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PERFORMANCE EVALUATION AND DESIGN CRITERIA OF ROBOT DESIGN

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ABSTRACT

The most obvious application of the criteria and tools described in this chapter is in the mechanical design of a robot. Robot design differs from the design of single-degree-of-freedom machinery in that the latter is intended for one specific task, e.g., picking up a workpiece from a belt conveyor and placing it on a magazine. Moreover, the conveyor is synchronized with the manipulating machine and the magazine is stationary, with well-defined locations where each workpiece is to be placed. Manipulation robots, in contrast, are not intended for one specific task, but rather for a family of tasks falling within one class of workpiece motions, e.g., planar, spherical, translational, or motions produced by systems of the Selective Compliance Assembly Robot Arm (SCARA) type, also known as Schönflies displacements. The challenge that robot designers face is therefore one of uncertainty in the specific task that the robot will be required to execute. Design criteria have been devised to help the designer cope with uncertainty as discussed herein.

ROBOT DESIGN PROCESS

Given a family of tasks that constitute the functional requirements in the design process, besides more-detailed design specifications, the role of the designer consists in producing a robot that will meet all the requirements and specifications. The various stages in the robot design job at hand are intended to:

- Determine the topology of the kinematic chain underlying the mechanical structure. Under this item we consider first the robot type: serial, parallel or hybrid. Then, a decision is to be made on the layout of the various subchains in terms of the type of joints, most commonly, revolute and prismatic. Recently, one additional type has been recognized to be equally useful, the Π-joint, coupling two links under relative translation by means of two other links undergoing identical angular displacements, although about different parallel axes. The four links form a parallelogram four-bar linkage
- Determine the geometric dimensions of the various links defining the robotic architecture, as required to fill a table of Denavit–Hartenberg parameters. so as to satisfy workspace requirements. Although these parameters are usually understood to include the joint variables, these variables do not affect the robot architecture; they determine instead the robot posture;
- Determine the structural dimensioning of the various links and joints, as needed to meet static load requirements, where load includes both forces and moments – wrenches – under either themost demanding or the most likely operation conditions, depending on the design philosophy adopted at the outset;

- Determine the structural dimensioning of the various links and joints, as needed to meet dynamic load requirements, where loads are inertia effects of links and manipulated object;
- Determine the elastodynamic dimensioning of the overall mechanical structure, including the actuator dynamics, to avoid a specific spectrum of excitation frequencies under either the most demanding or the most likely operation conditions;
- Select the actuators and their mechanical transmissions for the operation conditions adopted at the outset to cope with task uncertainty.

The above stages can be performed sequentially, in the order given above:

(i) First, the topology is determined based on the family of tasks specified at the outset and the shape of the workspace;
(ii) The link geometry is defined based on the workspace requirements, which include the maximum reach, and the topology defined in stage 1;
(iii) With the link geometry thus defined, the structural dimensioning of links and joints (unless the robot under design is parallel, which does not fall within the scope of this chapter, all joints are actuated) is undertaken, so as to support the static loads assumed at the outset;
(iv) With the links and joints dimensioned for static-load conditions, the link centers of mass and link inertia matrices are determined for a preliminary evaluation of the motor torque requirements (this evaluation is preliminary in that it does not consider the dynamic load brought about by the actuators; this load can be significant, even in the case of parallel robots, which can have all their motors fixed to the robot base);
(v) With the links assumed rigid, joint stiffness is assumed, based on experience or using data from a similar robot, which then leads to an elastodynamic model whose natural modes and frequencies can be determined at a selected set of robot postures (dynamic behavior of the structure is dependent on robot posture) by means of scientific code such as Matlab or computer-aided engineering (CAE) code such as Pro/Engineer or ANSYS; and (vi) if the frequency spectrum of the robot structure is acceptable, the designer can continue to motor selection; otherwise, a redimensioning is required, which means returning to stage 3.

