bending joints of a jointed manipulator is an effective way to eliminate degeneracy-related problems.

The "workspace" of a manipulator is the space composed of all points which can be reached by its arm end or some point on its wrist but not by the end effector or a tool tip. The reason for such a standard is obvious: The workspace is a characteristic of the robot, but end effectors, tools, etc., could have various shapes and sizes, sometimes significantly influencing the dimensions and shape of the effective workspace. Manufacturer specifications may exclude some segments of the kinematically defined workspace if performance with required velocity, payload, etc., is not possible in these segments. Degeneracy in both major and minor (wrist) linkages in certain points of the workspace



(a)

Fig. 1.1 Performance characteristics of a jointed robot through its workspace. (*a*) Payload-handling capability, (*b*) maximum end-of-arm velocity, cm/s, and (*c*) maximum end-of-arm acceleration, in/s^2.