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# Borrowing Some Ideas From Biological Manipulators to Design an Artificial One

Vincent Hayward

McGill Research Center for Intelligent Machines
McGill University, 3480 University Street
Montréal, Québec Canada H3A 2A7

**Abstract.** The design of robotic manipulators is a difficult question because most of the traditional disciplines needed for the design of robots, like kinematics and dynamics, are mostly analytic and have little synthetic power. We first discuss design seen as a generative process and suggest that analogy is a powerful design method. Then a spherical mechanism actuated in parallel with a large workspace that can be used to construct a complete limb is discussed. The design synthesis is performed by translating ideas borrowed from the design of biological manipulators.

## 1 Introduction

Commercially available robot manipulators exhibit a degree of elegance and adequacy which is far from approaching what can be observed in biological manipulators. Hence, seeking inspiration from Nature remains quite an appealing approach. In fact, even the most application oriented industrial manipulators always bear some degree of resemblance with human arms: a sequence of articulated bodies with a distinguishable shoulder, elbow and wrist, see Figure 1 for example; while submarine manipulators, for another example see Figure 2, recall crustacean limbs.

This suggests that despite the claim that artificial manipulators really must match their applications and that no valid reason exists for using anthropomorphism (and zoomorphism), the models of Nature remain, consciously or not, an inexhaustible source of inspiration.[1]

Design of manipulators entails a decision making process which concerns many attributes of the device, encompassing materials, assembly methods, mechanical structures, computational structures, sensor, motor and motion transmission technologies, and so-on, to achieve a desired level of functional capacity. The organic quality of biological systems, which any person engaged in engineering research can easily appreciate, is far from being achieved by any technological systems, except perhaps by those artifacts which have been developed and refined over centuries. Such examples can be found in hand tools and musical instruments. The violin, for instance, achieves the integration of

[1] As J. Phillips puts it: "There is of course no reason to believe that robots (which are machines) should resemble us or animals, both of which are also machines; but the occurrence of anthropomorphism in our thinking and the consequent discussion about its appropriateness in design is almost inescapable" [14].

several of the above mentioned aspects of design at an extraordinary level of harmony.

The general objective of robot manipulator design is to devise a machine capable of (1) displacing tools within the largest possible amount of space while minimizing spatial intrusion or interference with the environment, and (2) imparting forces and torques onto the environment in a delicate and controlled fashion once a desired collision occurs, while (3) at the same time it is also capable of moving in free space at high velocity [4]. The problem stated above separates into two parts. The givens which are decided by the *design* and the *controls* which confer properties not exhibited by the original device.

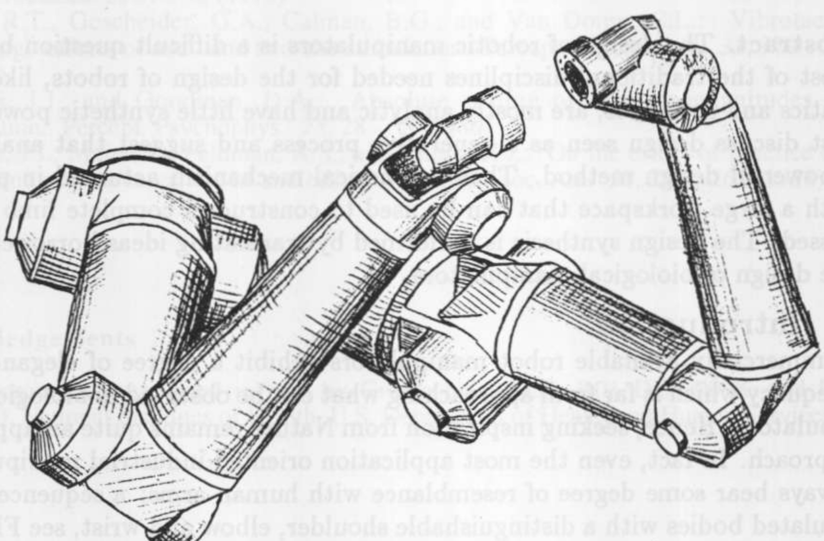


Fig. 1. Pair of manipulators designed by Robotics Research Inc.

