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Preliminary Study of a Serial-Parallel Redundant Manipulator

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Abstract

The manipulator design discussed here results from the examination of some of the reasons why redundancy is necessary in general purpose manipulation systems. A spherical joint design actuated "in-parallel", having the many advantages of parallel actuation, is described. In addition, the benefits of using redundant actuators are discussed and illustrated in our design by the elimination of loci of singularities from the usable workspace with the addition of only one actuator. Finally, what is known by the authors about space robotics requirements is summarized and the relevance of the proposed design matched against these requirements. The design problems outlined in this paper are viewed as much from the mechanical engineering aspect as from concerns arising from the control and the programming of manipulators.

1 Introduction

In general, *design*, seen as a problem solving activity, is very unconstrained. It has been observed that design is less a goal-driven activity than a process-driven activity: the design 'process' is picked by the designer according to a complex set of reasons.[1] In the case of manipulators, only a surprisingly small number of design processes have been utilized by the industry, resulting in a small number of design styles. In the recent years, a greater amount of manipulator design problems have been tackled in research laboratories.

Optimality is a notion which is difficult to incorporate in the design activity, because optimality entails the existence of a well defined objective function. In design, it is difficult to define 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 model and particular criteria defined over the variables of this model. The relevance of the model is then of course an essential question.

Design occurs by satisfying an open 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. Kinematics and dynamics have little synthetic power: they only permit a designer to improve a proposed design through analysis or optimization. However, qualitative explorations seem possible as demonstrated by Salibury in the context of whole arm manipulation.[2]

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 have to do with culture, tradition, personality, wit, corporate image, budget, trends, fashion, and so on.

As a result, a design goal often cannot be formalized; instead, as commented above, a generative method is selected. Possibilities are matched against the criteria that have been decided upon before hand. 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." The definition of quantitative criteria may help to automate part of the search process. The final goal is known once successive generations have been filtered by the constraints. For example, the approach elaborated by D. Tesar for the design of manipulators, employs a selection method based on a hierarchy of criteria.[3] However, it is unlikely that the design process can ever be reduced solely to an explicit search process.

The most common methodology first entails the creation of generic modules which can be instantiated 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 computer science literature. The principles put forward in computer science are standardization (interface rules), polymorphism (hiding implementation), and composition (larger blocks made of smaller ones). They promote abstractions, reliability, ease of maintenance, and top-down design. These principles clearly apply a great deal to electro-mechanical design as well. The second part of this methodology is to decide upon a framework structure, which describes how modules relate to each other. In order to deal with complexity, hierarchical organizations are predominantly proposed. However, a number of other alternatives are also available.

2 Goals

Vastly different 'designer goals' can be noticed in discussions pertaining to robotic end-effector designs, from "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",[4] to "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."[5] In the case of walking machines, other motivations are sometimes invoked, for example in the following proposal: "Among the animals that one might wish to emulate, an obvious class is that of the dinosaur."[6] The list of justifications given by the author are no less convincing than those given in the other references.

In our case, an exploratory study of redundancy was our motivating factor for the arm design. It has been previously recognized that redundancy is not only desirable, but necessary to the design of general purpose manipulators.[7] From this initial premise, a set of thirty reasons why redundancy is useful are exhibited. Resulting from this discussion, a mixed serial-parallel kinematic structure has been proposed.

Parallel designs, because of their possibility to achieve low inertia and structural rigidity, are very appealing. Unfortunately, the theory of mechanisms shows that the workspace is generally limited. Hence, the structure we proposed is a hybrid structure, designed to allow a trade-off between conflicting requirements. It has the following properties:

1. Hand motion decoupled from that of major links to augment ability to conform to obstacles achieved by redundancy.
2. Limited seriality.
3. Parallel actuation to achieve high bandwidth and rigidity.
4. A truss assembly can be devised to achieve rapid impact transient damping and good load/weight ratio.
5. Possibility to de-locate actuators through tendon motion transmission.
6. Workspace augmentation and backlash elimination achieved through actuator redundancy.

The proposed design (see figure 1) consists of a spherical wrist and a shoulder joint with an interposed revolute elbow joint. We see that a compact spherical element with a large range of motion and sound mechanical design is essential. This can be achieved through in-parallel actuation with actuator redundancy.

