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Modular Dextrous Hand

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Abstract

We describe the design and virtues of a new version of a robot hand which is based on the division of function principle. The hand consists of two modules: a fine manipulation stage and a grasping stage. These stages function independently, and the grasping stage of the mechanism can be used by itself as a medium complexity hand. The fine manipulation stage uses the Stewart platform mechanism.

1 Introduction

During the spring semester of 1988 we have been designing a multi-purpose gripper with the goal of simplifying some aspects of robot hand technology. The well known examples of robot hands, the Stanford/JPL hand [1] and the Utah/MIT hand [2,3], are elegant mechanisms which nevertheless present significant challenges in actual use. Difficulties are partly due to the intrinsic complexity of the tasks they need to perform, but also partly due to their design philosophy.

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Both of these hands are multifingered where each finger is a kinematic chain, and where typical tasks require simultaneous actuation of all or almost all joints. The coupling between different functions is often difficult to assess, and control of these hand mechanisms remains an active research problem.

Another aspect of robot hand technology we saw as important at the outset is the need for a medium complexity grasping tool, a fact which has also been recognized by [4]. In many instances a complete hand mechanism is not required, and yet a simple parallel jaw gripper does not suffice. The paper [4] addressed this issue in a way which is significantly different from ours.

Finally, there is the macro-micro manipulator concept being advocated by [5], which we see as very promising. The key idea is this: robot arms are currently very massive, low bandwidth mechanisms, and their mechanical impedance is not suitable in many instances. A micro manipulator added at the end of a robot arm can be used to present a different mechanical impedance to the environment.

2 Division of function

The key concept which we believe has been neglected in hand design is the division of function. There are three distinctly identifiable functions which a robot equipped with a hand should perform:

- Firm grasping of objects of various shapes and sizes
- Fine manipulation of grasped objects with precision, speed, and well controlled mechanical impedance
- Moving the grasped objects within a large workspace

The Stanford/JPL hand and the Utah/MIT hand are examples of designs which couple the first two functions and rely on the existing robot arm technology for the third. As we shall show in this paper, going a step further and designing a system which decouples all three functions has several advantages.

2.1 Features of previous designs

Salisbury [1] argues that a robot hand should be capable of (1) secure grasping and (2) fine manipulation of the grasped objects. He then proceeds to analyze the types of contact between objects and selects his design (known as the Stanford/JPL hand) among 600 different mechanisms of the kinematic tree type. One of his main conclusions (which we used in our design) is that three point contacts with friction are a good choice for an immobilizing grasp.

On the other hand, the Utah/MIT design [2] was based on the anthropomorphic model from the start. Although in general this approach does not guarantee an optimal machine design, human experience indicates that it is highly functional. The Utah/MIT hand has proven to be highly dextrous and particularly suitable for master/slave control by a human operator.

2.2 Advantages sought by our design

While the mechanism proposed here is non-anthropomorphic and does not quite have the human dexterity, it has the advantage of simplified operation which results from the division of function. A grasped object can be manipulated without affecting the grasp configuration. We see this as an important factor which will significantly improve the precision of handling the grasped object.

By contrast, in both the Stanford/JPL and the Utah/MIT hands fine manipulation requires rolling the object between the fingertips. This can be done [6] and in fact humans do this all the time, but positional certainty can be lost if the rolling process is not modelled well. This modelling requires a knowledge of the shape of the object near the contact points, as well as the behavior of the compliant fingertip material during rolling. Both are hard to come by, and a strategy which does not use rolling has an advantage.

By dividing the hand mechanism into a grasping stage and a fine manipulation stage, we can optimize each stage for its function separately. In particular, we wished to eliminate rolling during fine manipulation. While our mechanism can use a limited form of rolling (eg. as required during grasp reconfiguration), fine manipulation can be performed without altering the grasp configuration.

As another benefit of our approach, the grasping stage can be used as an independent module in situations where fine manipulation is not needed. The medium complexity hand [4] was motivated by the same reasoning, but its design indicates different intended grasping strategies. While it seems best suited for enveloping grasps between its clamps, our design follows Salisbury's "three point contacts with friction" strategy.

