MASSACHUSETTS INSTITUTE OF TECHNOLOGY
A.I. LABORATORY

Artificial Intelligence
Memo No. 274

January 1973

PROPOSAL TO ARPA
FOR
CONTINUATION OF MICRO-AUTOMATION DEVELOPMENT

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Work reported herein was conducted at the Artificial Intelligence Laboratory, a Massachusetts Institute of Technology research program supported in part by the Advanced Research Projects Agency of the Department of Defense and monitored by the Office of Naval Research under Contract Number N00014-70-A-0362-0005.

Proposal For
Continuation of MICRO-AUTOMATION Development

This proposal discusses practical aspects of our project to produce a replicable research tool for development of real-world computer-controlled hand-eye systems. If this proposal is read out of context, it will not seem very sophisticated because it is concerned mainly with the practical aspects of putting together an engineering system. The theoretical and conceptual context is described more thoroughly in the memo, supplementary to our main ARPA contract proposal, that describes in detail robotics research at the MIT A.I. Laboratory.

Most of the points herein explain ways in which the original proposed program is progressing, or has been modified. There are two main changes in the plan. First, we are proceeding toward the "micro" domain in a somewhat different route than originally planned, because of the intermediate development of a high-quality mechanical manipulator that takes us halfway with no difficulty; this will allow more time for innovation at the next stage, still meets our conditions for desk-top operations, and involves identical software and systems. Second, we now intend to proceed more rapidly than originally planned toward a particular practical application domain, or "world", because of a similar decision within the project's main robotics group. The application area, electronic assembly, presents a reasonable level of challenge to the developing systems, should certainly have some valuable outside applications, and deals with a variety of shapes and structures that are encountered in many other environments.

CONTENTS

1.1 What's Been Done

A study has been made of manipulator geometries and trade-offs. A simple arm has already been designed and built by David Silver as a test-bed for some of the ideas. Its degrees of freedom are split between motions in the arm and motion of the work table, simplifying many mechanical elements (see 3.5). It incorporates the force-sensing wrist developed by Minsky and Shah earlier in the project. Experience with this arm has contributed to our ideas of how arms should be controlled when direct, sensitive force feedback is available. It was gratifying to find that the programs for a number of diverse goals turned out to be fairly similar. For example, the feedback techniques for turning a crank need little change for putting a nut on a bolt. There is more to learn, practically and theoretically, about force-controlled manipulation of constrained systems by compliant hands.

MECHANICAL ARM: A new arm has been designed by Victor Scheinman and is in the process of being built. This arm is moderately small in scale, and should be precise enough and easy to control. We plan to use it for the next year or so. It is of the serial degree of freedom type. We expect to develop theories of good design for arms built on smaller scales during this period; these will almost surely use less orthodox arrangements of the degrees of freedom (see 3.5). The Scheinman arm, being built now, fits the size range for our next manipulator problem domain, that of electronic assembly, inspection and repair.

FORCE AND TACTILE SENSORS: We have studied a variety of force feedback schemes. The so called "force-reflecting" or "bilateral servos" that are popular in human-operated remote manipulators have only limited application in controlling arm motion and preventing overloads. These devices depend on measurement of loads on the driving motors, and delicate balances are required for approximate cancellations of inertial and gravitational terms. It should be much more efficient to measure real forces close to the hand and for guiding its interactions with the objects it holds or touches. For fast, delicate operations, we think that high-compliance but brakeable members will be desirable. Also useful, will be touch sensors on the fingers themselves for the most rapid and sensitive measurements.

Different servoing techniques apply to these different kinds of information. It would be best to perform all the servo calculations in the computer since analog circuits would not be able to incorporate the non-linear interactions between the links of the (model) arm and the force sensors, at least not without a very complex development program. The most plausible servo strategies seem to require combinations of force and position control analogous to combinations of current and potential sources.

Experimental studies, up to now, have been done using our PDP-6 as the "mini-computer" with our interim arm and force sensing wrist.

Communication with the time-sharing computer was via shared core and did not model accurately the character-level link we will have to deal with later.

COMPUTER SELECTION: A detailed study was made to determine which mini-computer would be best for interfacing to the manipulator, the vision and force sensors, and to the remote larger computer. Size and ease of program development were taken into account. It was found important that the mini-computer be able to handle the details of the mechanical servomechanisms (see below) as well as a great deal of picture processing. Only if these are done locally can we achieve the goal of having the "high level" planning done in real time by a remote larger computer system, via the network. No special hardware need be developed for the network control. A PDP/11-40 was chosen and ordered.

1.2 What We are Doing Now

MECHANICAL ARM: At this time the new arm is being built. Several copies will be constructed, aside from ours; Stanford will be getting two and the University of Illinois is planning to get one. Other institutions have expressed interest, which is satisfying since it is in line with the intent of the mini-robot proposal that other researchers should use compatible modules. The new arm was designed by V. Scheinman while on loan to MIT from Stanford.

D. Silver's Arm, which is available now, will soon be controllable from our time-sharing computer by evaluating expressions in the LISP language. Since it is less dangerous, more accurate, and easier to use than our old equipment, it will invite experimentation by people interested in such topics as language understanding. Thus, we shall soon have a prototype of the facility that will become available later when our mini-computer will be interfaced to the new mini-arm and the time-sharing computer. We certainly can expect an attempt to interface it to Winograd's language-understanding system.

EYES: While building the linear-array and mirror system, we will continue to study other sensors and obtain information from groups successful in specialised applications, such as the M.I.T. Space Research Center. We are also in contact with Binford, at Stanford, who is completing a sensor study. There is a problem in determining which trade-offs and problems are inherent in the devices and which are due to poor design and manufacture.

CONTROL: As the hardware is assembled it will become easy to attract students to the problems of servo control, manipulation languages, and representations of physical models. Work on the latter is under way in several of the projects discussed in the A.I. Main Proposal, and will not be repeated here. We are keeping an eye on a possibly similar effort in Professor Dertouzos' group at MIT.

1.3 What We Plan to Do:

SYSTEM: The first task will be to integrate the various pieces of hardware. The mechanical hardware will first be assembled in a modular system to allow easy change and expansion. We do not have enough practical experience to decide which motions of the eyes, for example, are indispensible; is the apparent convenience of an eye mounted on one of the hands worth the extra complexity it would add to the vision programs? Probably, yes. Early experience with the application domain should then supply a basis for choosing between generality and special features of the minirobot configuration.

Next, the programming system must be put together. It will need an executive to stand between the character-level network link and the minirobot system primitives. Commands like "pick up that resistor" must be translated from high-level description in the large computer into a language of feature-location, tracking, and motor commands. Most such actions have to be goal-directed and translated into interrupt-driven sub-procedures in the minirobot, and this is probably best done by demons or production-like conditionals. The programming system at the minirobot end has to work in terms of geometry, coordinate transformations of visual features, motor torques, and such quantities, while the high-level system talks about objects, paths in space, relations between objects.