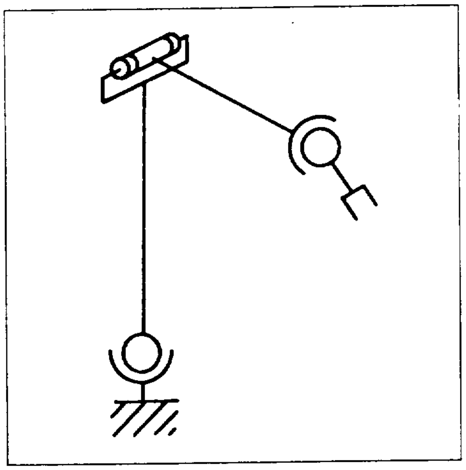

Figure 1. Spherical joints are actuated "in-parallel."

From the general case of a fully parallel wrist an particular arrangement has been derived (see 2), and its models written.[8]

The results of this study are presented in the following subsections.

3 Parallel Wrist Properties

3.1 Workspace

Assuming that the geometry of the mechanism can be represented in terms of cylinders, the interference of all moving parts can be analytically derived. The following plot (figure 3) depicts the range of swivel θ for each value of ψ and ϕ. θ, ψ and ϕ are three Euler angles where ψ is a rotation about the x-axis, ϕ is a rotation about the new y-axis, and θ is a rotation about the new z-axis.

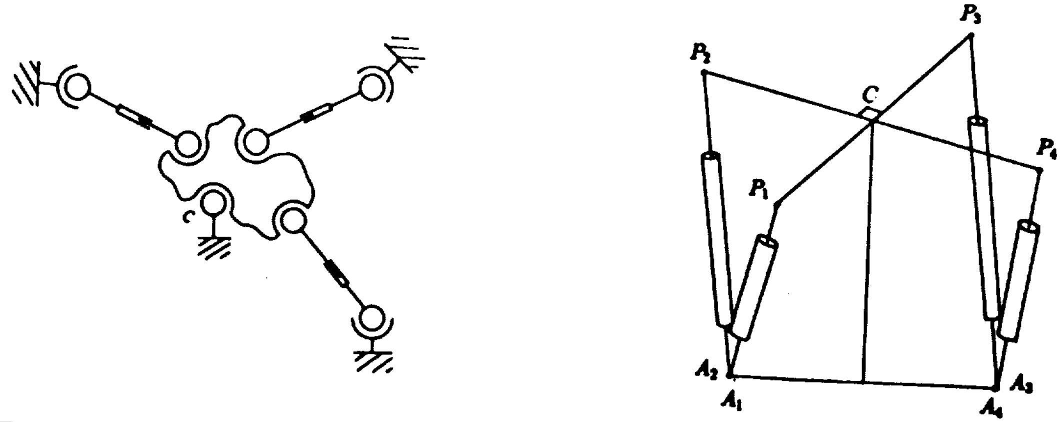

Figure 2.

Left: General case of a fully parallel wrist; Right: Practical proposed redundant mechanism.

