A Translation in Artificial Terms of the Design of Biological Manipulators

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ABSTRACT

The design of manipulators is a difficult question in robotics because most of the traditional disciplines, like kinematics and dynamics are analytic and have little synthetic power. Design is a generative process. Powerful design methodologies come exploiting modularity and analogy. These are used in this paper to create a spherical mechanism actuated in parallel with a large workspace that can be used to construct a complete limb. The design synthesis is performed by translating ideas borrowed from the design of biological manipulators.

INTRODUCTION

The underlying mechanics of robotic manipulators has a high impact on the nature of the control that can be applied to them. Hence, the importance of the mechanical properties conferred by design to manipulators.

The largest amount of effort in the field of robotics has been concerned with the development of analytical tools such as kinematics and dynamics. These disciplines rest on well established physical principles. However work on design still relies mostly on intuition because the synthetic power of these disciplines if difficult to exploit.

Design, seen as a problem solving activity, is very unconstrained. It has been observed that design is more a process-driven activity than a goal-driven activity: the design 'process' is picked by the designer while the goal may remain fuzzy [1].

Design occurs by satisfying a set of constraints resulting in part from the laws of nature, some of which, in the case of manipulators, are captured by the equations of kinematics and dynamics. Other constraints result from technological feasibility. These are of course difficult to model. The remainder of the constraints encompasses a set of desired properties which can be quite arbitrary.

The general approach to design is generative. Possibilities are matched against criteria that have been decided upon before hand. Unpromising alternatives of successive versions are filtered in a process which is reminiscent of a technique known in artificial intelligence as "means-end analysis." In this technique, not only immediate choices are made to progress toward a goal, but also choices about the operators that are likely to lead to progression.

One common methodology proceeds first with the creation of generic modules which can be instanciated into a collection of objects having scaled properties (size, power and so on). The advantages of such an approach are well known and discussed at length in computer science literature (standardization: interface rules, polymorphism: hidding implementation, and composition: larger blocks made of smaller ones). The second part of this methodology is to decide upon a framework structure, which describes how modules relate to each other. In order to cope with complexity, hierarchical organizations are often proposed.

Another common methodology uses analogy. In one given context, designs are described in terms of objects and relationships. In another context, an image set of objects and relationships is proposed. If the correspondence between objects and relationships is properly chosen, a successful design in one context will map into successful one in the other context.

USING MODULARITY AND ANALOGY

We will use modularity and analogy to propose an artificial manipulator.

Limbs in nature come in two varieties: endo-skeletons and exo-skeletons. In the endo-skeleton case, most of the material used in compression is located *inside* the material used in extension (bones), whereas the opposite situation is observed in the exo-skeleton case (shells). So far, the design of artificial manipulators has followed mostly the exo-skeleton case. We will follow here the endo-skeleton path because natural endo-skeletons seem more dexterous than the exo-skeleton ones.

Without going into much details, the most identifiable anatomical elements at a macroscopic scale, in the endo-skeleton case, are: muscles, tendons, bones and joints. These elements correspond to a separation of mechanical functions: extension, compression, mobility.

A great deal of mobility in biological endo-skeletons limbs is achieved through revolute (elbow, knee) pairs or spherical pairs (e.g. shoulder, hip, eye). These correspond to the two symmetries that allow continuous surface contact under motion: axial symmetry (revolute) and point symmetry (sphere). The other pairs (planar, prismatic and screw) are not used in natural limbs. An essential element of biological limbs is the spherical pair. The theoretical possibility of a spherical pair has been discussed by Phillips from a purely theoretical view point [2]. Biological systems actuate spherical pairs using parallel actuation. The technological analogy is the parallel manipulator. From the kinematics point of view, a parallel manipulator possesses closed kinematic chains.

The pantograph mechanism is a simple example of a parallel mechanism. The theory of mechanisms demonstrates the existence of an immense variety of such mechanisms from which only a few examples have been applied to the design of manipulators although they are often used in other type of machinery (earth moving equipment, variable wing foils and landing gears in aeronautics, helicopter rotors, and so on).