Because of limited data rates, it is not practical to transmit pictures to the main computer. That machine must send requests to control the picture processing facility in the minirobot to derive and return intermediate level descriptive data. There are similar, if milder, limits on remote control of mechanical activities; we must transmit, instead, descriptions of control strategies. This is a new kind of control problem, we think, but not inherently too difficult. Experience with real applications will suggest useful primitives for both manipulation and vision.

APPLICATION: We plan to develop and test the complete system in an environment of assembly, inspection and repair of discrete electronic circuits. This should prove out the hardware as well as the programming concepts. We have to develop ways to marry the senses of sight and touch in order to control such activities as component insertion, soldering and unsoldering, wiring, etc. Some tasks are well suited to using either visual or tactile feedback, many require both. Little work has been done on such problems.

MICROMANIPULATION: We are deeply interested in the problems of micromanipulation. There are serious engineering problems in scaling down tc very small sizes, the conventional serial arrangement of links with motorized joints. There is no fundamental problem of principle here, for one sees solutions in insects and crustaceans. But there are also alternative designs that appear to be much easier, using tendon-controlled "parallel" arrangements (see 3.5). We have not yet thoroughly studied the engineering problems of such configurations: micro-manipulators have new problems and design choices. We have studied several designs of tendon controlled, parallel degree-of-freedom manipulators, but have not looked at the down-to-earth details of how to build one to compete in accuracy, versatility and solvability with its larger, well-understood brothers.

The Electronics Application

2.1 Introduction

Our original proposal described at length what we feel are urgent problems that require the development of a generally available set of laboratory tools for research in machine vision, manipulation, and advanced production technology. We want to fully develop a laboratory system that is inexpensive enough for widespread use yet powerful enough to permit serious research.

Our primary objectives during the coming year are to develop vision, manipulation, and debugging languages and equipment, toward the development of an application demonstration to test out the laboratory's modules and stimulate interest in using the laboratory elsewhere.

2.2 The Electronics Problem

Concurrent with the development of general software tools, we want to work out a specific application using the evolving system. This is important for two reasons: first, only a successful piece of application research can demonstrate the mini-robot's competence (utility?) as a laboratory tool; second, the development of general hardware and software of this kind is more likely to be relevant to real problems if a real problem is attacked in the course of the research.

In our original proposal we cited a need for advanced, visually conscious machines in such areas as manufacturing, mining, housing, transportation, space, farming, and medicine. Of these we feel that manufacturing is the best area for our initial effort since the visual world encountered in typical manufacturing situations is relatively simple and constrained.

In particular, we believe that the assembly, inspection, testing, and repair of electronic circuit boards offers a rich variety of problems in a form that allows rapid progress and eventual generalization.

We next discuss this application in detail. One might wonder whether this is a realistic area for practical application. Electronics assembly is already one of the most automated of industries; and for mass-production problems it is hard to compete with special-purpose assembly machines. However, we are not concerned so much with the value of any one application, but with stimulating growth in this area, and it should be remembered that fabrication and assembly are not all of production; testing, repair, installation, and inspection are important problems.

2.3 Scenario

As a first step, we propose to work toward a system that looks at a scattered set of resistors, diodes, and integrated circuits on a table, selects the proper ones, bends the leads if necessary, and inserts the components in the proper holes. While doing this, verification and testing of the part would be a relatively simple matter.

We believe that such capability would be much more useful than one might at first think. We have found that in the mini-computer industry much of component insertion is still done by hand rather than by special purpose machine. This is probably typical of manufacturing in general. Except for very long production runs, it is too expensive to design special-purpose assembly machines, and present-day "general-purpose" machines are simply not general enough, or economical enough. As our technology advances, inexpensive minicomputer systems will acquire sophisticated visual and tactile senses and the modest intelligence needed to be useful in many such manufacturing points.

In any case, the assembly project we propose is a way of initiating work on visual and tactile skills with very wide potential application in other areas. The very fact that the immediate application, electronics, is already substantially automated might be considered to favor the project's chances of maintaining neutrality in economic arguments.

Within the electronics industry itself, the assembly skills of part recognition, orientation, and attachment are prerequisites to an automated repair facility. We imagine a demonstration in which a user requests the replacement of a bad diode or perhaps even an integrated circuit DIP. The mini-robot, acting as a repair specialist, would then:

1. visually locate the specified part
2. clip off its connecting leads

3. desolder the clipped-free leads from the board using a force sensitive tug to pull them out
4. visually inspect the holes to be sure they are free of solder
5. insert the new part guiding it to the correct position with a combination of visual and tactile feedback
6. solder in the new part
7. inspect the newly solder joints and resolder if necessary.

The problem of visually locating a troublesome part is another form of the general problem of finding parts in a box or bin. The problem of inserting a replacement part is a low precision, high tolerance special case of the general parts orienting and assembly problem.

Next we would work toward circuit debugging aids to give the test programs the same capabilities that technicians now have. The mini-robot should have the ability to:

1. visually locate a part and connect a probe to one of its leads

?. disconnect a part from the board for testing in isolation
   This might be done by removal or by sawing narrow gaps in PC board wires, to be re-bridged after the test.

2.4 Why We Can Do It

Electronics assembly and repair is particularly attractive to us because a substantial part of our hardware and software experience from earlier work on the blocks world is carried over:

1) Our present programs for locating blocks in space depend on relations to the surfaces on which they rest. Although use of range-finding will change this, the general simplicity of planar circuit assemblies will simplify the transition.

2) The parallel faces of blocks permitted our successful use of industry's primitive, simple, parallel jaw hands. The tubular or rectangular shapes of most electronic components require only small augmentations or indentations in the hands. Manipulating wiring is a new subject, but one that would seem to be more a matter of software than mechanics.

3) Searching for insertion holes at the ends of printed circuit wires should require only slight modification of existing line tracking and vertex-finding programs.

4) Turning cranks and screwing on nuts has been done in our Laboratory, using force-feedback operation. The problems of jiggling parts into place and inserting them ought to succumb to similar methods.

We have some experience with analysing curved surfaces, intensity distributions and highlights (Ph.D. Theses of Horn and Krakauer)-- which should help in examining soldered joints for flaws, etc. But this area is still very poorly developed and we would hope that success of the project as a whole, in getting robotics equipment into other research centers, will lead to more rapid progress on sub-topics like this.

2.5 Why It's Important

The practical benefit of devices that could descend from such a prototype will be enormous. For example, in the mini-computer manufacturing business such inspection, testing and repair operations can account for as much as half the cost of getting raw components together into a functioning, debugged device. Repair is today an unavoidable manufacturing operation.