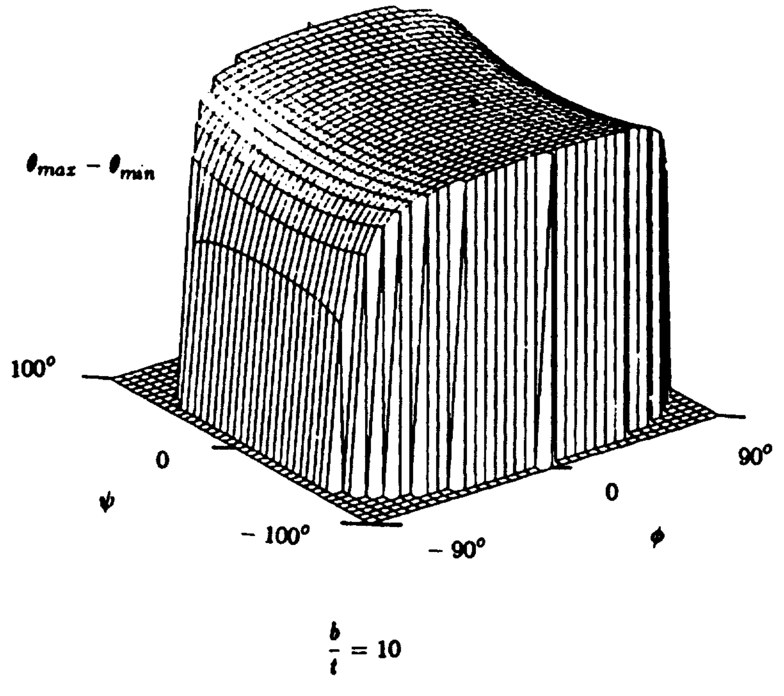

Figure 3.

Workspace with a length to thickness ratio of 10. The dependency of variations of θ is plotted against those of ϕ and ψ

3.2 Kinematic Equations and Jacobians

The inverse and forward kinematic models can easily be derived in analytic form, as well as the forward and inverse Jacobian matrices.

3.3 Singularities

A remarkable feature resulting from the addition of a fourth actuator is the elimination of the loci of singularities. It is in fact possible to show that for the grouped actuator case, all singularities are eliminated except when the plane containing the points P_i's also contains the A_i's. This configuration is in fact outside the usable workspace of the manipulator as previously defined.

3.4 Dexterity

We have analyzed the dexterity of the parallel redundant wrist by looking at the Jacobian condition number $k(J)$. The condition number can be physically interpreted as the amplification of round off error when going from input to output coordinates, and hence is a direct measure of the accuracy of the wrist in a specific configuration. The condition number ranges in value from one (isotropy) to infinity (singularity) and thus can be used as a measure of the "distance" the particular wrist configuration is from a singularity. The condition number is given by:[9]

$$k(J) \equiv \|J\|\|J^{-1}\|$$

where we can use the frame invariant Frobenius norm with weighting matrix W:

$$\|J\|_F \equiv \sqrt{tr(J^T W J)}$$

For a redundant manipulator J is non-square, and hence the condition number is defined as the maximum singular value of JJ^T divided by the minimum singular value.

Figure 4 plots the dexterity (defined as $D = 1/k(J)$) of the grouped actuator wrist against three Euler angles. It is interesting to note that there are several configurations where the wrist is isotropic ($D = 1$), providing good operating points for fine and accurate motions. As the tilt angle ϕ increases there is a general loss of dexterity, culminating in the singularity ($D = 0$) at $\phi = \pm 90^o$. Large values of ϕ lie outside the workspace, so the poor dexterity at these points can be ignored. For this design the dexterity is high in the range:

$$-60^o \leq \phi \leq 60^o, \quad -90^o \leq \psi \leq 90^o, \quad -135^o \leq \theta \leq 135^o$$

This provides a large usable workspace free of singularities and well suited for accurate motions.

4 Inclusion Into An Arm Design

Once the kinematic feasibility has been shown, the next step is the inclusion of the spherical assembly into a truss structure. The figure 5 shows one possibility using rather simple technology.