3 Our design solutions

3.1 Large motions

There are many commercially available robot arm designs which can fulfill this function. An interesting result by [7] shows that among all designs with six rotational degrees of freedom the elbow configuration is in a certain sense optimal. This theoretical result provides an explanation of the well known fact that such manipulators have large work volume, and perhaps even gives us a hint about why human arms are designed that way.

Our Intelligent Servosystems Laboratory has been given a GE GP-110 robot which follows this design philosophy and provides a large 50 Kg payload capability. Our intent is to use this equipment to move our gripper around, without making any extensive modifications of the manufacturer's configuration.

3.2 Fine manipulation

This stage of the mechanism must be lightweight and yet very strong and compact. A parallel mechanism like a Stewart platform immediately suggests itself for that reason. The main disadvantage of the Stewart platform (its limited workspace) is not significant in this context because only small motions need to be performed. A good recent reference on Stewart platforms in general is [8].

The use of a Stewart platform is a major departure from the Stanford/JPL and the Utah/MIT designs, which did not use parallel mechanisms. While Salisbury's design could have potentially gone in the direction we chose, he limited his investigation at the outset to mechanisms without kinematic circuits. Our work has been based on his analysis, but without this initial limitation.

Although our prototype does not yet have its Stewart platform legs actuated, the potential for adding those actuators is there and we intend to do so in the near future. An important source of information can also be added by placing force sensors in the mechanism's legs. This capability can significantly enhance the controller's knowledge about the total forces and torques which are being applied to the grasped object.

Finally, our goal is to ensure that the Stewart platform mechanism has high bandwidth (close to 10 Hz), so that the mechanical impedance which the system presents to the environment at that time scale can be actively controlled.

3.3 Grasping

We intend to use grasps utilizing three point contacts with the grasped object. However, the fingertips which are holding the object are not points, and they have to be of finite size and have a shape. We have chosen to use spherically shaped fingertips in order to avoid the need to control their orientation in addition to their position. Given a set of three spherically shaped fingertips which are holding an object, we can reason backwards and design a suitable mechanism to which these fingertips will be attached.

Since we are assuming that the grasping stage can be positioned and oriented as needed, and since the fingertips are spherical, we need to adjust only the relative positions of the centers of these fingertips. These centers form an important triangle (fig. 1) which we call ***the grasp triangle***, and it becomes clear that the grasping stage ought to have at least three degrees of freedom. While mechanisms with prismatic joints were considered briefly, our goal of maximizing mechanical simplicity of the mechanism quickly suggested the exclusive use of revolute joints.

We have evaluated a number of 3-DoF mechanisms in terms of their ability to create a wide variety of triangles. Clearly, equilateral triangles are very important, and the mechanisms we chose to look at are particularly suitable for realizing a range of sizes of such triangles, as well as many other types of triangles. While the examples presented in fig. 3 all seemed promising, a small model which we built convinced us that there is another important factor to consider, namely that the grasping mechanism's intrusion into the volume of interest must be minimized.

Furthermore, as we often want to pick up objects lying on a flat surface, it is advantageous to have fingertips which move in a fixed plane during grasping (see fig. 2). The fingers which carry these fingertips link them to the actuators and serve the purpose of distancing the rest of the mechanism from the fingertip plane (fig. 5). The most natural direction of the fingers follows the symmetry of the situation, i.e. perpendicular to the fingertip plane. One can easily verify that in typical grasping situations (picking up an object on the table or at the bottom of a cup) this choice adequately eliminates interference between the fingers and the surroundings.

Since we wished to preserve the possibility of using direct drive actuation, single degree of freedom fingers were chosen in order to maximize their mechanical stiffness with minimum weight. The circular paths which the fingertips follow in this design have to intersect at a point if very small triangles are to be realized. Furthermore, we have already argued that the paths have to lie in the same plane. While asymmetrical designs may have some advantages in special cases, we did not see how they would be generally useful, and thus our design is fully symmetrical. All three circular paths are of the same radius and their centers form an equilateral triangle (fig. 4).

The final design, including both the fine manipulation stage and the grasping stage, is presented in fig. 6. It consists of a Stewart platform carrying three revolute actuators which drive fingers shaped like cranks. The fingertips are spherical and we intend to make them touch sensitive.

3.4 Prototype

A prototype mechanism has been designed (fig. 6) and constructed during the summer of 1988 (fig. 7). Since Stewart platform mechanisms are not new, we have decided to initially concentrate on the grasping stage, and only later add actuators for the Stewart platform.