On another order of sophistication, a command like "replace that 200K resistor" would generalize to things like "remove that engine, grind the valves, and put it back" or "repair that leaking pipe" or "replace all the burned-out light bulbs in this factory" or "chip off all the bad paint on this ship and repaint it".

3. NOTES

3.1 Mini-Robot Programming Concept

The Mini-Robot computer can be used in a variety of modes. Mini-Computers are quite powerful and can provide many of the features (such as file-handling on a cassette tape or cartridge disk) available on a time-sharing system. The importance of such features, as well as the value of local editing, assembling, and debugging, depend on the bandwidth of the associated network and on the costs of remote computation; we are inclined to begin with a relatively high level of local autonomy.

When used as a slave from a distant computer over a character-level interface (such as a teletype or the network), the minicomputer supervisor will run a command interpreter and a set of primitive subroutines which define its behavior. There can be several sets of these primitive subroutines depending on the users' interests. These routines will handle the A/D and D/A (for servoing, force sensing, etc.), switch contact inputs and relay contact outputs (touch sensors, brakes), the eye and ranging devices, as well as the real-time clock.

The character strings will be in the form of lists. Both the commands to the Mini-Robot and the values returned will be in this form. Usually the values will be returned when the requested action has been taken, but many commands will create or delete demons that run programs without network interaction. There will be interrupt features for both directions.

The communication protocol may be highly compressed for encoding blocks of data and transmitted program code.

The heterarchical programming style will require dynamic allocation and dynamic creation of primitives. This will need a strong function definition facility with some sort of local compiler.

3.2 Manipulation Languages:

This is still a new field. A good manipulation language (system) needs access to a good description of the specific manipulator and its properties. That model is needed not only in straightforward geometric matters like determining hand position from joint position, but in chosing motion strategies compatible with the dynamics of the motions, the constraints on forces, etc. A manipulator with servo control separately for each joint cannot move fast in constrained trajectories or in a fashion independent of the loading on the various joints. Computer servo control, on the other hand, can allow for the interactions of inertias and joint angles. The arm language, therefore, must allow easy specification of servo strategy. Somewhat more complicated is the incorporation of three levels of force and touch sensing. The language must allow goal oriented task specification as well as taking care of unexpected events. Some extension to the ideas embodied in Ernst's program are needed to handle more complex force and touch sensing. We expect some of the simple force and position control programs we have used on our simpler arm to turn out to be fairly general, many tasks requiring only simple additive combinations of force and position control.

3.3 Considerations in the Design of a Manipulator

Many trade-offs were incorporated in designing Scheinman's new mini-arm. The result is hoped to be robotic's most useable research arm to date.

Maximum load will be about 3 lbs.

Speed will be sufficient to allow almost all motions to be completed in less than one second

Workspace will have a radius of about 15"

Accuracy will be about .01".

Easy solution methods are available because the last three rotory joints have intersecting axes.

Stiffness is largely a matter of motor torques, portability is assured because the complete arm will weigh only 10 - 20 lbs. Highly reliable D.C. torque motors are used. The arm will be versatile because of its high "aspect ratio"--volume of work-space compared to volume occupied by manipulator as seen from the hand. The cost will be about $3,000 to produce in small quantities, and the arm "looks right". A lot of thought went into the decision to make all joints rotary. A number of other factors such as sensitivity to environmental factors were considered when the materials were chosen.

3.4 Choosing a Minicomputer:

More than 45 companies offer minicomputers available locally. Most have 16 bit word-length and address up to 32k words. Many are copies of DEC machines or DGC Novas. Some have immediately obvious problems such as fixed page position rather than addressing relative to PC. Other deficiencies are the poor register structure of the Varian machines and the primitive I/O structure of Texas Instrument machines. Some companies may or may not continue to exist very long, others have no software. The ones looked at in some detail include:

DGC Nova 1200, Nova 800, DEC PDP11/40, PDP11/45
Lockheed Electronics SUE, Honeywell 716,
Interdata 20, Texas Instrument 960A and 980A,
Varian 6201 and 23, Microdata 1600, and H.P. 2115A.

Considerations included ease of generating software, ease of interfacing to specialised equipment, availability of peripherals, speed and cost, reputability of manufacturer, hardware architecture, instruction sets, availability of optional features like D.M.A., Multiply/Divide, addressing modes and ease of handlng interrupts, physical size, and delivery time.

The choice finally narrowed down to the Nova 800 and the PDP11/40. The latter was chosen for reasons of compatibility with machines in and around the project and to avoid having to duplicate programming and hardware interfacing efforts.

	PHASE A	PHASE B	PHASE C
TIME SCALE	end of '2	end of '3	after that
MINICOMPUTER	PDP 6	PDP11/40	same
MANIPULATOR	Silver arm	Scheinman arm	Tendon controlled micro-manipulator
FORCE SENSING	Shah wrist LVDT's	One-piece wrist SC strain guages	same
HAND/FINGERS	Silver hand	Scheinman hand	Multi-finger gripper
TACTILE SENSE	--	Micro-switches	Fibre optic
VISUAL SENSOR	Image dissector	Photo-diode	Vidicon/Image dissector
RANGE FINDING	--	--	Projected slit
COMMUNICATION	Core link	Fast ASCII link	ARPA network

3.5* SERIAL VERSUS PARALLEL DEGREES OF FREEDOM

A manipulator needs many degrees of freedom. To understand the resulting complications, we need some sort of general framework for analysis, but we don't even have a useful taxonomy for classifying the problems. Here we will contrast two extreme kinds of anatomical approaches; quite a few issues emerge clearly even from this primitive dichotomy. The two extremes are "serial" and "parallel".

> In a SERIAL arm, we have a sequence of bodies, usually rigid rods, whose positions are determined by a series of constraints -- joints -- in which each constraint fixes the position of a body that serves as the support for all its successors. Thus the degrees of freedom have a distinct order.

All the industrial manipulators are of this character. The human arm is representative of the serial variety, in general plan, although it is really an intermediate case because each joint may combine two or even three degrees of freedom. The human wrist, from the outside, appears to have three degrees, but the rotation is really associated with the radius-ulnar relation which should be considered a separate joint.

> The PARALLEL concept is perhaps best illustrated by the way an animal's body is supported by its legs. Here several constraints simultaneously determine the relation of one body to another (the ground, in this case). A clearer example is that of a crane or antenna mast supported by guy wires. Because six constraints are needed to fix an object in three dimensions, that bounds the amount of parallelism possible at each "joint".

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* Sections 3.5, 3.6, and 3.7 were excerpted from A.I.MEMO 267, Marvin Minsky, MANIPULATOR DESIGN VIGNETTES.