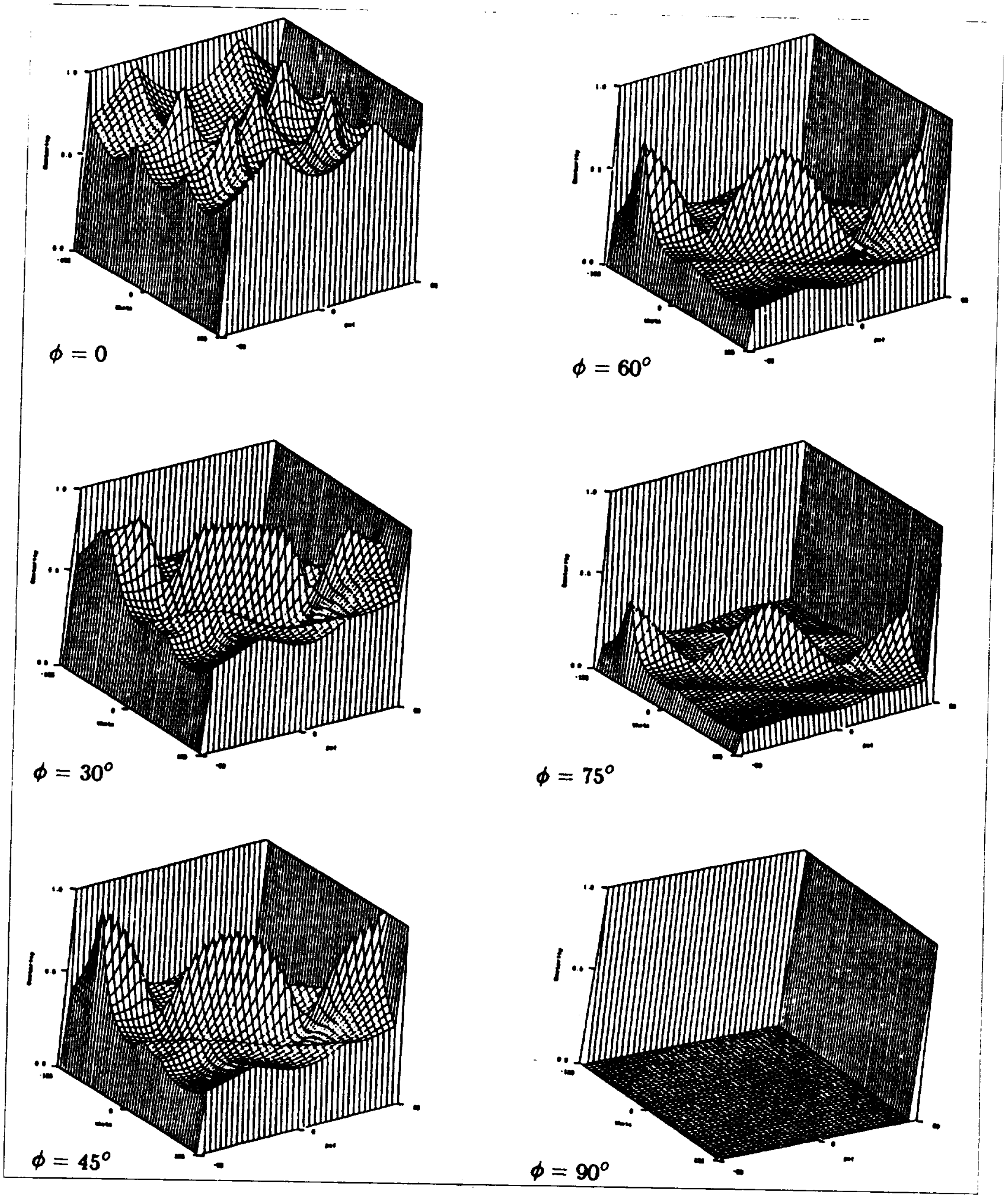

Figure 4.

Dexterity plotted for all lengths set to 1 versus angles θ and ψ. Each plot is for a different value of φ. The isotropic points ($D = 1$) are present for $\phi = 0$ and $\phi = 45°$. Only when $\phi = 90°$ is the manipulator singular and the dexterity identically zero.