The prototype is capable (by design) of applying a tangential force of about 50 N at the fingertips, and withstanding over 200 N of radial force. Assuming the coefficient of friction of at least 0.2 between the rubber fingertips and the grasped object, this prototype can pick up objects of up to

1 Kg. The practical limit would be higher, up to about 5 Kg in cases where friction is not the limiting factor.

Our immediate priorities include the construction of suitable pressure-sensitive fingertips and bringing the mechanism under computer control. As the work progresses, we will continue reporting our results.

4 High level control

Controlling an anthropomorphic hand can be easy because a master/slave arrangement can be used. Unfortunately, this advantage does not translate well to those applications where the communication channel between the master and the slave is subject to appreciable delays or bandwidth limitations. Furthermore, this strategy requires full dedication of a skilled human operator. Thus, the direct master/slave control of robot hands is not practical in many instances where those hands would be most useful (eg. robots in space, untethered submersible robots, autonomous robots).

The incentive to construct an autonomous mechanism capable of detailed planning of all stages of manipulation is still present. The modular dextrous grasping tool we have designed helps simplify this goal by dividing each manipulation task into distinct stages, during each of which a different portion of the mechanism is active. For example, a typical pick-and-place task would consist of the following steps:

1. Robot arm moves the grasping tool into position.
2. The grasping stage grasps the object.
3. If the tactile information indicates regrasping is needed, fine manipulation stage can be used to adjust the position of the grasping stage.
4. Robot arm moves the grasping tool holding the object into a new position.
5. Under force feedback, fine manipulation stage makes precision adjustments until the object is in the desired location.
6. The grasping stage releases grasp and the task is completed.

Note that performing the above tasks does not require modelling of the rolling process during step 5, and that the dedicated fine manipulation stage of the mechanism can be omitted if the robot arm can perform the steps 3 and 5 with adequate precision.

5 Conclusions

The modular dextrous grasping tool presented here does not look like a human hand, but it is well suited for executing a wide variety of grasps based on the three point contacts with friction idea. While the grasping stage of the mechanism would be sufficient in many applications, adding the fine manipulation stage makes this tool's capabilities comparable to the more complex mechanisms we have used as examples.

The key benefits of our design are its mechanical simplicity, its modular nature, and the possibility of using decoupled control strategies (where each stage of the mechanism would be controlled by a corresponding control module). As our work progresses, we will evaluate these benefits and try to uncover potential limitations.

Some limitations of our mechanism are already clear: it cannot make enveloping grasps, and it can use only a limited form of the rolling strategy. We believe that these limitations are not very significant, and that the advantages already mentioned justify using our design in many situations in spite of these limitations. The prototype which was built will serve as the test of such ideas.

6 Acknowledgement

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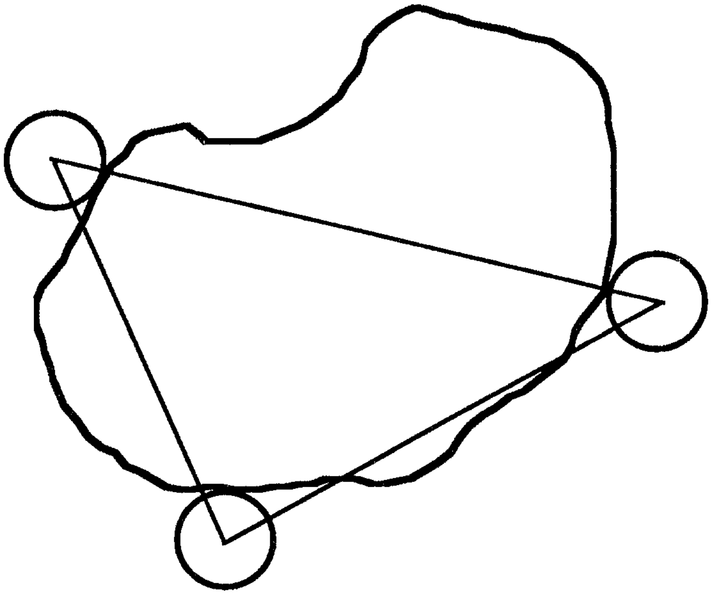

Figure 1: The centers of spherical fingertips grasping an object form the grasping triangle.