The sequential succession of constraints in the serial arm causes many problems that seem to grow in a multiplicative way:

> Errors and uncertainties are cascaded and cumulative.
>
> Rigidity is relatively low because of long moment arms.
>
> Inertial and gravity effects are large, especially if the proximal joints have to support the mass of the distal motors. This and the low rigidity combine to produce large, annoying, low frequency vibrations. These make precise positioning slow (to avoid dangerous overshoots) and make delicate force-feedback measurements impractical.
>
> Power supply and "innervation" require complicated "threading" through or around joints, especially if the motors are not built in, but work through tendons.
>
> Some of these problems can be reduced by making the proximal joints much larger than the distal ones, but this yields a massive and clumsy system, viz., a milling machine.

All these problems can be controlled to various degrees, given enough attention to weight and dynamics, as in the vertebrate and insect arms. More dramatic illustrations of serial cascading of joints are seen in vertebral columns, especially of the serpent. Strictly speaking, none of these are purely serial, each having two or more actuators for each joint. This is one way to reduce the amount of serialization.

Another way to reduce the amount of cascading is to divide the mobility of the whole system into two parts by moving the work as well as the manipulator. Example: in some milling-machines that need three degrees of freedom, the bed on which the work is mounted has two horizontal axes; the third axis moves only the cutting-head. Another "solution" is the moving-robot approach: by walking or driving about the floor, one gets two degrees of freedom without the cost of transmitting power and information through two joints. The machine has to be attached to the floor anyway, one can argue, so why not exploit this? One can regard the floor as a ball-joint with zero curvature!

In any case, the parallel approach promises to reduce complication. Ball joints, with three degrees of freedom, have no more parts than single hinge joints. What really is difficult is to make a two-degree joint, with freedom to bend but stiff axially; this is the "universal joint" problem.

Parallel Manipulators

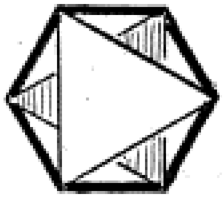
The parallel approach is complementary, with quite different problems and features. To introduce it, begin by considering the general problem of positioning a rigid body in space relative to a frame of reference.

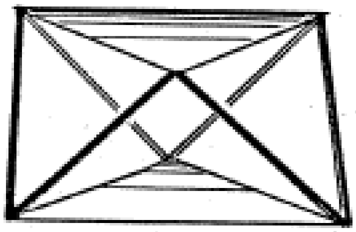
> Suppose given three fixed reference points in space and three points on the rigid body. Then there are nine distance-pairs between these points, but specifying almost any six of these causes the other three to be determined. This observation suggests a very simple and direct approach to design. Choose six of these distances. Then construct a manipulator by realizing physically each length constraint as some mechanical length-determining device, such as a hydraulic cylinder or other "linear actuator".

Each actuator must be terminated by a spherical joint or elastic coupling. Then we acheive complete mechanical control of the rigid object simply by instructing separately the motors for all degrees of freedom, without cascading their effects.

A particularly symmetrical example of such a design is shown below: we choose six edges of a cube to position one equilateral triangle with respect to another. The resulting structure outlines an octahedron:

The six edges are the ones that form the hexagonal shadow when a cube is balanced on one of its vertices!





In principle, it follows from the basic constraint-determination idea, that one can position the body in any location and orientation in three-dimensional space. However, there are practical problems:

> In certain positions the constraints degenerate (e.g., two rods coincide) making the position indeterminate. The structure will flop.
>
> As we approach a degenerate situation, the mechanical advantages become too small, great forces are needed, and the structure will buckle.

In practical implementations, it is hard to find large ranges in which the supports do not interfere with one another by colliding. This is particularly severe in regard to axial rotations.

The supports must subtend a substantial space angle to get much stiffness. On the other hand, an arm should subtend a small space angle (looking from the hand) to achieve dexterity. In optical jargon, one wants a hand to have a large "f-number"!

The ability to get around obstacles is limited. With a serial arm one can use redundant degrees of freedom to get a tentacular effect. It is an illusion, however, that serial arms inherently provide dextrous access, since unless the elbows are redundant, the multijointed arm doesn't allow for alternative paths. Of course, with six degrees of freedom one has a three-dimensional selection of ways to reach a point in the workspace, and one can trade between global arm-path configuration and the precise direction of arrival at the work.

The actuators must be length-changers, in contrast to those in the serial arm, which can be linear or angular. This is usually a large advantage, because in the parallel system, the natural way to effect constraints is by pulling tendons. Cable-pulling mechanisms are easy to design and can be very compact.

Although parallel systems have disadvantages, these seem quite different from those of the serial system. There are important advantages, as well.

Very great simplicity, because of the non-interactions.

The instrumentation of force-sensing is particularly convenient; the longitudinal stresses in the supports determine completely the forces operating on the mobile plate (unfortunately, including gravity). As shown in 1.3 below, one can exploit this to get very elegant and useful kinds of force- and tactile- feedback.

The forces are entirely axial, so that light, thin tubes can yield great strength. Serial arms in general, and angular actuators in particular, have bad weight-strength characteristics.

3.6 FORCE SENSING

I wish I understood better the issues concerning kinesthetic feedback. The advantages of "bilateral" servomotors over "open-loop" control are easily demonstrated, but my own experience is that the quality of the "feeling" one gets in operating a bilateral master-slave manipulator is very low. If the gain is high, the system is unstable, while if the gain is modest it feels mushy. Presumably the inertial forces, when reflected back to the human user, cannot be opposed quickly enough because of our 200 millisecond reaction time problems.

How does the human arm and control system manage so well? We have at least three levels of not-too-tightly coupled systems with sense and motor devices of different characters: motor-force (as in the bilateral servo manipulators), local strain sensing at the joint areas, and tactile sensing at the exterior surfaces. This information is used, then, in a heterarchical control structure.

How does this control structure work? I do not know the literature very well. I suspect that it is not well understood, and the control-theory analyses I have seen (but not studied) do not seem to get to the point. Presumably, the heterarchical system uses several different kinds of information, about position, pressure, speed, etc., in local systems each with its own loops and parameters. The control structure couples them by sending around signals that adjust gains, time-constants, etc. The higher levels computer these by combining state information with goal information.

What's wrong with the simple "bilateral servo" system? (This is the system that measures the forces reflected through the motors that actuate the joints.) One trouble is that the force on an exterior object is the SUM of the driving force and the inertial force of the moving system, as it is decelerated by pushing on the obstacle. The "force-reflecting" servo can never see the latter force. Forces at the hand depend on momentum terms from all the way up the arm. "Theoretically", the control system can contain a dynamic model of the arm, compute the inertial forces, and subtract them from the actual measurments, but this means measuring small differences between large numbers, and there is a lot of noise from friction, dynamical vibrations, and so on. The gravity forces have to be subtracted, too. Notice that in the serial arm this is not an all-or-none argument. The signal-noise ratio just mentioned is poor for the "upper" or "proximal" (near the arm origin) joints and good for the "distal" (near the hand) joints. For a non-redundant mechanism there is no sure way to guarantee that the sensitivity required for a delicate manipulation will be reflected to a suitably distal joint!

