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DESIGN OUTLINE FOR MINI-ARMS BASED ON MANIPULATOR TECHNOLOGY

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The design of small manipulators is an art requiring proficiency in diverse disciplines. This paper documents some of the general ideas illustrated by a particular design for an arm roughly one quarter human size. The material is divided into the following sections:

A. General design constraints.
B. Features of existing manipulator technology.
C. Scaling relationships for major arm components.
D. Design of a particular small manipulator.
E. Comments on future possibilities.

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1. INTRODUCTION

The literature on mechanical arms is in a slightly unsatisfactory state as the total number of papers existing is somewhat smaller than the number of model arms that have been attempted. Most of these papers deal with arm types requiring predominantly direct manual control input, a type we will call manipulators. Arms controlled primarily by stored programs will be called robot arms. Robot arm design problems seem to be even less well documented in the literature than manipulator arm design.

While many of the papers on manipulators and robot arms are parochial in approach, the literature in adjacent fields like prosthetics, orthotics, and materials handling is even less helpful as they rarely address themselves to the more crucial problem confronting the manipulator or robot arm fields. Some overview publications of terse descriptive nature[1,2] exist but anything resembling a viable and systematic theoretical treatment of this family of topics seems to be completely absent.

Yet these topics have one common but as yet undefined goal, which is the creation of machine dexterity comparable to the dexterity exhibited by the human arm when aided by all its other motor, sensor, imaging, processing and control subsystems normally available. While orthotics people seem constrained to restore this dexterous capability, prosthetics to create spare parts for it, and manipulator people to remote it, it is the field of AI robots that attempts to recreate essentially all the systems involved. In this last endeavor one is seemingly free to choose whether one would like to mimic the prototype human system or seek entirely different configurations to accomplish the goal.

It is not clear that AI robot people have had time to address themselves to the selection from above approaches as far as their robot arms are concerned.

One is struck with the fact that among the various types of manipulators one can distinguish a difference of at least two and possibly three orders of magnitude in dexterous capabilities.[3] If we further recognize that even the best manipulators available today are nearly an order of magnitude less dexterous than the average human working directly, one can see that the dexterous capabilities one could expect any manipulator or robot system to achieve could easily vary over four orders of magnitude depending on the approach used.

Yet it has not been established how much the dexterous capability of a robot arm might be influenced by the arm design alone. After all in studying dexterous capabilities of manipulators, large differences in dexterity can be identified with improvement in man-machine integration used for controlling the manipulator. Man-machine integration, of course, addresses itself to the degree that the control input of a device has been adapted to the preprogrammed biochemical and biosensor interfaces available, while minimizing reprogramming (learning) processes. While such an approach might yield valuable clues possibly aiding one in programming AI robots, adaptation to an existing very complex system preprogrammed with limited interface accessability has not been the prime problem of AI robot activity.

On the other hand very nearly all existing robot systems, both of the AI and industrial variety, resemble in the design approach of their arms, the family of manipulators which is lowest on the scale of dexterous hierarchy. This in itself is understandable as the early programming problems encountered in AI robotry were not involved with dexterity per se. Employment of robot arms of limited capability which were relatively simple to conceive, design and build was more or less satisfactory and did not appear to hamper progress unduly. However, as we address ourselves to problems of flexible automation and other applied problems of medical, industrial or social significance, the dexterous capability of systems used becomes quite significant. With the more demanding tasks one is going to attempt, none of the major subsystems constituting an AI robot system can possibly be anything less than of peak state of the art capability, as none of the subsystems will be allowed excess capability to compensate shortcoming of others.

It therefore seems sensible to examine what contributions manipulator technology can make to the improvement of robot arms. The contribution we might look for might be based on the existence of:

I. Considerable familiarity with the requirements of mechanized dexterous work.

II. An array of ready mechanism which might be suitable in the solution of problems encountered.

III. Considerable experience in integrating the mechanical end of the arm with complex control system.

IV. Known strategies of manipulator usage which might suggest possible clues to new programming schemes.

The attempt to utilize this technology will be carried out as follows:

A. As much as possible the design constraints and objectives existing for a mini-robot or micro-robot are defined.

B. The major features of existing manipulator technology are examined. Included in this is the evaluation of historical accidents insofar as they distort true evaluation of existing hardware capability.