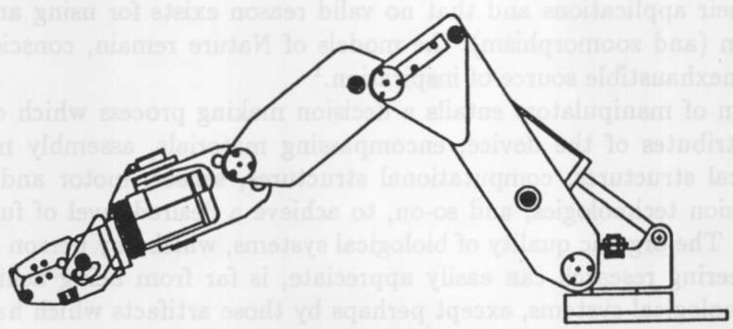


Fig. 2. Sketch of a submarine manipulator built by International Submarine Engineering Ltd.

Clearly, the properties defined by design set bounds on what can be achieved by control. In the sole domain of kinematics, it is not the goal of robotics research to find all possible arrangements (which may be a the goal of the Theory of Mechanisms), but to find the most relevant ones for manipulation.

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

The design of biological systems transcends human comprehension and is expected to remain as such well beyond the foreseeable future. It is however clear that the observation of salient features of examples found in Nature can lead to insights readily usable in technological systems. This paper attempts to suggest that Nature's example can point to kinematic and structural suggestions quite applicable to current technology and which are directly derived from anatomical features observed in natural limbs.

Contemporary and historical examples of this abound. Robotics takes its roots in the development of machines to extend human capacities. Thus, the history of robotics may be traced back at least to the Bronze age with the discovery of levers and wheels (rotary motion). Through-out the ages, developments have been contributed by various civilizations. Examples come from the Sumerians, Greeks, Romans, the Renaissance, the Age of Enlightment, the Industrial Revolution, and not even including the less known in the West Asiatic Cultures, in a pattern chronologically aligned with the history of technology. In the honor of the province of Tuscany which hosted this meeting, Leonardo da Vinci should be singled out as an illustrious precursor of the design methodology based on the observation of Nature. The following example is particularly relevant to the theme of this paper.

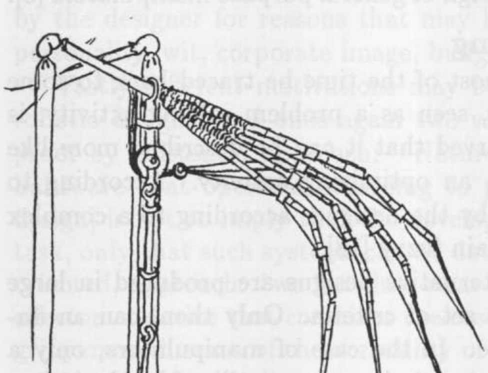


Fig. 3. This study suggests the emulation of bird wings [Cod. Atl. f. 308r.-a].

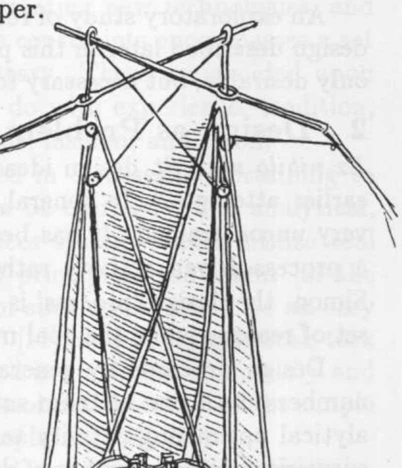


Fig. 4. Leonardo envisaged springs to store energy in this "Ornitottero" [Cod.Atl.f.314r.-b.].

Leonardo made extensive studies about bird wings in an attempt to emulate flight, see Figure 3, for example. As far as we know, these attempts were unsuccessful. He probably convinced himself that flight emulation could not be achieved by wing flapping mechanisms actuated by human muscular power and imagined to use springs to provide power, see Figure 4. It is nevertheless likely that the attempt to utilize aerodynamic forces in a more efficient manner led him to imagine the famous "air screw", see figure 5 [3].

Since Nature optimizes her designs for reasons which we are not fully aware of, there is limited justification for attempting faithful emulation of these designs. Rather, the approach might be the re-exploitation of certain design features found in Nature. It is manifest that biological manipulators are not optimized for many tasks of interest: a human arm is obviously ill suited to intervene in a nuclear reactor core. This does not mean that structures observed in Nature cannot be re-utilized.