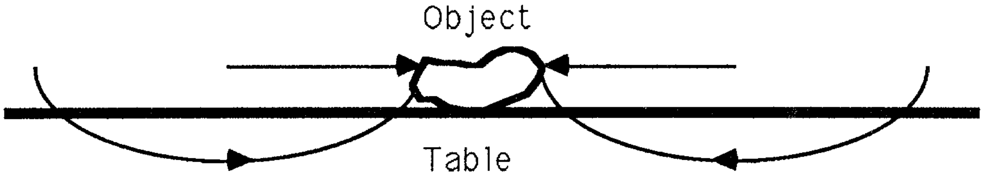

Figure 2: Two alternative fingertip approach paths during grasping of an object on a table. The curved paths shown are not physically possible, and the mechanism which uses paths parallel to the table surface should be used.

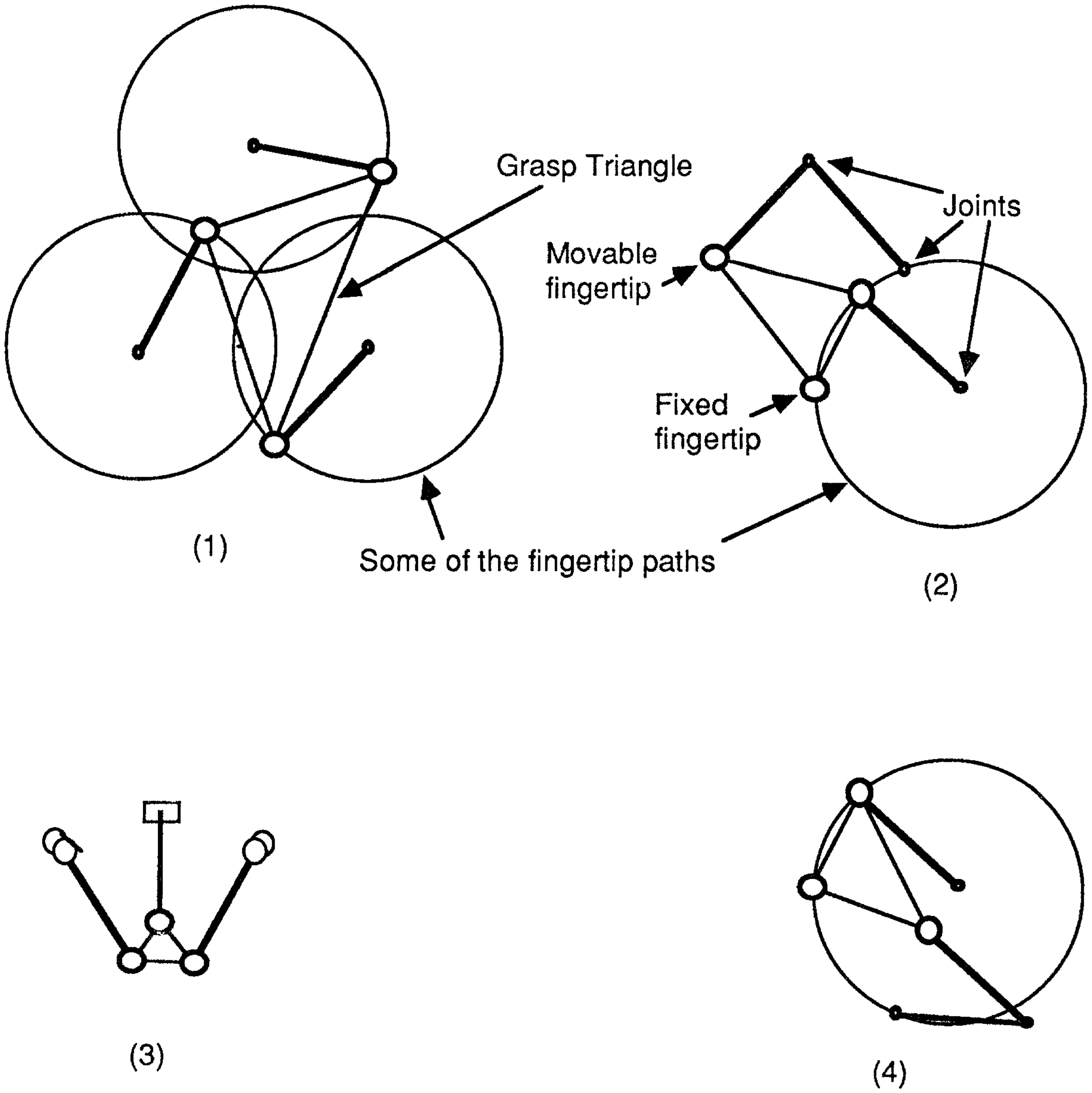

Figure 3: Four interesting design possibilities.