This argument shows a fundamental advantage, I think, for having a complete set of force-sensors in the wrist or very close to the workpoint. That is, for a system like that described under "Force Feedback" below for measuring forces near the workpoint without the noise of large inertial components. With a wrist force-sensor, one knows instantly when the hand has made contact, and how hard. If the arm is moving rapidly, one cannot stop it instantly, but if the wrist can be relaxed while the upper arm decelerates, the contact can still be gentle.

What, by the way, is a relaxed wrist? In a non-redundant configuration one can have high compliance -- low-inertial gentle contact -- only along those dimensions whose actuators are close -- in the serial sequence -- to the hand. This is why one should give a high design priority to getting at least three degrees to combine in a recognizable wrist-like structure. Anthropomorphism has a lot going for it. But it is hard to put all mobility at the wrist, and even the human hand is vulnerable to thrust through the radial axis: as in catching a ball on the end of one's finger.

In any case, if a redundant wrist is relaxed, and the force sensors signal a collision, there may still be time to react before the pressure gets large; with a non-redundant bilateral servo, the poor signal-noise ratio requires us to wait until the force is larger.

If we cannot afford full motorization of the wrist, it would still be valuable to have a spring-loaded, lockable, compliant joint there.

The same arguments, in micro-form, apply to fingers as well, and dictate a third stage of sensing. This again might be a combination of joint-force elements and, of course, the ultimate dispersion of nerve-endings on the tactile surfaces.

Force feedback for position-sensing.

Speaking of tactile sensors, it is an amazing mathematical fact that, under certain conditions, one can use joint force-sensing (or even bilateral servos) to get the effect of tactile sensors over a surface. That is, the measurements can tell where a surface has been touched! The "certain conditions" are simple and somewhat restrictive; the surface must be touched at just one point. This is not so bad, because this usually happens at a "first contact". If the condition is not met, one still gets important information that can be useful when combined heterarchically with other knowledge.

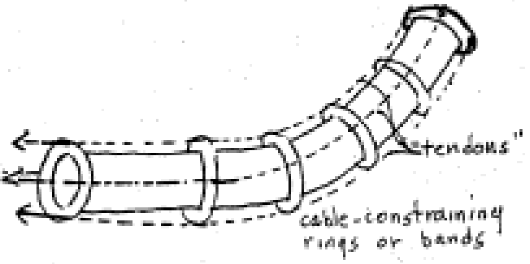
3.7 THE FOURIER WRIST PRINCIPLE

A wrist needs mobility, strength, and a protected instrumentation channel for its hand. To give the hand access to the work from different directions, a wrist should be slender -- the arm should subtend a small space angle as seen from the hand. Because the wrist is near the hand, large angular errors mean relatively small absolute errors, so absolute accuracy of angular control is not very critical. For the systems we envision, wrist control would be adequate even with increments of several angular degrees.

These requirements suggest the use of a deformable tubular structure. In very small scale systems the requirements of strength and rigidity virtually dictate using "exoskeletal" or tubular structures: central rods are not stiff enough and pin-joints are too weak. The tubular construction is also attractive for instrumentation, because the information channels are insulated by the exoskeleton, and the interior is a nearly constant-length environment.

Discrete (localized) joints cause serious problems both for exo- and endo- skeletal structures. The bending radius is very small at a discrete joint, and to avoid this one has to route tendons and other elements along complicated paths.

An apparent solution to all these problems is to use a continuously flexible tube. This section is about some aspects of such a design. The simplest such wrist, no doubt, is a plastic tube or rod deflected by external tendons constrained to its exterior, as shown here. This has problems and advantages:



STRENGTH: Tubing has the best strength-weight characteristics. However, flexible tubing has to be weaker, and tends to buckle and collapse under load. A compromise is discussed below in 5.1.

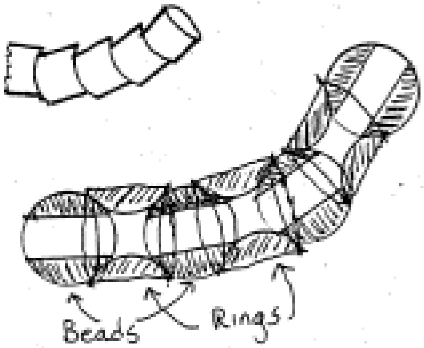
BENDING: Under a pure bending force, the curvature tends to be uniform. Under more complicated loads an elastic beam tends to be wobbly, and bends non-uniformly. We discuss stablilization schemes in 5.2 below.

CONSTRAINT: Tendons tend to span across concave arcs, and have to be constrained. The constraints may cause friction and wear problems.

"Vertebral" Segmented Columns

Many of these problems stem from the fact that to make a beam flexible we must either make the tubing thin, or use a material with small elastic modulus -- in short, make it weak. One kind of solution is to use a strong material and get the flexibility by slipping.

Two ways to do this are shown here: The segmental method solves the problems of longitudinal strength, tubular collapse, and suggests several methods for tendon constraint. The segmental approach makes the column stability problem worse. It offers the possibility of variable stiffness in exchange: one can use friction to lock the system by pulling all the tendons, to get greater rigidity.



Also, one can make the friction very low, to get an extremely compliant wrist, by relaxing the tendons that act counter to the desired direction of motion. This principle is used in several commercial holding and positioning devices.

An idea that has come up from time to time is to mechanize a vertebral column digitally, that is, to make each joint have just two or four states. One might binary-code the angular deflections. This ought to be feasible, for a wrist, since one ought not need more than about 5 bits of control. The purely binary scheme does not seem too good, however, because one would not want any one joint to have to rotate through a large angle.

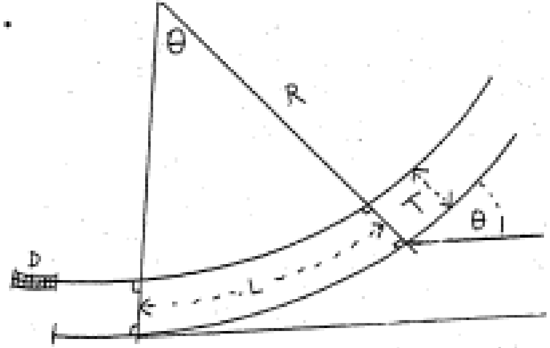
3.8 FLEXIBILITY AND HARMONIC ANALYSIS

If we want to distribute angular deflections over appreciable path lengths, we have a theoretical problem about controlling the excess degrees of freedom. (To count degrees of freedom for a continuous rod, one has to use a signal theory method. If one describes the configuration in terms of spatial frequencies, there is a rapid attenuation of high frequencies.) In any case, we are interested in the case where there are more degrees than we are prepared to control explicitly.