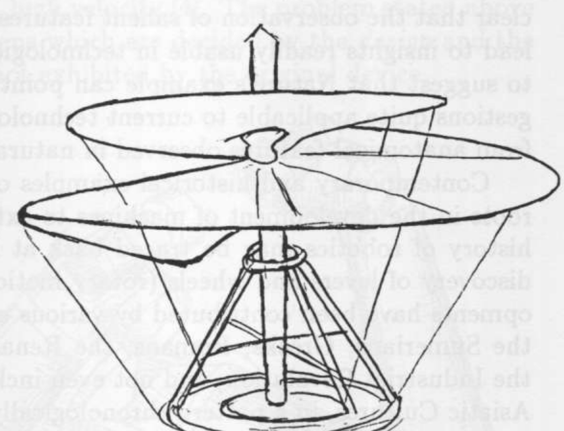


Fig. 5. Leonardo's "Air Screw" [Ms.B.f. 83v.]

An exploratory study of redundancy was our motivating factor for the arm design described later in this paper. It was recognized that redundancy is not only desirable, but necessary to the design of general purpose manipulators [6].

## 2 Design as Problem Solving

*Ex nihilo nihil fit*, design ideas can most of the time be traced back to some earlier attempts.[2] In general, design, seen as a problem solving activity, is very unconstrained. It has been observed that it can be described more like a process-driven activity rather than an optimizing activity. According to Simon, the design 'process' is picked by the designer according to a complex set of reasons while the goal may remain fuzzy [18].

Design proceeds by generation alternative designs are produced in large numbers until one of them satisfies a set of criteria. Only then, can an analytical optimizing activity take place. In the case of manipulators, only a surprisingly small number of design processes have been utilized by the industry, the result being a limited number of design styles, possibly because the robot manipulator technology is quite recent. It is interesting to look back for a moment at the past few decades during which industrial manipulators were developed. Apart from a few notable exceptions, current design concepts more

[2] For R. Buckminster Fuller: "When you and I speak of design, we spontaneously think of an intellectual conceptualizing event in which the intellect first sorts out a plurality of elements and then interarrange them in a preferred manner." [1].

or less follow the machine tool engineering tradition. This can be observed for robots used in the automotive industry.

Most of those manipulators are designed for high positional accuracy and high rigidity, which makes them adequate for machine-tool-like applications. A number of difficulties are created when it is attempted to use these devices for other kinds of tasks, particularly those involving the control of forces when in contact with the environment.

Among all existing kinematic structures, a four-bar mechanism for inner joints augmented by a three axis wrist with intersecting axes has emerged over time as the vastly dominant structure, as in a kind of a Darwinian evolution process. Similarly, one other kinematic structure known as the SCARA design (Selective Compliance Assembly Robot Arm) is overwhelmingly used in precision assembly applications because of its adequacy for the task (dynamic and kinematic decoupling along the vertical and horizontal directions).

Manipulator design occurs trying to satisfy an open set of constraints resulting in part from the laws of Nature, some of which are captured by the equations of kinematics and dynamics. Kinematics and dynamics have little synthetic power: they permit a designer to improve a proposed design through analysis or optimization, or to determine local features such the shape of cams. Sometimes, qualitative exploration of many arrangements in order to reach a functional goal is possible as demonstrated by Salisbury in the context of arm manipulation [16]. Other constraints result from technological feasibility. These are of course difficult to obtain since they depend on the accuracy of available information, the risk involved in creating new technologies, and the rate of improvement. The remainder of the constraints encompasses a set of desired properties which can be quite arbitrary. These are decided upon by the designer for reasons that may have to do with experience, tradition, personality, wit, corporate image, budget, trends, fashion, and so-on.

Vastly different motivations may be noticed in discussions pertaining to robotic designs, and once again two views can be opposed. The analytical, proof by existence, approach: "Nature produces systems which utilize real hardware that operates according to physical principles...the intent [of the design] is not to imply that the development of such systems will be an easy task, only that such systems can be developed" [11]; and the synthetical, task oriented, approach: "we feel that what is needed is a *medium-complexity* end effector: a device that combines the ease of control characteristic of the simple grippers with some of the versatility of the complex hands" [20].