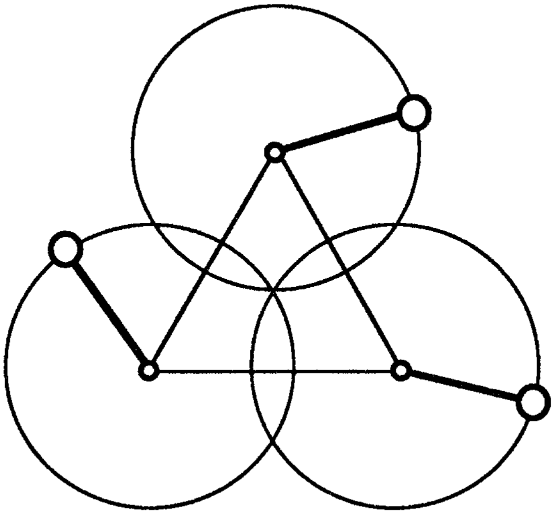

Figure 4: The axes of rotation in our grasping mechanism form an equilateral triangle. All three fingertips move along paths of the same radius, and their paths intersect at the center of this equilateral triangle.

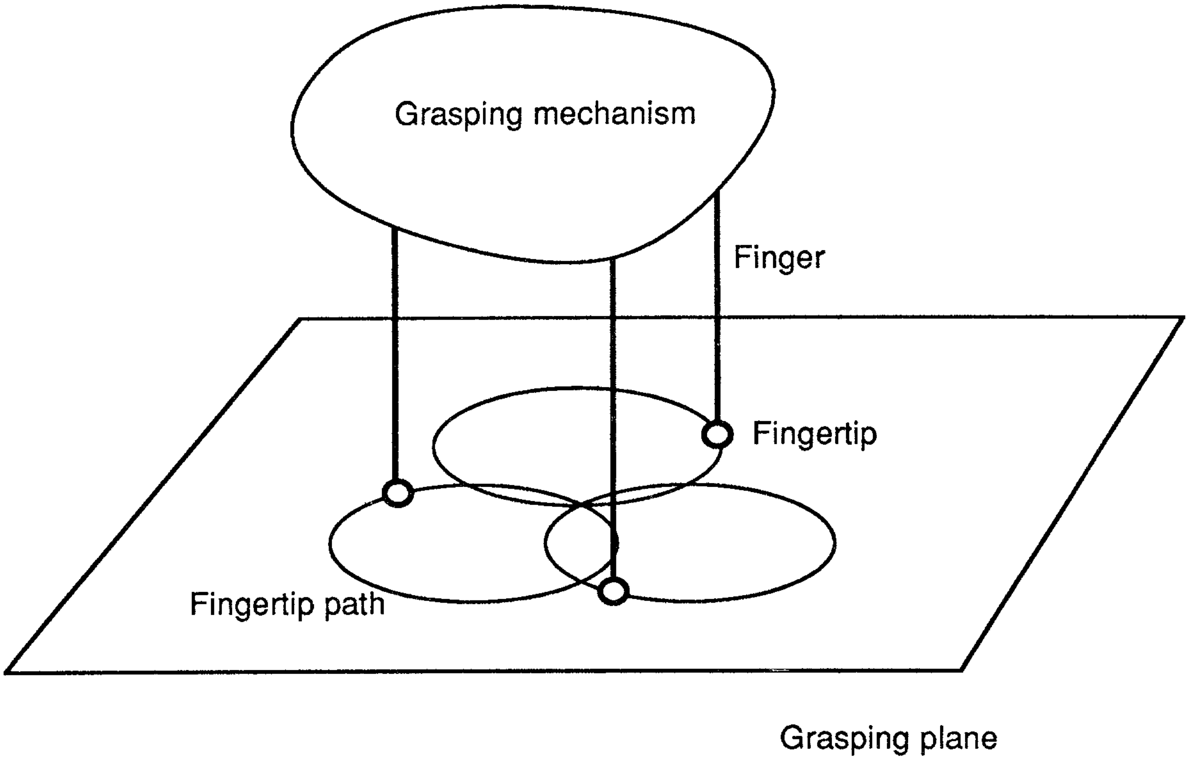

Figure 5: The physical relationship of the plane within which the fingertips move, the fingers, and the grasping mechanism.