C. Scaling relationships for major arm components are examined.

D. The relations of (C) are applied to the features of (B) and are examined for suitability of satisfying constraints and objectives of (A).

E. This procedure plus the application of experience and intuition should crystallize an attractive design approach if such exists. This design will be outlined and examined.

F. Any other ideas suggested by this procedure will be discussed briefly, leading possibly to a suggested outline for future developmental activity.

During the study, copious use is made of a rather large spectrum of manipulator design aids developed by the authors during years of activity in the field. In such cases only results are shown. The calculations leading to these results would require documentation far in excess of the scope of this study.

2. DESIGN CONSTRAINTS

Before one starts examinations of the various technologies that might be applicable to mini-robots it seems very useful to summarize in as general terms as possible, the design constraints known at this time. Not only can this serve as a suitable study framework, but hopefully will also stimulate feedback and discussion which will help crystallize the requirements of mini-robots. Some of the constraints mentioned here are more of an intuitive input as to what the general shape of the device should be. Such input will be so identified and only retained if it turns out to be useful.

2.1 Size

The mini-robot project has a multiplicity of goals.[4] The first of these is the creation of a desk-top AI robot arm system whose primary aim is to allow AI experimental work to go on in a medium size office and thereby allow a large number of universities to acquire the basic equipment. This requirement alone can probably be satisfied by a fairly broad optimization. An arm scaled by 2/3 might be small enough nor will a ½-sized arm be too small.* Since one wants to also start doing a variety of micro-operations of medical, biological, mechanical, and electrical nature we have in reality two different arms, a mini-robot arm scaled down by less than a factor of 10 (or our scalling factor L = 1/10) and a micro-arm scaled down further.

For this study an attempt will be made to find a compromise scale useful in both mini- and micro-region, provided this can be done without compromising effectiveness for either scale.

2.2 Aspect Ratios

At least two aspect ratios must be distinguished. The first is the arm aspect ratio and relates to the arm length versus diameter ratio. This would be of interest if the resulting mini-robot arm resembled in over-all look existing larger manipulator or robot arms. Aside from intuitive esthetic arguments the aspect ratio of that portion of the arm near the terminal devide (T.D.) must be kept within reasonable bounds in order to reduce obscuration of vision for the imaging system in use. Also access to recessed volumes becomes restricted if the arm aspect ratio is allowed to become too small.

The second aspect ratio relates to the ratio of the cube root. of the accessible working volume to manipulator or robot arm length. The traditional motivation in making this ratio large stems from nuclear hot cell practice, where is is desirable to have remote access to volumes kept small by shielding cost considerations. Except in special cases, like surgical manipulators, no motivation seems to exist to demand extreme volume aspect ratio for mini-robots.

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*See section 4.1 for definition of unity-sized arm.

2.3 Position Accuracy

In a robot arm, accuracy refers to the tolerance with which the arm may be placed in six D.O.F. using position transducers information only. Present programming practices, particularly in industrial robotry, use position information only for the placement of objects by the robot arm. In industrial robotry, better placement accuracy than that is achieved by use of appropriate fixturing, a fact that contributes to the slow adoption of robots in industry. The use of absolute position programming still seems to be a matter of convenience in AI robot practice. However, in an effective hand-eye-force sensing system it seems reasonable to try to follow a position programming scheme analogous to the human scheme.

Critical examination of the human arm anatomy fails to detect anything which could possibly be analogous to a position transducer. Postition accuracy seems to be achieved solely by successive approximations in the arm-eye-force sensing systems. Complete adoption of such programming schemes would eventually require only the most rudimentary accuracy capabilities. But, since the present mini-arm design must be considered to be a transitional arm which will be required to accept absolute position programming, reasonable accuracy should be provided. Also if multidegree of freedom force transducers are used, transformations from transducer coordinates to actuator coordinates are required. The accuracy of these transformations depends on the on the precision of position information available. Investigation of the exact dependency is beyond the scope of this study.

A reasonable accuracy number to strive for seems to be 1/1000 of the largest available arm excursion, taking into account all the effects influencing final positional accuracy.