As a result, an all-encompassing design goal can never be formalized; instead, as commented above, a generative method is selected. Possibilities are matched against the criteria that have been decided upon in advance. Unpromising alternatives of the 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. The definition of quantitative criteria may help to automate part of the search process. The final goal is known once successive generations have filtered through the constraints. However, it is unlikely that this design process will ever be reduced solely to an explicit search process, or to an optimizing process, game theoretical or otherwise.

Optimality is difficult to include in the robot design activity, because optimality entails the existence of a well defined objective function, which opposes the requirement to create a general purpose machine. It is impossible to think of such a function since the space over which this function would be defined cannot be known before the end-result of the design process has been satisfactorily described. Nonetheless, a design can be declared optimal with respect to a particular mathematical model and a particular criterion defined over the variables of this model. The relevance of the model is then of course an essential question. It has been our experience that oversimplification leads to physically non realizable structures [12].

A common methodology first entails the creation of generic modules which can be instanciated into a collection of devices having scaled properties (size, power and so on). The advantages of such an approach are well known and discussed at length in the computer science literature. The principles put forward in computer science are standardization (interface rules), polymorphism (hidding implementation), and composition (larger blocks made of smaller ones). They promote abstractions, reliability, ease of maintenance, and top-down design. Clearly, these principles significantly apply as well to electro-mechanical design. The second part of this methodology requires a decision upon a framework structure describing how modules inter-relate. In dealing with complexity, hierarchical organizations are often proposed.

## 3 Overall Approach

Some of the properties observed in biological manipulators that can be put to use in technological designs are now discussed. The most general observations fall in two categories: (1) on actuation and (2) on kinematics and structures. It is the purpose of this study to explore the second category in greater details.

Limbs in Nature come in two varieties: endo-skeletons and exo-skeletons. In the endo-skeleton case, most of the material used passively (bones) is located *inside* the material used actively (muscles), whereas the opposite situation is observed in the exo-skeleton case (shells). This opposition is also observed to some degree of approximation in the distribution of material used in compression is compared to that of material used in extension.

So far, the design of artificial manipulators has followed mostly the exo-skeleton case. In contrast, we will follow here the endo-skeleton path (vertebrae) simply following the intuition that natural endo-skeletons seem more agile than the exo-skeleton ones (crustaceans).

The most identifiable anatomical elements (anatomy deals with structure and morphology) are at a macroscopic scale, in the endo-skeleton case: muscles, tendons, ligaments, bones, and synovial joints. These elements correspond to a separation of mechanical and structural functions: extension, compression, mobility. We will also attempt of incorporate this separation in our design.

A great deal of mobility in biological endo-skeletons limbs is achieved through joints which approximate revolute (elbow, knee) pairs or spherical pairs (e.g. shoulder, hip, eye). These correspond to 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 found in natural limbs. An essential element of biological limbs is the spherical pair. Biological systems actuate spherical pairs using parallel actuation. The technological analogy is the parallel manipulator discussed below in greater details.

The traditional design of manipulators is based on a completely 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 [10]. Despite the drawbacks of such an approach, it is the most commonly found structure. One of the reasons might be that their models lend themselves to easier analytical studies than those of parallel manipulators.

The serial robot manipulator technology mostly uses massive metallic structures designed to counteract the cantilever effect. An direct 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 and the minimization of spatial intrusion. 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 sensors directly within the actuators at the microscopic scale and provides motion transmission devices with very small losses (tendons and sheaths). Of course, this idea as been utilized in the design of manipulators and mechanical hands despite numerous practical difficulties. A parallel kinematic structure with linear actuators can be viewed as a deformable truss.