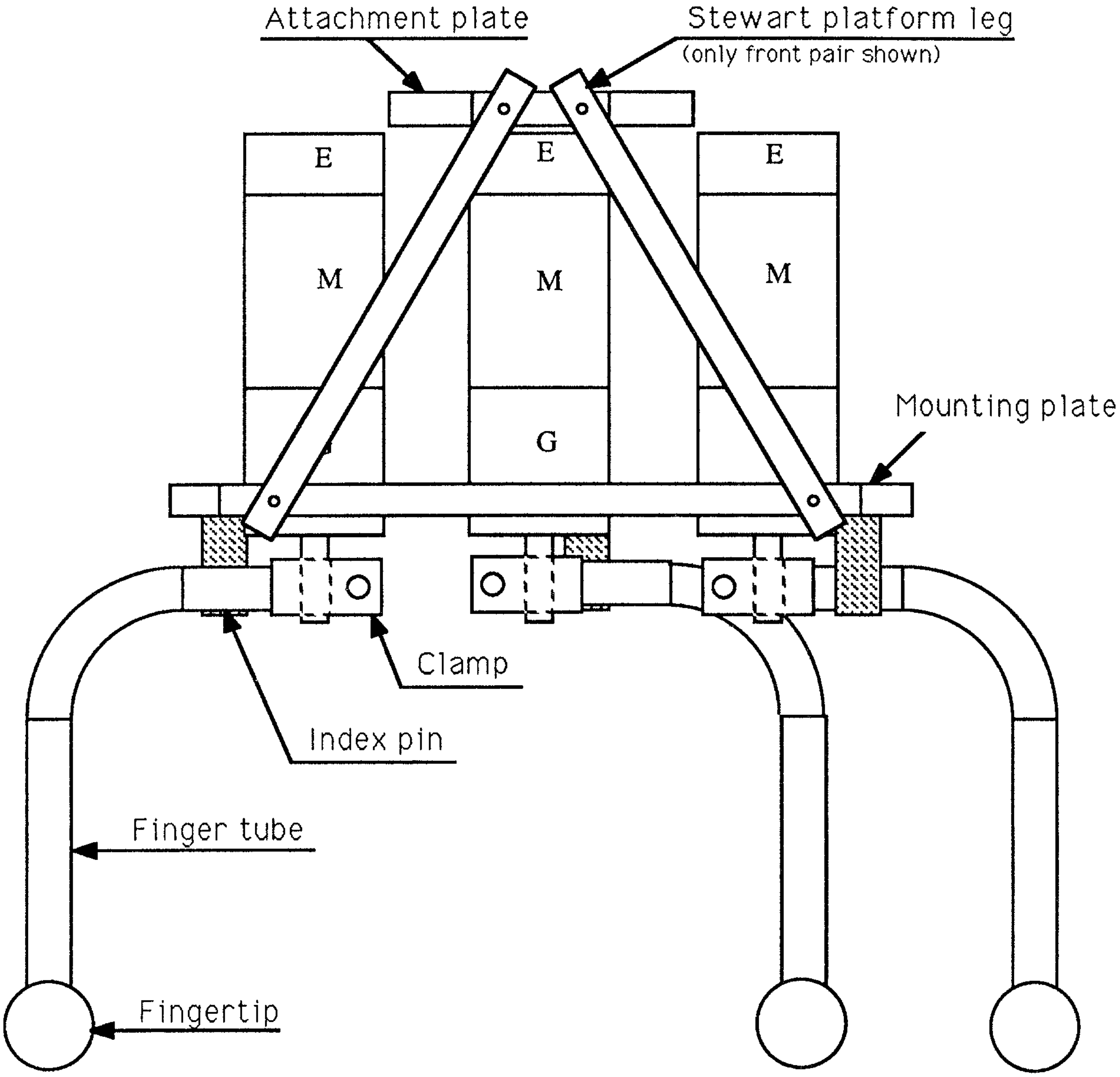

Figure 6: A side view of the prototype modular dextrous hand.