2.4 Positional Resolution and Repeatability

In order to take advantage of more advanced programming techniques a position resolution at least 10 times better than the absolute accuracy should be provided.

In setting the accuracy limitation, capabilities of transducers with reasonable cost limitation have been tacitly introduced. Peculiarities of some of these allow one to obtain extremely high resolution with ease. The resolutional limits are then given by the resolution of the ADC used.

We also must be aware that actuator smoothness must allow position changes within resolution limits.

Repeatability will automatically be better than absolute accuracy as it is not limited by linearity effects. But various thermal effects usually limit repeatability to less than resolution limits.

Repeatability of course becomes the accuracy obtainable if one is willing to store a linearity correction map for each D.O.F. It is hard to give a general number for this, but 3 to 5 times better than accuracy seems to be feasible.

2.5 Force Accuracy and Resolution

Force information has quite a different character than position information. In principle, position may be referred to any convenient origin of the coordinate system and required accuracy is independent of the position with respect to the chosen origin. Yet in force measurements we must recognize the existence of an absolute zero state and required accuracy is significantly related to the magnitude of the non-zero force that is measured. Of particular significance is the resolution with which the zero point can be established. The latter is usually limited by hysteresis and thermal drift effects. It is unfortunate that established rules of "specmanships" allow force transducer manufacturers to lump hysteresis and thermal drift effects together with linearity and quote these as percentage of full scale. It is not easy to establish sufficient requirements as they are intimately connected to programming techniques that will be employed. We, therefore, suggest the following specifications which seem achievable:

Zero crossing errors of all kinds 0.2% F.S.

Linearity in region $(1.0\% \text{ F.S.}) < \text{reading} < (100\% \text{ F.S.})$

3% of reading.

Furthermore, in choosing placement and design it might be wise to allow for retrofitting with better transducers.

2.6 Compliance

Deflection under full load should ideally be limited to the amount allowed for accuracy. To make this statement meaningful one must define how this is to be measured. For instance, if we are concerned about the difference in position as indicated by transducer readings and real T.D. position we can get these to agree within the limits of accuracy by just making the arm structure shift enough and placing the position transducer close to the T.D. In this way one can remove actuator and motion transmission stiffness from the specifications. While this probably constrains structural stiffness sufficiently to allow working within desired accuracy limits, it is not a practical approach for small arms, primarily because of position transducer sizes.

The stiffness due to motion transmission links, which may or may not be different from structural members, and that due to transmission link deflection must also be sufficient to place natural frequencies outside the response regions of the arm. This is a requirement for which each proposed design must be examined.

3. MANIPULATOR TECHNOLOGY

To get an effective overview of the possible contributions of manipulator technology a quick summary of the present state of the art is presented. The various types of manipulators are arranged by their respective control modes.

3.1 Open Loop Manipulators

Among existing power manipulators these are the most common. They consist of actuator packages arranged in a variety of geometries to yield four, five, six and sometimes even seven D.O.F. Control consists of setting actuator velocity by means of an array of small levers sometimes arranged into elaborate hand controllers. Actuators are placed in proximity of the driven joint and are predominantly electrical in nature. Hydraulic actuators, which are suitable for this application, are shunned by the nuclear users, which are presently still the largest group. This attitude is due to historical reasons, as early hydraulic devices developed leaks while working in a hot cell thereby effectively spreading alpha contamination. However, underwater manipulators are preferably hydraulic. The degrees of freedom (D.O.F.) are usually arranged in an articulated design with only rare cases of linear motions. The proximate placement of actuators without counterbalancing results in a severe cascading of torque requirements for the elbow and shoulder D.O.F. which, of course, is coupled with a loss of torque resolution applicable to the load. This is not a big loss as the operator has practically no knowledge of the magnitude of applied torque. Experienced operators use visually observed deflection under load as an indicator of forces applied. This is the reason that most of these devices have more mechanical compliance than would otherwise be necessary.

By and large, the control scheme does not allow parallel actuation of more than one D.O.F. Since control input effects are only fed back by visual observation on the part of the operator the class of devices is termed open loop manipulator. But as lack of feedback restricts operational speeds severely, the unsuitable dynamic arrangement of this class of device is not unduly restrictive.