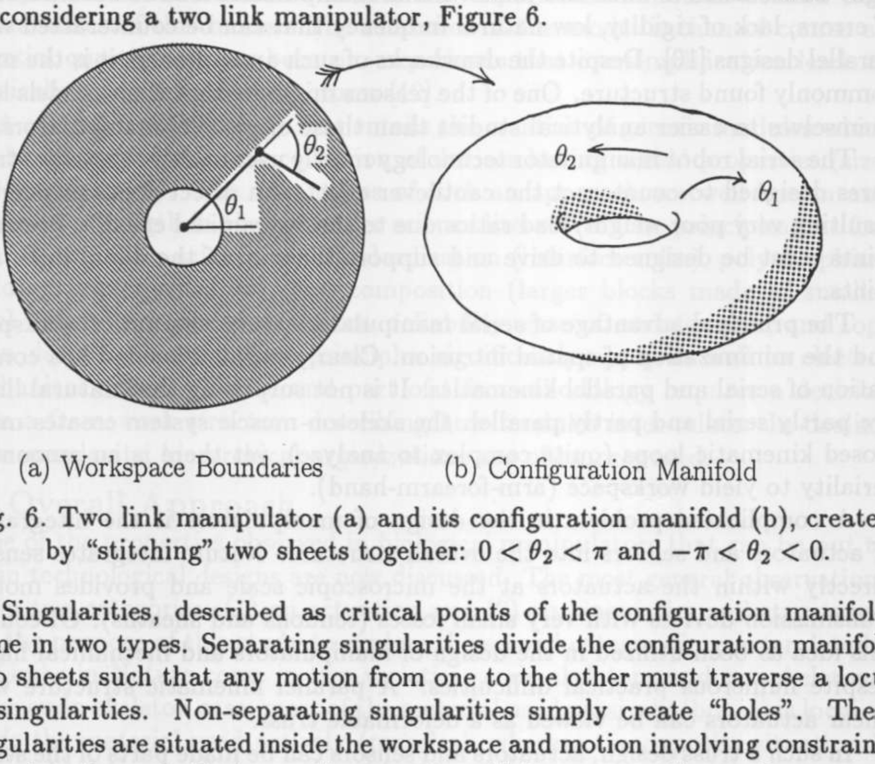
In such a truss design, actuators and sensors can be made parts of the structure, thus achieving a high degree of integration that characterizes biological designs. Yet, the various parts of the structure can be made easily accessible and similar to others. This promotes modularity and interchangability [8].

An additional remarks adds weight in favor of the endo-skeleton case. Regardless of the structure which is chosen, position, velocities and forces need to be measured for control of manipulators. It is a fact of mechanics that the greatest amounts of velocity and smallest amount of forces in a manipulator in action will manifest themselves at the exterior parts of the structures. This suggest that force production elements as well as sensors should be placed as close to the external regions as possible. Thus passive elements should be placed inside to complete the structure which is made possible by the use of trussed structures.

Truss structures have also interesting properties which are quite appealing for limbs designs: the load on parts of the structure and on joints is always axial, they can be made out of a small vocabulary of elements, and a great deal is available on the design of such structures.

## 4 Topological and Geometrical Observations

Mechanisms may become "singular". In fact, the map from input coordinates (joint variables) to output coordinates (active link coordinates) displays singularities. To better illustrate that concept we will use topological terms as proposed by Burdick [2]. Homotopy allows to view mechanism at "order zero", to describe qualitatively their kinematic properties. This can be easily grasped by considering a two link manipulator, Figure 6.




(a) Workspace Boundaries (b) Configuration Manifold

Fig. 6. Two link manipulator (a) and its configuration manifold (b), created by "stitching" two sheets together: $0 < \theta_2 < \pi$ and $-\pi < \theta_2 < 0$.

Singularities, described as critical points of the configuration manifold, come in two types. Separating singularities divide the configuration manifold into sheets such that any motion from one to the other must traverse a locus of singularities. Non-separating singularities simply create "holes". These singularities are situated inside the workspace and motion involving constraints placed in the end-effector motions must avoid the surrounding region.

The workspace of robot mechanisms is determined by three factors: self-interference of parts, travel limits of actuators, and one special locus of singularity of the separating type. In the case of a planar two links manipulator, it is easy to see that this locus is a circle centered at the first joint. There is also a geometric interpretation of singularities. In the case of serial manipulators, singularities occur, for example, when the axes of revolute joints align because two joints become mutually redundant. The manipulator becomes "locked" for motions around a direction perpendicular to the mutual axis due to loss of a degree of freedom.

As an example, we will illustrate this interpretation on the advanced manipulator designed by Salisbury and Townsend described in this proceedings. This arm, the geometry of which is seen Figure 7, has of two elongated links.

It has been designed so as to be able to utilize the entire surface of its links in contact tasks. Thus, a complete mobility of both links is essential. From a geometrical view-point, the objective of orienting arbitrarily the two links in space is completely achieved (four parameters, four joints). However, the existence of a "hole creating" singularity when joint 1 and 3 are aligned prevents full usage of the arm within its workspace, although it can freely maneuver around it.