> The curvature in a beam tends to be constant, other things being equal, because the strain energy is a faster than linear function of local curvature. So the energy of the beam has its minimum for a given total curvature when it is uniformly distributed. Unfortunately, this quadratic minimum means that the resistance of the system to perturbations that transfer a small amount of curvature between two different segments is very small. Thus the uniformizing tendency is poorly coupled to the gross spatial configuration.

Now observe an interesting phenomenon that occurs in a flexible wrist with tendons constrained close to the surface of the tube.

> To a very good approximation the net change in direction is independent of the tube's conformation.



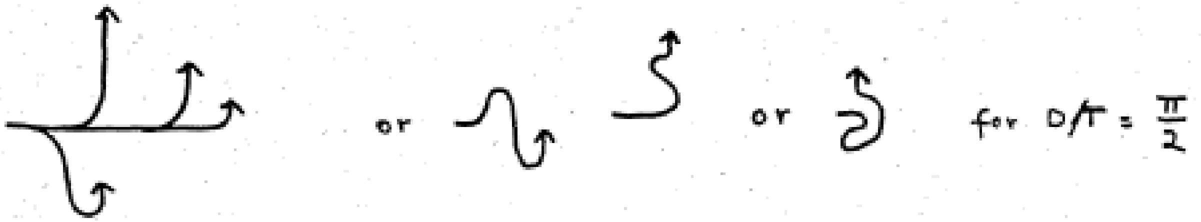
The basic phenomenon stems from the fact that for small angles the x = sin x approximation is very good. Consider a flexible rod with opposed deflection tendons, and shorten the upper one a distance D: (Actually, the tendon on the convex side will be pulled in by about the same amount. In the analysis below, let D be the difference.)

If the rod has thickness T and length L, and one side is D shorter than the other, the rod will bend in a curve for which

$$A(R+T) - AR = AT = D$$

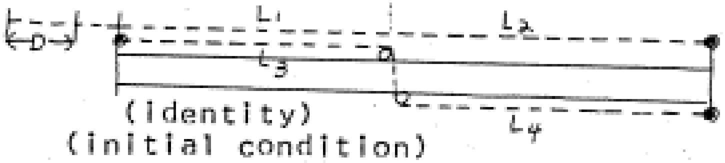
Hence A = D/T, where A is the bending angle in radians. Note that this is independent of L.

Now, we assumed uniform curvature in this argument. But suppose that the rod is actually bent sharply in one part and gently in another. Then A = D1/T + D2/T = D/T again, so that for a given total difference in tendon length one gets the same net angular deflection of the tip independent of how the curvature is actually destributed along the rod! In other words, the same D is compatible with all configurations that begin and end with the same directions, such as in



One might be able to make a nice parallel-ruler device exploiting this principle. Handling such a beam is an experience; it seems completely free for translation but firmly constrained for direction of the tip, which seems to have a mind of its own.

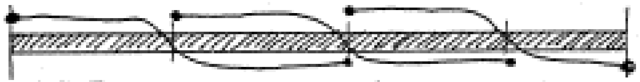
Now to enforce uniform curvature, we must distribute increments of D uniformly (in length) along our beam. Consider a first approximation in which D = D1 + D2, in two equal halves of L; then we want somehow to constrain D1 = D2. Solution: add an extra tendon firmly attached at both ends but crossing through the rod at the middle.



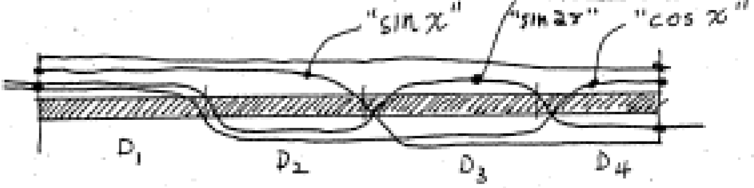
Then one can write:

L1 = L3 (identity)
L3 + L4 = L (initial condition)
L2 + L4 = L (good approximation)

Hence L1 = L2. Thus the extra constraint divides the curvature equally between the two halves. One could add still other constraint-cords, crossing over at other points: the problem is to equalize the deflections in each segment. Two examples of how one might do this for for more segments:



Example 1.



Example 2.

Discussion of Example 1: To the extent that the oblique cords are inextensible, this scheme ought to be quite effective in uniformizing the deflection. It is like the well-known "lazy-tongs" device. It tends to have a cumulative error, in that the curvature can slowly drift from one end to the other if there are many segments. As drawn, there is also a problem about unconstrained parts of the rod near the cross-over points; this should be corrected by running each constraint over three segments, and this also relieves the sharp curves experienced by the stabilizing tendons.

Example 1'.

Note that each wire needs a symmetrically opposite one for negative curvature control.

Discussion of Example 2: We have shown several constraint cords with suggestive labelling. Each cord runs the full length of the rod, so that the effects are global (no accumulated error). Let Di and -Di be the length changes at the top and bottom of the i-th segment. Then we have:

sin A: $D1 + D2 - D3 - D4 = 0$
cos A: $D1 - D2 - D3 + D4 = 0$
sin 2A: $D1 - D2 + D3 - D4 = 0$

The first two equations yield $D1 - D3 = 0$
The last two equations yield $D1 - D2 = 0$
The first and last yield $D1 - D4 = 0$

So all four segments have equal change: the total change D is controlled by the top straight fibre.

Our choice of trigonometric labels was based on a strong analogy. We can use the "constraint" cables for control as well! If we shorten the "sin X" cable by an amount D* the equations still yield D1 = D2 and D3 = D4, and (assuming the straight fibre is unchanged) the rod assumes a sigmoid for still with the original tip- direction:

If we let C(x) be the curvature of the rod as a function of length, we now have

$$C(x) = D* \sin \left(\frac{2\pi x}{L}\right)$$

Controlling the other fibres similarly, we can develop the curvature of the rod in a Fourier series:

$$C(x) = \sum_{j} D_{\sin jx} \sin \frac{2\pi j x}{L} + \sum_{j} D_{\cos jx} \cos \frac{2\pi j x}{L}$$

It would be impractical to do this for more than eight segments, and four would be quite enough for most purposes.