In operation, open loop manipulators are over 100 times slower than more advanced types[3] and are also capable of only relatively simple operations.

3.2 Unilateral Manipulators

Unilateral manipulators usually differ from open loop ones only in that there is a control input device (CID) which is often of exoskeletal configuration. The manipulator itself differs really little from an open loop one, except that the exoskeletal "CID" results in anthropomorphic arrangement. However, parallel actuation of several D.O.F. as well as a sufficient control to allow larger terminal velocities bring out dynamic problems at the manipulator. As far as man-machine integration is concerned, the so-called resolved motion rate control system achieves nearly the same dexterity using a smaller CID, but much more complex control systems.

Unilaterals have usually less capacity than open loop devices as some attempt is made to reduce arm masses so as to minimize dynamic effects of arm interia, brought about by somewhat better velocity capability.

3.3 Bilateral Force Reflecting (BFR) Manipulators

The BFR principle was discovered by the Argonne National Laboratory Remote Control group while developing mechanical manipulators working through hot cell walls. The term bilateral is used here in the sense it is used in network synthesis and refers to a two-way flow of energy.

These manipulators are without argument the most dexterous devices existing. Several thousand mechanically connected manipulators of this type exist. These are interesting but one must recognize that they are constrained to work through the wall of the hot cell, and therefore not truly remote. Nevertheless important conclusions can be drawn from their construction and behavior.

The BFR manipulator is capable of parallel actuation of motions as is the unilateral, yet capable of nearly an order of magnitude better operating speed and dexterity than the unilateral type. This improvement can in no way be explained by the added ability of touch control as is often represented. The ability to pick up a raw egg without breaking it is important, but really trivial. The real importance of bilateral force reflection lies in two other categories:

1. Even for motion in unobstructed space, bilateral force reflection gives the operator desired dynamic feedback. Lack of this feedback deteriorates operation enormously. This is an effect similar to the one which makes one slow down when starting to walk on ice.
2. The ability to be guided by work geometry. Examples might be: opening of a door or turning of a crank. In each of these, the desired work path is very constrained by the geometry. The bilateral force reflection feature makes following the constraint easy.

So few powered BFR manipulators exist to date that they can be enumerated:

I. The Argonne National Laboratory E2, E3, E4,[5,6] group (and Italian mascots which started as copies of E3).[7] These are firmly based on 1950 technology and have not freed themselves from the wall constraint (even though the wall has gone). E1 was a quick (not successful) and expedient exercise of cutting the cables of a mechanical manipulator and placing actuators at the ends. In the course of improvement E2 through E4 one forgot to get rid of the wall. Use is made of actuators mounted in the shoulder, tendon transmission of motions, and complete counterbalancing by mass addition. A pair of commercially built mascot III exist at CERN (Switzerland) and a pair of commercially built E4's (CRL model M) at National Accelerator Laboratory in Illinois. The latter are not operational for fortuitous reasons. None of these reach the potential of the tendon technology mainly because the obsolute servotechnology base cannot easily be updated.

II. General Electric Handyman.[8] Use is made of hydraulic actuators distributed in limbs, analogue computed counterbalancing and inertia compensation via actuators and analogue computation. Somewhat ambitious for its technological base (mid-1950) and very expensive. Also post-analysis reveals some system approach errors which made this not a lasting success.

III. Brookhaven Arm[9,10] (conceived and developed by the author of this study). Started out as an exploratory exercise by a new group dealing with particle accelerator applications. It differs from other designs in many respects. It is much smaller than other arms of this kind. (This was a prime objective.) Most actuators are mounted in proximity of motions, yet are kept sufficiently light to allow full counterbalancing by use of added mass. It is also the only manipulator which makes use of explicit force transducers. It is, in general, based on mid-1960 technology and has much improved compliance.

It is now felt that proximate mounting of actuators is not the most promising approach, as performance is somewhat inertia-limited. The only reason the Brookhaven arm performance looks good compared to the Argonne E series is because of the shortcomings of the E series.