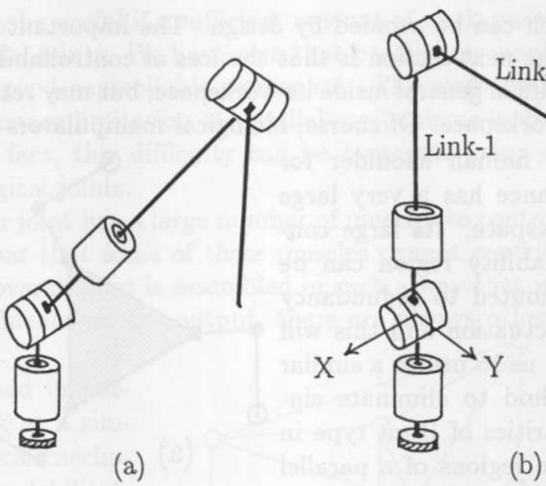



Fig. 7. (a) Geometry of WAMS. (b) Link-1 cannot rotate around axis Y.

The problem of loss of mobility of serial manipulators can be treated with supplementary joints which enhance the global mobility of the mechanism in such a way that local loss of mobility can be counteracted with its kinematic redundancy [6]. The example of a four revolute joint mechanism which provides full orientation capability has been worked out by Long and Paul [13]. This strategy has only limited applicability for a number of reasons. Adding more serial joints only increase the problems that affect serial manipulators such as accumulation of errors, and degradation of dynamics that have been alluded to earlier.

In addition, augmenting the number of revolute joints does not remove any singularities for reasons that are clear from Burdick's topological arguments. In fact, the more serial joints are added, the more complex the topological map of the manipulator becomes and the more complex the control and programming become. Thus this possibility for designing a highly dextrous manipulator has been discarded. We now turn our attention to parallel manipulators, since it is the intention to include them in the design.

As described by Hunt [10], for parallel manipulators, singularities also occur in special geometric situations such that motions cannot be controlled by the actuators (e.g. piston and crank system when the crank is fully extented or retracted). In other terms, the actuated joint velocities vanish for finite motions of the mechanism.

It is possible to classify the singularities of parallel manipulators into three types [5]: the singularities of the sheet separating type when one of the serial subchain of the mechanism is singular—loss of mobility—; the singularities of Hunt type—loss of controllability—see Figure 8, or both. The third case occurs only for special configurations which cause two singularities to meet, which can be avoided by design. The important observation that we will use in the next section is that the loss of controllability for a parallel mechanism occurs in general inside its workspace, but may retain mobility in large portions of workspace. Of course, biological manipulators do not escape this laws. The human shoulder for instance has a very large workspace. Its large controllability region can be attributed to redundancy in actuation and this will lead us to utilize a similar method to eliminate singularities of Hunt type in large regions of a parallel manipulator. The results of the above discussion are now utilized to formulate the design of a mechanism that does not display singularities in large portion of its workspace.

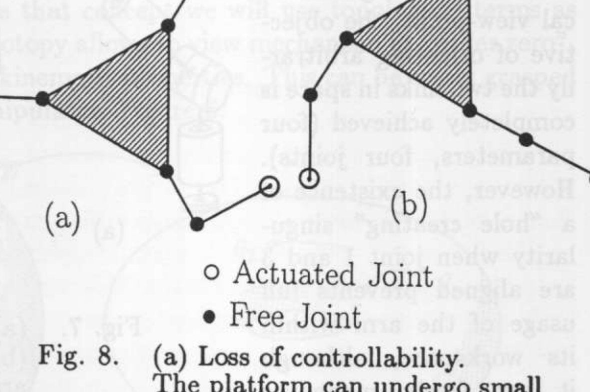



Fig. 8. (a) Loss of controllability. The platform can undergo small rotations while the actuators' velocities vanish.
(b) Loss of mobility. The platform is only able to rotate.

## 5 Kinematic Synthesis

Consistent with the goal to achieve a large workspace and limited spatial intrusion, it seems difficult to avoid the general architecture which consists of two elongated links assembled by a revolute joint. Such a manipulator, using a three revolute joints assembly at each end, was first described in the 70's by Takase, Inoue and Sato [19] and later discussed by Hollerbach [9]. As shown by Yoshikawa [22], its kinematic decoupling simplifies enormously many aspects of the control, in particular when the task prescribes the hand motions while collisions need to be avoided. Nevertheless, as commented before, this architecture still possesses "hole creating" singularities which defeat some of its advantages.