Three Dimensions

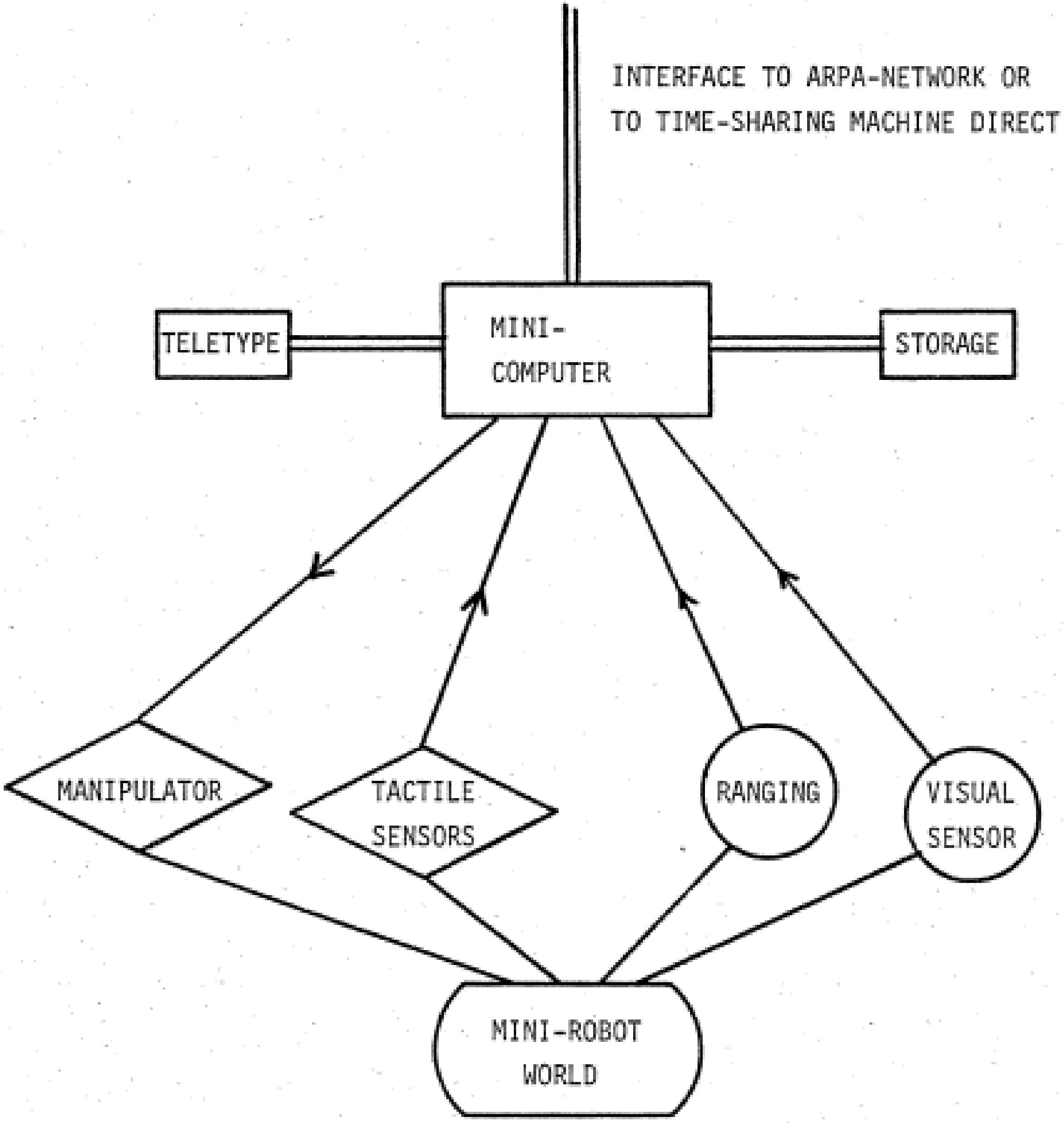
Extending this idea to controlling a space-curve promises to eliminate two nuisances. First, by winding the tendons around the beam instead of through it, we avoid penetrating the central core. (2) This same scheme can eliminate the occurence of "dead" intervals at which the tendons are near the axis and so provide little constraining force (poor mechanical advantage). Our scheme is to use Helical winding instead of Sinusoidal.

Using helical winding, one avoids the problem of tendons escaping from concave portions of the beam. It appears that a large number of fibres are required.

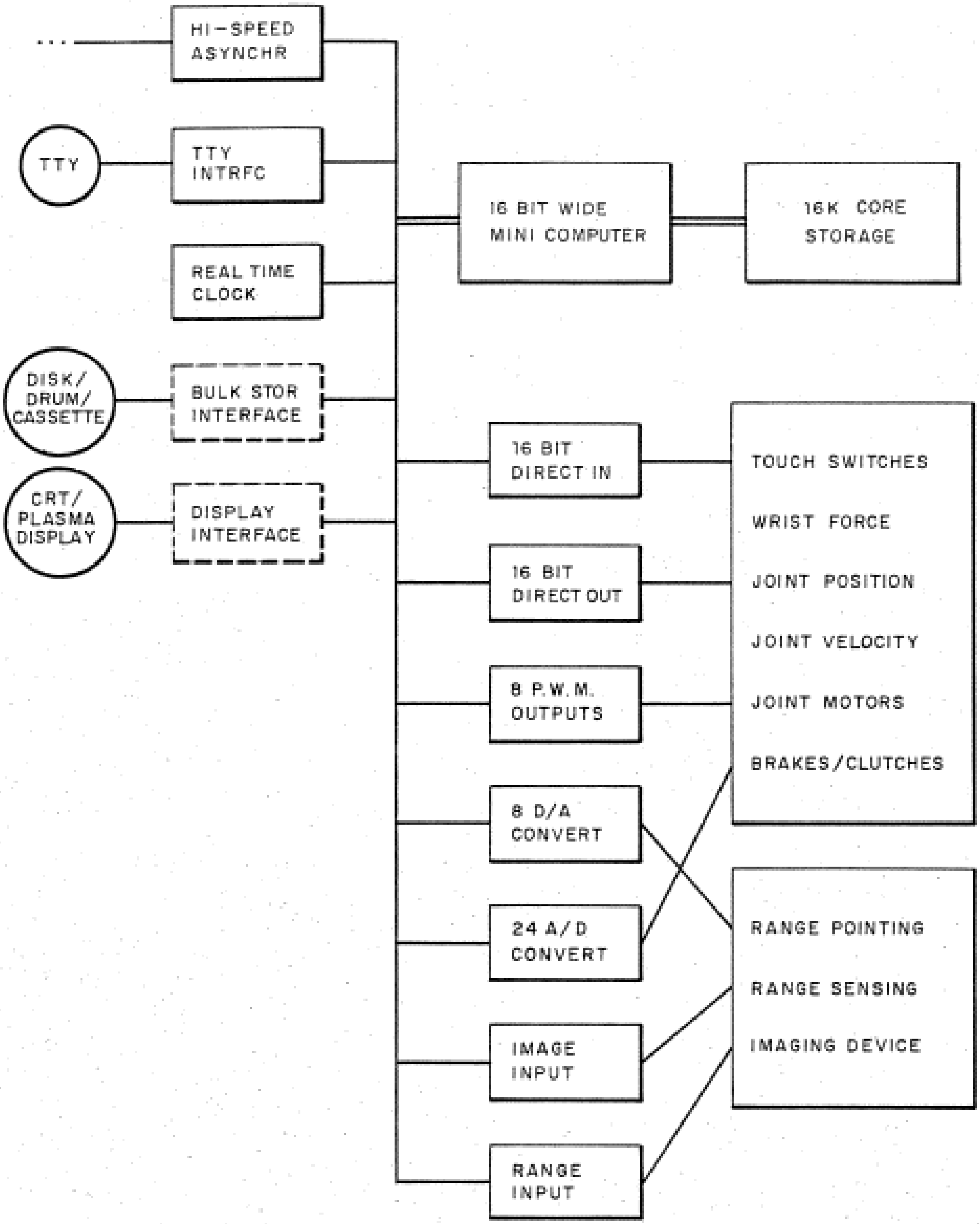
> The four pairs of the 2-d case must each be duplicated in two planes. Our idea is to make two sets of windings, 90 degrees out of phase, in both directions around the cylindrical rod. Each must be duplicated again, in the opposite direction, to oppose the effects of axial torque. That makes 16 pairs of fibres. Since we really do have 8 degrees of freedom, the system certainly needs 8 tendon pairs. Possibly, half the windings could be eliminated if the tube has enough inherent axial stiffness, but this is not easily compatible with longitudinal flexibility. One way to get the required kind of stiffness is to have hinge joints in alternating orientation, as in the lobster arm.