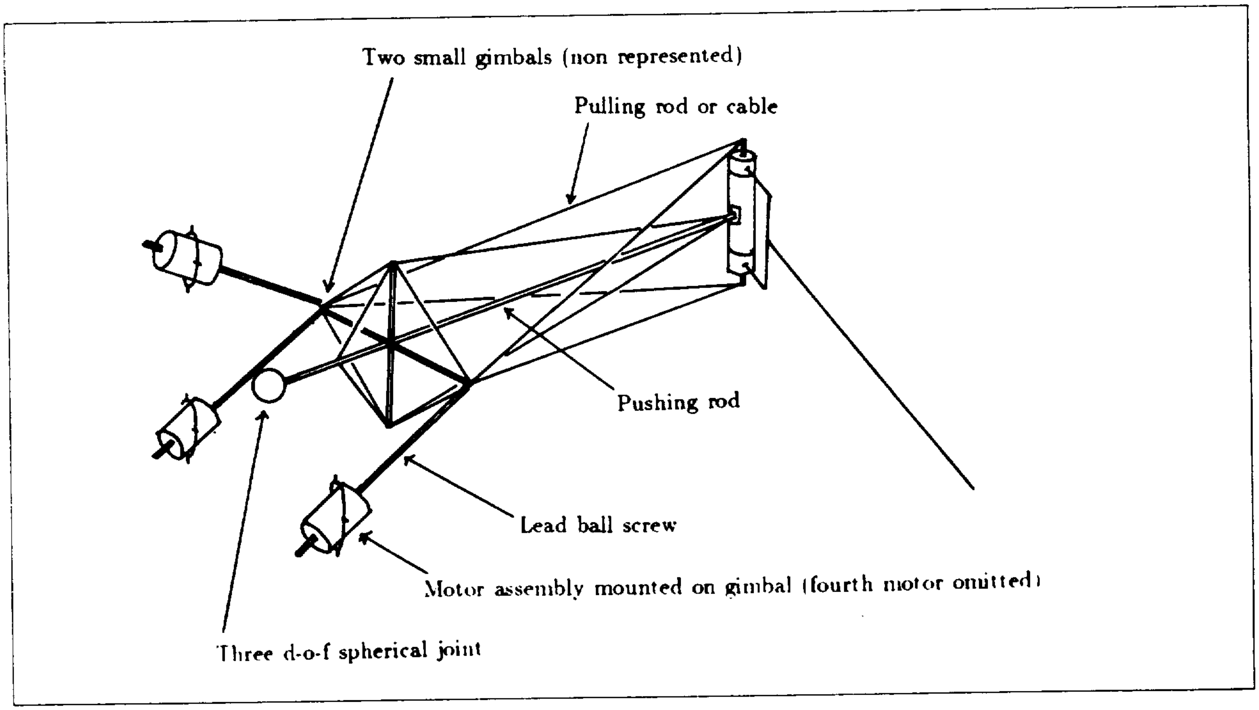

Figure 5.

Truss assembly of the proximal link with integrated parallel actuation. Note the de-located actuators.

The figure does not show how a wrist can be integrated. At the present, we are investigating the possibility of a tendon-driven spherical parallel mechanism which has identical properties as when dual action actuators are used.

Several remarks can be made about this design:

- *Skeletons:* Limbs in nature come in two varieties: endo-skeletons and exo-skeletons. So far, the design of artificial manipulators has followed a similar categorization (linear actuators: exo-skeletons, rotary actuators: endo-skeletons). Clearly the proposed design falls in the endo-skeleton category with the material used in compression located *inside* the material used in extension.
- *Actuator and Sensor Integration:* The truss design offers the advantage of making actuators and sensors an integral part of the structure, thus resulting in an economy of means.
- *Modularity:* The elements that make up such a design fall into a very small number of categories which facilitate design and construction. These are:
  1. Linear actuator, preferably slender, light and back-drivable.
  2. Pushing rods. From the load requirements, structural mechanics will tell the desired characteristics.
  3. Pulling rods. Same as above.
  4. Universal joint. Same as above.

5. Spherical joint. Same as above. An attractive possibility is a true ball-and socket assembly.
6. Multiway rigid connection for rods.

5 Relevance to Space Applications

In addition to the mobility criteria which have guided our choices through-out this discussion, a few additional points could be made with respect to space requirements.

- *High-reliability:* Space hardware has a mandate for reliability. The modular design outlined above can only help reliability. In addition, the actuator redundancy preserves some of the maneuverability in case of failure of one actuator.
- *Weight:* This issue is of course very well addressed by our proposal.
- *Power Consumption:* This requirement must be satisfied by an appropriate motor-reductor technology independent from this particular proposal.
- *Lubrication:* Same as above.
- *Back-drivability:* Same as above.
- *Temperature gradient* The deformation of structures under temperature gradient can be measured and compensated for. In fact, an arm made of a struss structure offers quite interesting possibilities. For example, the temperature of the rods can be measured and deformation computed from this information.
- *Control:* All the kinematic models are easily obtained in closed form. The control of the kinematic redundancy can easily be performed because of the decoupling of the arm self-motion from the hand motion. The dynamic model can be derived very simply because of the various decouplings. The structure can be tuned to absorb impact transients which improves the frequency response.