Even though a design cycle can be completed as outlined above, the designer must now incorporate into the elastodynamic model the structural and inertial data provided by the motor manufacturer. This requires a return to stage 5 and a new elastodynamic analysis. It is thus apparent that the robot design process has one element in common with engineering design in general: both are iterative and open-ended. Remarkably, however, the various items driving each design stage are, to a large extent, independent of each other, e.g., topology and geometry can be determined independently from motor selection. Obviously, all issues interact in the overall design process, but, within certain design specifications, the various items do not contradict each other, as to warrant a multi objective design approach. That is, the optimum design of serial robots can be accomplished fairly well by means of a sequence of single-objective optimization jobs. Again, the results of the last stage, motor selection, must be integrated into an overall mathematical model to test the overall performance.

One reference addressing practical optimization issues in the conceptual design of industrial robot is Only when the physical limits of components have been exhausted may a radical redesign requiring a return to stage 1 be warranted. This is the case with SCARA systems. Current industrial topologies of these robots are usually of the serial type, with some exceptions, like the Konig and Hartman RP-AH series robots with parallel architecture, which feature two serial SCARA systems sharing one common end-effector. The quest for shorter cycle times, as for an industry test cycle, has prompted the industry to look for alternatives to serial architectures. This is how ABB Robotics is currently marketing a parallel robot, the FlexPicker, built upon Clavel’s Delta robot, to which a fourth axis has been added in series with the first three. The latter are laid out in a symmetric, parallel architecture that enables Delta to produce pure translations of its moving platform. The shortest cycle time reported by Adept Technology is 420 ms for a payload of 2 kg (with the Adept Cobra s600, a serial robot) but other manufacturers claim even shorter times. This chapter is organized according to the various stages of the robot design process outlined earlier. Noting that topology selection and geometric dimensioning are tightly coupled in the kinematic design process, we first begin with an examination of workspace criteria: we review methods for determining the topology of the kinematic chain, followed by the geometric dimensions so as to satisfy workspace requirements.We then review in detail the various criteria developed for characterizing a robot’s manipulating capability, focusing on quantitative notions of dexterity based on both kinematic and dynamic models. We then examine methods for structural dimensioning of the links and joints so as to meet both static and dynamic load requirements. Finally, we discuss elastodynamic dimensioning, and actuator and gear sizing, taking into account properties such as the natural frequency of the robot, and force and acceleration capability requirements.

WORKSPACE CRITERIA

The most obvious consideration in designing a robot is that its workspace has a set of required characteristics. This is a fundamental problem in classical mechanism design, and raises the obvious question of how a user can specify those characteristics.

Issues to consider here pertain, mostly, to what Vijaykumar et al. termed the regional structure of a manipulator. This applies to manipulators with a decoupled architecture, whose last three revolutes have concurrent axes, thereby forming a spherical wrist, the point of concurrency being the wrist center. The manipulation task of architectures of this kind thus allows for a decoupling of the positioning and the orientation subtasks: the regional structure, consisting of the first three joints, is first postured so as to locate the center of its wrist at a specified point C(x, y, z); then, the local structure, i. e., the wrist, is postured so as to make the end-effector (EE) attain a specified orientation with respect to a frame fixed to the base, given by a rotation matrix. Most algorithms reported in the literature to determine the workspace of a given robot refer to the workspace of the regional structure.

Here, we should distinguish between the workspace of the kinematic chain, regardless of the physical implementation of the chain, and that of the physical robot. In the former, all revolute joints are capable of unlimited rotations about their axes; in the latter, joint limits are needed, for example, to avoid wire entanglement. In the early stages of robot design, joint limits need not be considered, the workspace thus exhibiting symmetries that are proper of the type of joints of the regional structure. If the first joint is a revolute, the workspace has an axis of symmetry, namely, the axis of this revolute joint; if the first joint is prismatic, the workspace has an extrusion symmetry, with the direction of extrusion given by the direction of motion of this joint. As prismatic joints are infinitely extensive, so is the kinematic workspace of a robot with a prismatic joint. The kinematic workspaces of robots with prismatic joints are usually displayed for a finite portion of this workspace. In the case of parallel robots, the regional structure is elusive, in general. The usual practice when displaying the workspace for these robots is to assume a constant orientation of the moving plate, the counterpart of the EE of serial robots. A common architecture of parallel robots, which arises quite naturally in the design process, entails identical legs symmetrically placed both on the base platform and on the moving platform. Each leg is, in turn, a serial kinematic chain with one or two active joints, all others being passive.