In addition, such a manipulator requires to cascade seven joints which makes it difficult to obtain good dynamics and accuracy. Following Nature's example, it seems possible to achieve a similar amount of workspace, but using at each end two parallel type mechanisms. This leads to the general architecture on Figure 9.

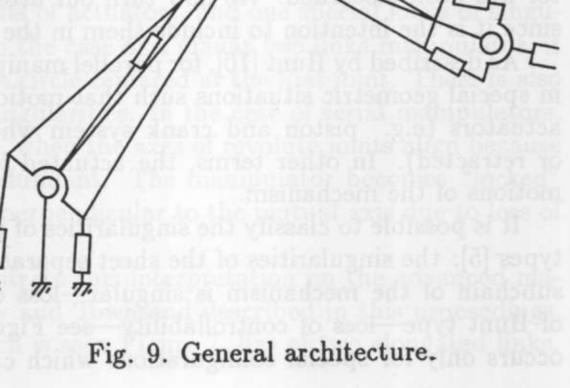


Fig. 9. General architecture.

35 mm

Such an architecture can only be useful if a sufficient amount of workspace can be obtained from these parallel joints. We have seen that parallel mechanisms made it difficult to achieve good controllable workspace. The main point is that a major source of workspace limitation in parallel mechanisms is due to Hunt type singularities. In fact, this difficulty can be overcome using once again inspiration from biological joints.

For example, the shoulder joint has a large number of muscles to control it. In certain positions, it is clear that some of these muscles cannot contribute to certain motions, but the overall joint is assembled in such a way that when some muscles loose their influence on the output, there are always others to supplement them.

This idea can be readily used in parallel mechanisms. If we look at a simple arrangement of a spherical mechanism, Figure 10, it displays a debilitating singularity right in the middle of its workspace. Because of the underlying topological properties of its kinematic map, this does not depend on the geometry of the mechanism. Regardless of the placement of the actuators, it will always exist. Now consider again a planar type parallel manipulator as shown on Figure 11.

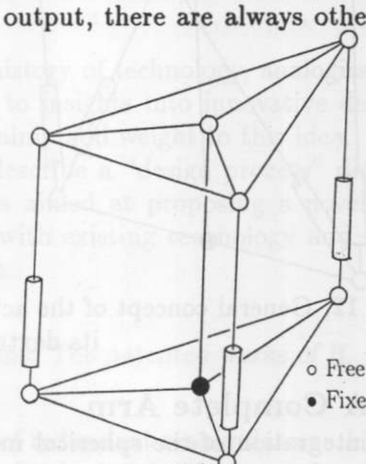



Fig. 10. Possible arrangement.

In the middle of its workspace, the addition of one actuator supplements the loss of controllability. In fact, we have shown that the addition of only one actuator can remove Hunt singularities from a very large portion of the work space from our initial design. The mathematical details of the proof are beyond the scope of this paper, but can be found in [7]. The arrangement shown on Figure 12 possesses a useful range of motion with no self-interference of parts and high and smooth dexterity in the range: $120^o \times 180^o \times 270^o$.

Once physical considerations such as the size and stroke of actuators are taken into account these figures may reduce somewhat. Nonetheless, we have constructed an hydraulically actuated prototype which exhibits a $100^o \times 100^o \times 180^o$ useful range. If desired, it can even be made isotropic, that is optimally dextrous, for several configurations.

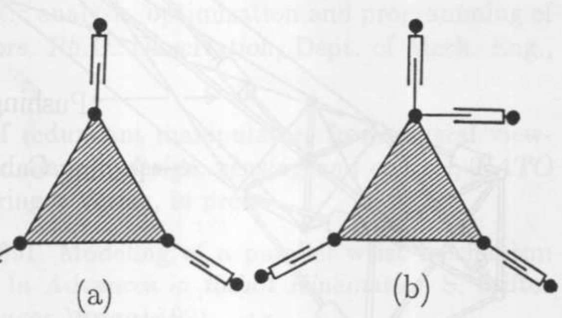



Fig. 11. (a) Hunt type singularity. The reader might agree that it is hard to resist the idea of adding one actuator as in (b).

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The measure of dexterity is based on the condition number of the Jacobian matrix of the kinematic map [15]. It has several physical interpretations including mechanism accuracy and a measure of quality for the transmission of forces and velocities from actuators coordinated to output coordinates. Details about kinematic optimization can be found in [12].