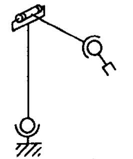
The traditional design of manipulators is based on a a serial design: a succession of links and joints. Serial manipulators lead to accumulation of errors, lack of rigidity, low natural frequency that can be counteracted with parallel designs [3]. Despite the drawbacks of such an approach, it is the predominant design because their models have been extensively studied. The serial robot manipulator technology mostly uses massive metallic structures designed to counteract the cantilever effect. An immediate consequence is a resulting very poor weight/load ratios due to the "pyramidal effect": Proximal joints must be designed to drive and support the sum of the distal links and joints. The principal advantage of serial manipulators is the amount of workspace.

Clearly, what is needed is a combination of serial and parallel kinematics. It is not surprising that natural limbs are partly serial and partly parallel: the skeleton-muscle system creates many closed kinematic loops (quite complex to analyze), yet there is an amount of seriality to yield workspace (arm-forearm-hand).

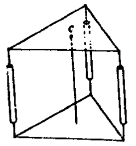
A complicated problem in the design of manipulators is the integration of actuators and sensors into the overall structure. Nature integrates the sensors directly within the actuators at the microscopic scale and provides motion transmission devices with very small losses (tendons). Of course, this idea as been utilized in the design of mechanical hands despite numerous practical difficulties [4,5]. A parallel kinematic structure with linear actuators can be viewed as a deformable truss. In such a truss design, actuators and sensors can be made a parts of the structure, thus achieving a high degree of integration as in biological designs.

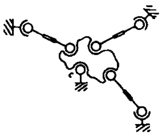
SPHERICAL PAIR

Let us now concentrate on the design of the spherical pair actuated in-parallel with linear actuators. Theory tells us that three actuators are needed such as:



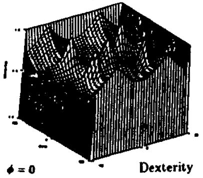
Proposed manipulator.

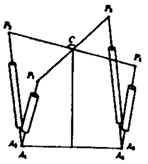


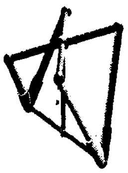


At that stage, design choices only have to do with placing the respective positions of actuator attachement points. Before proceeding further, one must account for a result of the theory of mechanism which states that all mechanisms can become "singular". In fact, the Jacobian matrix of the map from input coordinates (joint positions) to output coordinates (active link) becomes singular. All manipulators become singular at the boundary of their workspace but also in two other circumstances. For serial manipulators, singularities occur when the axes of revolute joints align (that will not happen with spherical joints). The manipulator becomes "locked" for certain motions for loss of degrees of freedom. For parallel manipulators, singularities also occur in special geometric situations and motions cannot be controlled by the actuators (e.g. piston and crank system when the crank is fully extented or retracted). The mechanism depicted above is of course plagued by this problem and its usable workspace is quite small no matter the way the actuators are placed.

Let us recall that natural limbs use a large amount of actuator redundancy [6]. If we apply this principle to the mechanism and add only one extra actuator, it can be shown that the loci of singularity can be displaced at the boundaries of the workspace. A short argument about exploiting symmetries leads to the following structure: that we showed to have a high dexterity in the working range [7]: 120° × 180° × 230°.







The redundant actuators can be also seen as antagonistic actuators which can be used to: Increase the linearity of actuators by moving the working point toward a linear portion of their characteristic curve; Reduce backlash which disturbs accurate control; Prevent the vibration of link during impact by dynamical tuning of the natural frequency the joint link system: Simultaneously control position force and stiffness.

The elements that make up such a design fall into a very small number of categories which facilitate design and construction: Linear actuators and sensors; Pushing and pulling rods: Universal and spherical joint; Multiway rigid connection for rods.

A complete seven degree of freedom "arm" could now be easily constructed in terms of two spherical joints as described here with an ordinary revolute joint in between.

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