The workspace of this kind of robots also exhibits certain symmetries, but no axial symmetry. The symmetries are dictated by the number of legs and the types of actuated joints. Coming back to serial robots, the workspace can be defined by an envelope that is essentially of one of two types, either amanifold or a surface that is smooth almost everywhere, i. e., smooth everywhere except for a set of points of measure zero in the Lebesgue sense. Broadly speaking, a set of measure zero on a surface is a curve, e.g., a meridian on a sphere, or a set of isolated points on a line, e.g., the set of rational numbers on the real line. A paradigm for this second kind of workspace is that of the Puma robot, whose kinematic chain is displayed in Fig. 10.1. In this figure, the regional and the local structures are clearly distinguished, the former being fully extended. Design rules based on the shape of the workspace can now be drawn.

1. If the workspace required is axially symmetric and finite, use a serial robot with a regional structure composed of revolute joints only.

2. If the workspace required is prismatic and infinite, use a serial robot with regional structure having one first joint of the prismatic type. Here, infinite is used in a restricted sense, meaning much larger in one direction than the others. Moreover,
   - if one direction is required to be much larger than the others, then practical implementations of prismatic joints are available in the form of rails either overhead, thereby giving rise to gantry robots, or on the floor.
   - if two directions are required to be much larger than the other, then use a wheeled mobile robot carrying a manipulator on top. A famous realization of this concept is the National Aeronautical and Space Agency's (NASA) Sojourner used in the Pathfinder mission to Mars in 1997.

3. If axial symmetry is not required, but rather a workspace with various coplanar axes of symmetry, similar to those of regular polygons, use a parallel robot.

REACHING A SET OF GOAL FRAMES

Closely related to the problem of workspace specification is that of task specification. In mechanism design it is customary to specify a set of coordinate frames in space, and to design a mechanism with an a priori specified topology that can visit these frames. An order in which the frames must be reached may be given. In the event that not all of the frames are reachable, then one may seek a mechanism that comes closest, in some suitable sense, to the specified frames. The literature on this classical mechanism design problem is vast – see, e.g., and the references cited therein. Some further remarks in connection with this goal-frame approach to robot dimensioning are noteworthy.

1. Reaching exactly the desired frames may not always be desired or possible: in some cases it is better to use an optimization approach that allows for solutions that will visit the desired poses within a minimum error (provided that an error norm can be suitably engineered, of course).
2. It has been claimed that interval analysis allows not only a discrete set of desired poses but also a full six-dimensional (6-D) workspace to be met while taking into account manufacturing errors.
3. The branching problem occurring in single-degreeof- freedom mechanisms may also occur in robot design: design solution based on via points may indeed visit the prescribed poses, but not all of these may be reachable within the same assembly mode. This problem is exacerbated in the design of serial robots, as a six-degree-of-freedom, revolute-coupled robot may admit up to 16 distinct postures – branches – for one given EE pose
4. While a robot designed to visit a set of prescribed poses via its end-effector will be able to visit that set, we should not forget that the purpose of using robots is first and foremost to be able to perform not one single task, but rather a family of tasks. In this light, the set of poses for which a robot is designed might as well be a task that is representative of that family.

In connection with remark 4 above, we can cite the design or evaluation of SCARA systems. A SCARA system is a four-degree-of-freedom serial robot capable of tasks that lie within the Schönflies subgroup of the group of rigid-body displacements, namely the set of three-dimensional displacements augmented with a rotation about an axis of fixed direction. In these systems, the task at hand is given by two vertical segments joined by one horizontal segment. Moreover, the length of the vertical segments is 25.0mm, that of the horizontal segment being 300.0mm. While the endeffector is traversing the horizontal segment, moreover, it should rotate about a vertical axis through an angle of 180◦. This task specification, which has been adopted by SCARA manufacturers, does not indicate how to negotiate the corners, which is left to the imagination of the robotics engineer.

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