6 Conclusion

A number of issues remain to be addressed before such a proposal could reach the stage of implementation: choice of sensors, motors, and so on. However, kinematic feasibility has been established and a sound structural design is easy to obtain. Actuational redundancy also lead to interesting control issues.

7 Acknowledgement

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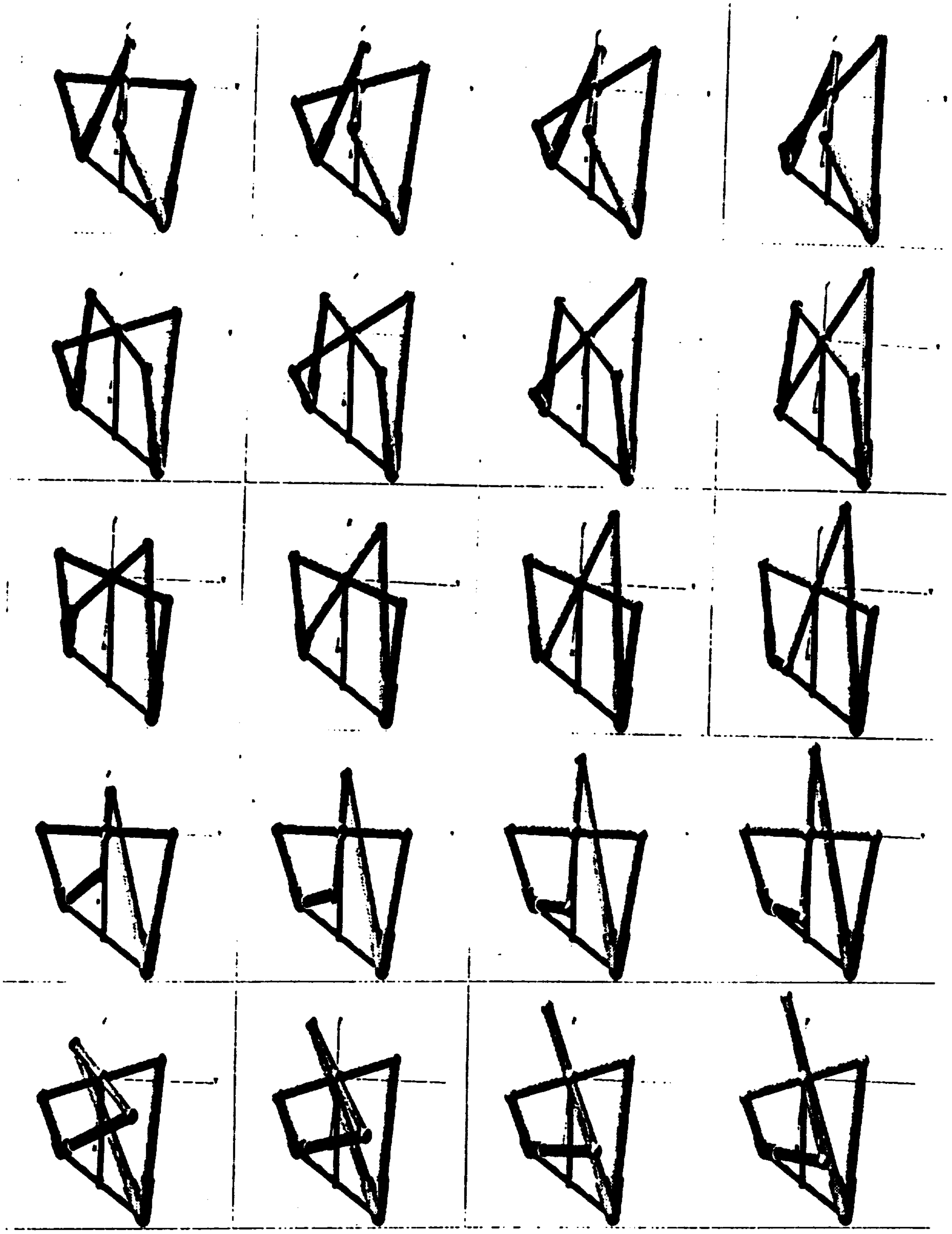
Appendix: CAD Modeling



TELEOPERATION 1