IV. New Developments. In the last year or so work got underway to bring BFR technology closer to its potential. The manipulators in question are the French MA-22[11] using actuators and electronics by "TOS" as well as TeleOperator Systems' own "SM" series starting with SM-2090. These devices are small, (sized approximately like the Brookhaven arm), make use of tendon technology coupled with an actuator servo drive system of improved compliance. While the number of innovations used in either arm is purposely limited by the need to minimize development cost and risk, several crucial ones appear. In particular, an integrated counterbalance-tendon compensation system which makes use of existing actuator mass for counterbalancing might be of interest. This system will be elaborated on later.

It should be pointed out that one should not judge the potential of BFR manipulators by the few examples that can be examined. Early technological limitations and severe lack of funding at the later stages has prevented these devices from reaching their potential. For instance, the prevalent servo scheme, often referred to as the position-position system, which uses device compliance as a force sensing system, is used in all but the Brookhaven manipulator. The shortcomings of this scheme are all too obvious as force sensing sensitivity must, even with the greatest care, be severely limited. Since all but one of the existing devices use this scheme, it is sometimes assumed the bilateralism is synonymous with position-position servo scheme. In fact, the latter is only one of a large number of ways to achieve this end.

The force-position system used in the Brookhaven manipulator is much superior, but also more difficult and expensive. In addition to this, progress has been hampered by the unfortunate publication of a doctoral dissertation dealing exclusively with bilateral servo-systems.[12] This dissertation asserts that a force-position bilateral servo-system cannot be stabilized.

Even the new MA-22 and SM-2090 manipulators use only a position-position system though a much improved one. The reasons for this are primarily financial. But at least with SM-2090 provisions have been made to allow updating of the arm when funding allows.

With BFR manipulators one wants to provide a certain amount of dynamic (inertial) feedback to the operator even when moving without external load. This prevents placing the force transducers at the wrist ends. In a robot arm this constraint does not exist as all the dynamic information necessary can be extracted from position information.

3.4 Summary of Manipulator Technology

From the robot builder's point of view manipulator technology covers two extremes. At the one end, we have configurations similar to unilateral manipulators. These can only be used for robot arms as long as one can afford to ignore motion dynamics and torque resolution of the upper joints. That is, as long as one requires no more than a programmable transfer device with little force modulation and no force sensing, robot arms based on this technology may be sufficient. Virtually all "industrial robots" are in this category. In some cases, the latter achieve partial counterbalancing by clever placing of actuators. The advantage of employing this approach is that simple concepts and engineering suffice to achieve a programmable transfer machine. The main disadvantages are: inefficient energy utilization which lead to power density problems in non-hydraulic devices and a choice between either slow speeds or jerky motions. If one likes to introduce force sensing in all D.O.F., and properly utilize this capability, proximate actuator placing results in the following difficulties:

I. Force sensing implies a desire to exercise force modulation. In some motions the ability to achieve this might be reduced by nearly an order of magnitude if one uses unbalanced, joint proximate actuator placement. This is best explained by the use of an example: Let us examine a unity scaled articulated robot arm with joint proximate actuators and low compliance. Likely such an arm requires a pitch* motion at the shoulder. The actuator for this motion might have to use 80% to 90% of its torque capability to counterbalance the actuators placed in the extremity joints as well as the beefed-up structure required to keep deflections due to these weights low. What is more, the counterbalance torque required is a function of arm position. The torque span available for work might be only 10% of the dynamic torque range of the motor. Furthermore, this small span might lie anywhere within the total dynamic range of the motor. If we like to modulate the applied force over a modest dynamic force range of only 50:1, we require a motor modulation resolution of 0.2% which puts severe requirements on motor linearity, uniformity of friction torque as well as the accuracy with which counterbalance torques are calculated. It also requires that one burden the computer with these calculations.

II. Unilateral manipulator technology yields inherently high inertia designs. This is partially due to the actuator masses in the arm extremity and the large inertias of the oversized motors in the shoulders. As there is also no attempt made to keep reflected inertias of actuators low or actuator linkages highly reversible, one will find as a result that adapting robot arm motion to work constraints is rather difficult. To return to the example cited when discussing BFR manipulators: suppose our program includes the tasks of turning a crank. With a low inertia bilateral arm we can compute a first order force vector from visual data, start to turn the crank slowly and increase the speed as force and position data are derived from corrections. In a way, such robot arm, properly programmed, can be likened to a very simple learning system. In the absence of a low inertia bilateral system a quite accurate knowledge of both origin and radius of the crank are necessary in order to map an accurate turning circle for any motion at all. Similar arguments apply to obstacle mapping by force sensing. The latter requires very short stopping distances as well as a bilateralism.