These issues are not so serious. Even a two "segment" arm, in three dimensions, would already be a splendidly mobile device, and its helical geometry problem does not look very difficult. Going to four "segments" may raise more serious problems about friction and tendon-crossovers. Higher terms in the series gets us involved with long cables (the "high frequency" sinusoids wrap around the rod a lot) and would probably cause severe frictional binding problems because the forces normal to the tube would become large. These forces don't look serious for the two and four segment designs.

3.8 MINI-ROBOT BLOCK-DIAGRAM



MINI-ROBOT SYSTEM



Massachusetts Institute of Technology
Artificial Intelligence Laboratory

Proposal to the
Advanced Research Projects Agency
for
MICRO-AUTOMATION DEVELOPMENT

1 April 1973, through 31 March 1974

January 1973

MICRO-AUTOMATION PROPOSAL

to the

Advanced Research Projects Agency

for

Continued Micro-Automation Development

Funded by ARPA Order #2094

Administered by the Office of Naval Research on Contract # N00014-70-A-0362-0005

at the

Massachusetts Institute of Technology

Artificial Intelligence Laboratory

Proposed Support Period: 1 April 1973 through 31 March 1974

Proposed Annual Budget: $200,000

Approvals:

Principal Investigator

Professor Marvin Minsky ______________________________

Administrative Director,

M.I.T.'s Division of

Sponsored Research

George H. Dummer ______________________________

4.1 BUDGET

ARTIFICIAL INTELLIGENCE LABORATORY
MICRO-AUTOMATION DEVELOPMENT
1 April 1973, through 31 March 1974
ONR Contract # N00014-70-A-0362-0005
ARPA Order # 2094, Renewal

Salaries and Wages (see personnel, section 4.2):

	dollars		(man months)	
Faculty:	25,500		(14.5)	
Minsky 25% effort				
Winston 50% effort				
Horn 75% effort				
Research Associates	5,500		(5)	
Research Staff	37,000		(34)	
Administrative Staff	5,500		(5)	
Technical Support Staff	6,500		(5)	
Secretarial & Clerical	8,000		(12)	
TOTAL Subject to E.B.	------	88,000		
Employee Benefits @ 17.1%.....		15,000		
Research Assistants		23,000	(36)	
TOTAL Subject to OH.	111,000			
Overhead @ 25.5%..............		28,500		
TOTAL		-------------		154,500

Space Rental (see space breakdown, section 4.3):	
Labs and Offices in 545 Tech. Sq.	18,500
Lab and Office Modification and Renovation	1,000
Publications & Postage	3,000
Office Supplies	1,500
Travel	5,000
Telephones, Dataphones & Data Lines	500
Materials & Services (see section 4.4)	15,000
Equipment (see section 4.5):	
typewriter & engineering calculator	1,000
TOTAL BUDGET	$200,000

4.2 PERSONNEL

Professor Patrick Winston and Research Associate Dr. B. K. P. Horn will direct this program under Professor Marvin Minsky's continued supervision. Professor Winston also directs the A.I. Lab's main vision research effort which is administered under ONR N00014-70-A-0362-0003, and supported on ARPA order 1984. Professor Winston's vision research programs will provide high level vision processing to ARPANET users of completed Mini Robots.

Dr. Horn is expected to become a member of MIT's Electrical Engineering faculty in September 1973 and has been included in this budget as first a Research Associate at 100%, then as an Assistant Professor at 75%. Professor Winston is budgeted here for 50% during his nine month academic year and 75% for a two month summer. Professor Minsky is included at 25% for the academic year and 50% for the summer.

The research staff consists of Mr. Lerman and Mr. Finin, programmers, and one electronics engineer to be hired. Administration includes purchasing, payroll and support staff management all under R. Noftsker, A.I. Lab manager, for a total of 5 man months. Eight Research Assistants now working on basic vision research are shared in this budget with the main Artificial Intelligence research contract.

4.3 MICRO-AUTOMATION SPACE

the MICRO-AUTOMATION development program now occupies 950 sq. ft. of MIT, A.I. Lab eight floor office space. It is planned to relocate these six offices to the third floor when computer space becomes available on 3/1/73. This coincides with the arrival of the first MICRO-AUTOMATION computer equipment.

The MICRO-AUTOMATION program space plan during this proposal period is to lease 1,500 sq. ft. of third floor, 545 Tech. Sq., office and 1,000 sq. ft. of airconditioned false floor space for development work. The annual space cost will be $18,500, or $18,500 during this contract period. Renovations, budgeted at $1,000, are for minor modifications to airconditioning, power wiring and lighting which could be performed under the lease at a 50% premium by the same construction contractors which the A.I.Lab will use.

4.4 MATERIALS AND SERVICES

The previous year's experience indicates that approximately $15,000 will be required for drafting, illustrating, minor computer and interface parts, replacement parts, computer and shop consumables, handling charges and other unforseen items.

4.5 EQUIPMENT

A scientific calculator has been budgeted for engineering work and a $500 typewriter item is included for a new secretary position in the new office/lab area. Other capitol equipment purchases were funded last contract year but deferred for temporary lack of space and personnel. The originally proposed PDP11 computer system has been ordered and MICRO-AUTOMATION electronic interfaces are now being designed, specified and ordered.

Victor Scheinman of Stanford University's Artificial Intelligence Project visited the MIT, A.I.Lab for 3 1/2 months during the fall of 1972, and designed a small manipulator (section 1.1) which will be constructed and paid for with first year funds.