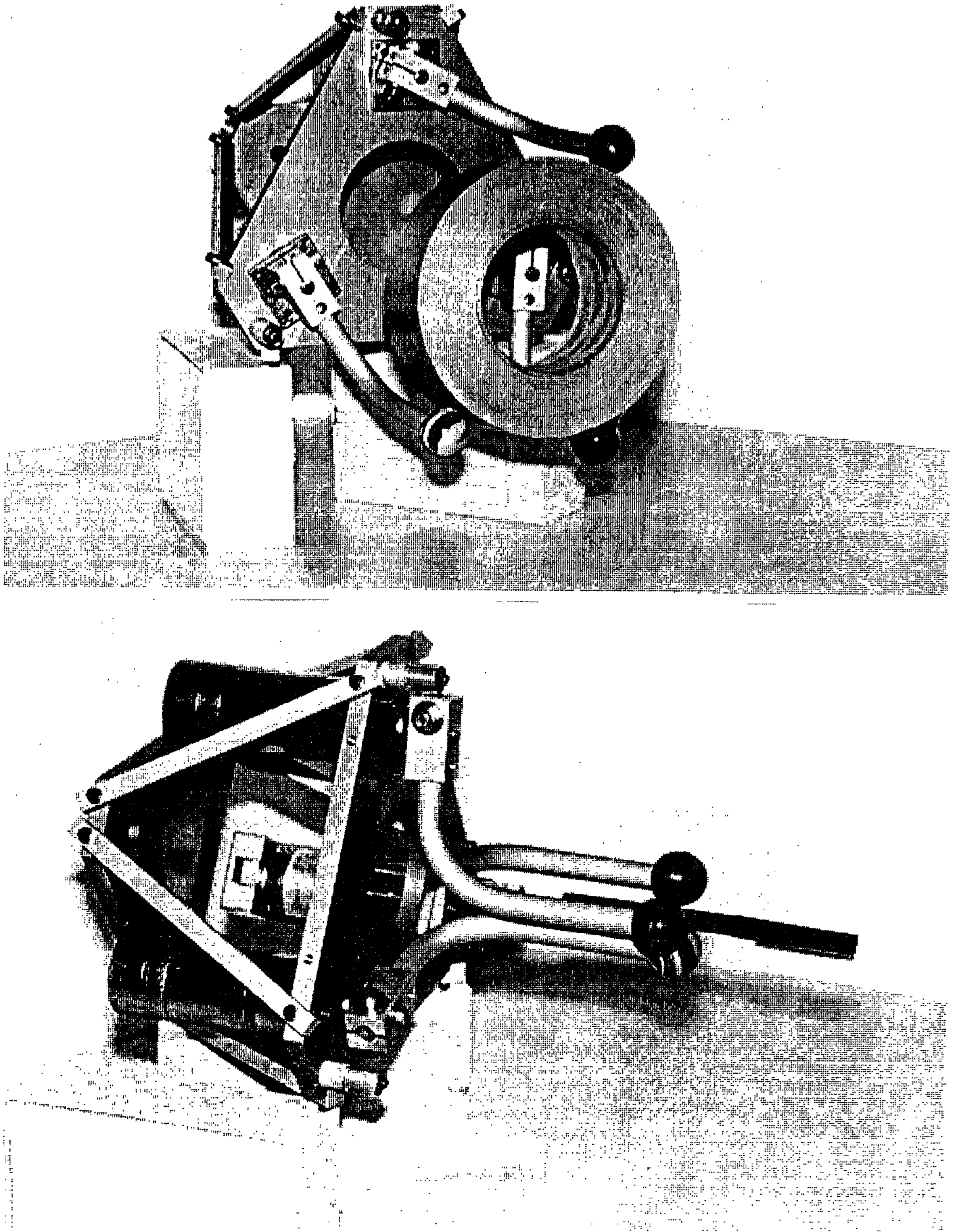

Figure 7: Modular dextrous hand can grasp both large and small objects. Internal grasps, although not shown here, are also possible.

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