Indeed, manipulating has been compared to a series of controlled collisions with the degree of control being a measure of dexterity. Some new programming approaches might be needed to make robot arms work by a succession of highly controlled collisions rather than by a succession of accurately controlled positions.

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*See AIR-5001 for definition of pitch motion.

III. Finally a low inertia arm can be made to work rapidly and smoothly with much greater ease. The work utility of this is really identical to point II. The psychological value, however, should not be underestimated. From experience of testing and demonstrating manipulators this is known to be important not only for impressing visiting VIP's but also for the people working with the devices.

We have examined briefly some of the ingredients of manipulator technology and its possible utility to the building of robot arms of any size. In order to assess the usefulness of this technology to mini- or micro-robot arms, a look at applicable component scaling might be useful.

4. SCALING RULES

4.1 Scaling Requirements

It is interesting to see what happens when one scales down the linear dimensions of typical manipulator components by a scaling factor L, such that $L \prec 1$ for components smaller than those of a man-sized manipulator. Unfortunately, agreement of what constitutes a man-sized manipulator is not unaminous. Based somewhat on the capability of 90 percentile man one may use the following numbers:

upper arm length: (A_u)	A_u = 12"
lower arm length: (A_1)	A_1 = 10.5"
distance from center of palm to wrist: (A_w)	A_w = 3.5"
lifting capability hand outstretched: (K_1)	K_1 = 30 lbs.
Best fit cube for comfortable working volume: (S_v)	S_v = 18" on side

If one linearly scales dimension such as A_1 or S_v, the objects to be handled must also be similarly scaled. But that would mean that K_1 should scale as L^3 if one considers the weight or mass of objects to be handled.

It is somewhat harder to find a suitable argument to what scale velocities and accelerations must be set. One could argue that velocities should scale such that kinetic energies scale the same as potential energies which would be $\propto mh$ or scaled as L^4. This would yield velocity scaling as $L^{\frac{1}{2}}$ or a slow decrease of linear velocity with reduced scale. Intuitively this feels right and maybe ultimately we may go to such speeds. If we scale from the no-load velocities of 3 ft/sec, used in ordinary BFR manipulators, a ¼-size arm ($L = \frac{1}{4}$) would require 1.5 ft/sec velocity and would traverse scaled distances in ½ the time of full-scale devices. This still seems all right except that we would frequently need aids (high speed movies) to find out what the arm is doing. One also might get into real-time computer problems so that the arm might sit and wait for instructions much of the time and then do things too fast to observe directly.

A better approach at this stage might be to require that scale independent observation of the scene look natural. This requires that angular velocities be scale-independent and linear velocities scale like as L. Since it might be hard to slow an arm down sufficiently, either velocity scaling approach could probably be tried with the same arm design.

Scaling linear velocities like "L" implies that we are dealing with a time invariant scaling exercise. This approach would require linear acceleration also to scale like L.

Scaling handling capacity as L^3 would imply that the robot's only work consists of moving masses about. While considerable portion of general activity involves this, we can think of some activities requiring different force scaling. Whenever reasonable close fitting objects must be assembled one must overcome friction. Friction alone would scale like L, but the coefficient of friction is dependent on surface finish which should improve with smaller objects. Assuming the coefficient of friction to scale as L one gets total scaling of L^2 for this mode of operation. L^2 scaling of forces also results from operational modes involving application of pressure. However, full force capability in unity scale arms is rarely used for this type of operation.

Pushing objects around a surface involves L^4 scaling for both the frictional component and the accelerating components of force.