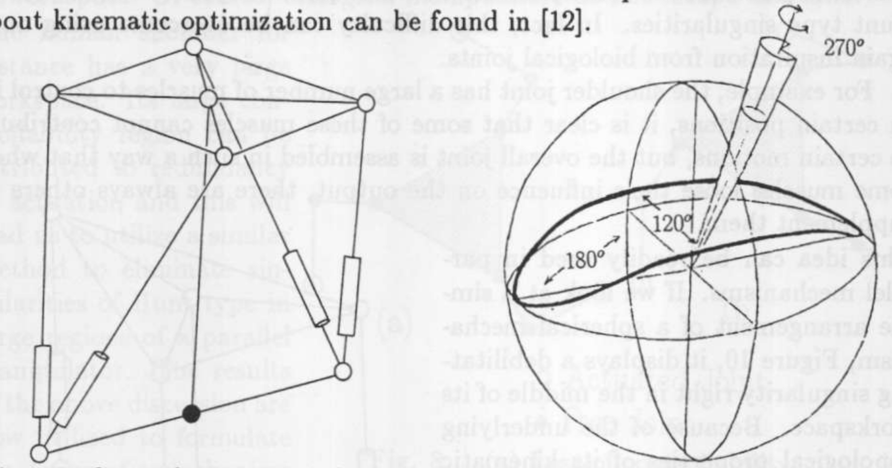


Fig. 12. General concept of the actuator redundant wrist and illustration of its dextrous workspace.

## 6 A Complete Arm

The integration of the spherical mechanism into a complete arm design will achieve the goal of a creating an arm with limited seriality (three links) and kinematic redundancy as seen from the task (seven freedoms to provide for self-motion that is finite motions with hand fixed).

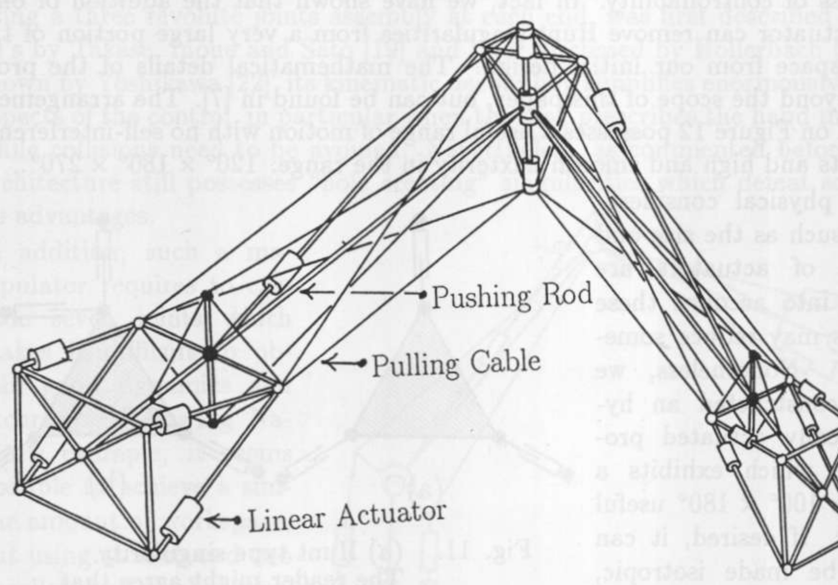


Fig. 13. Concept of complete arm.
This design follows closely Fuller's Tensengrity Principle.

Parallel actuation will lead to high bandwidth and rigidity as well as providing the basis for elaborating a truss assembly. In addition, this manipulator has no "hole creating" singularities since no revolute joints can align, nor Hunt type singularities within a reasonably large workspace. The only singularity left corresponds to the limit of the position workspace when the arm is completely stretched. See Figure 13 for a sketch of the design concept of this arm.

Of course there as many possible variations around this theme. In particular, it would be particularly interesting to de-locate the actuators of distal links. Some notable successes in this area have already been achieved [17, 21].

## 7 Conclusion

It has been argued that throughout the history of technology, analogies with biological systems have successfully lead to insights into innovative designs. Many papers in this proceedings will certainly add weight to this idea.

Introspection then has been used to describe a "design process" directed by analogies with biological manipulators aimed at proposing a novel type of robot manipulator which is realizable with existing technology and which possesses a number of desirable properties.

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