Operations involving impact (like driving a nail with a hammer) also has to be examined for scaling. To drive a nail a scaled distance requires energy to be scaled as L^4. To obtain that much kinetic energy in a hammer we either have to scale velocity like $L^{\frac{1}{2}}$ so that $\frac{1}{2}mv2 \propto L^3 \times (L^{\frac{1}{2}})^2 = L^4$, or we must scale arm force capability as L^2. Intuitively scaling arm capacity as L^2 will lead to severe design difficulties for even modest scaling factors. (This will be verified below.) But since one is likely to have excess velocity one can allow larger velocities than those obtained by scaling linear velocity like "L" when impact operations demand it. This approach will probably work for scale factors $L \geq 1/5$.

It is possibly best to scale arm capacity as L^3. This kind of approach is unlikely to get one into severe difficulty for $L \geq 1/5$. Before smaller scales are attempted one hopes to have further experience in this regard.

Scaling forces as L^3 implies of course that torques scale as L^4. Linear deflection should scale as "L".

When one compares the scaling characteristics of the various arm components to the scaling requirements we must distinguish between two types of characteristics. The first kind are desirable characteristics which one would like to maximize. Examples for these are motor torque, motor power, or mechanism strength. For these we require in the case of $L < 1$ that $P_c \leq P_r$, where P is the exponent of the scaling parameter and subscript c stands for component, and subscript r for requirements.

On the other hand undesirable characteristics which one wants to minimize one should have $P_c \geq P_r$. Components having scaling characteristics outside these limits will sooner or later lead to design difficulties but might retain their usefulness for modest scaling factors.

4.2 Scaling of Structures

The strength of structures in tension or compression is a maximizable parameter. The stress, however, is to be minimized and scales favorably as the cross-sectional area, or L^2. Consequently, stresses which should be scale invariant, go down like "L". The deflection of such structure, a parameter that should be minimized, scales as:

$$\delta = \frac{PL}{AE} \propto \frac{L^3 \times L}{L^2} = L^2$$

Behaving favorably by diminishing faster than required.

Indeed, most common loading conditions for scaled structures exhibit the same favorable behavior. Stresses diminish as the scaling parameter "L" and angular deflection behave likewise. Of course, both these characteristics could be scale invariant without causing difficulty. This scaling behavior applies to single point loaded beams in bending torsional members as well as compression and tension members.

Exceptions seem to be beams with distributed loads as well as a number of structural configurations for which elastic stability is a design criteria. For these cases, stress goes down even faster than in the more common cases.

There are second order effects which make the behavior of structures even more favorable when scaled down. These relate primarily to a slow but systematic improvement of material properties normally associated with reduction in component size.

On the other hand, capability to produce structural members with small enough cross sections might become a limitation for extremely small scaling ratios.

4.3 Scaling of Mechanism

There are a few standard mechanisms very commonly used in manipulators and of potential utility in the construction of mini-robot arms. The first of these are gears.

4.3.1 Scaling of Gears

There are a number of parameters of interest in the scaling of gears. The first of these relates to tooth strength. The ability of a gear to carry a load without breaking is essentially related to the single point loaded beam. The gear tooth, as expected, behaves similarly to these according to a number of common, semi-empirical, design equations. However, from experience and tests one knows that for gear trains critically designed according to any set of these equations smaller gears turn out to have a larger safety factor than larger ones. This effect exceeds by far the improvement one could expect due to material behavior in small samples. This effect has not been thoroughly investigated, primarily because instrument gears are very rarely used under highly stressed conditions. The one known exception to this is manipulator and robot arm design.

The second strength parameter relates to wear. A number of empirical and nonlinear relations are used in gear wear design. A rough linearization of some few of these yields a quasi-linear dependence on tangential force and tangential velocity. Since our scaling scheme is invariant for angular velocities the torque limitation (T_W) due to wear in a gear scales as L^3:

$$T_W \propto F \times r \times V^{-1} \propto L^3 \times L \times L^{-1} = L^3 \quad ,$$

where F = tangential force
r = gear radius
V = linear velocity.

Inertia due to scaled gears should go down as L^5, and if one takes advantage of available gear strength, as L^6. This means that effects of gear inertia, which in a properly designed arm are never substantial, will practically vanish.

Gear train efficiency should scale as an invariant when one neglects the effect of bearing which will be discussed later. Efficiency, of course, is a power output to power input ratio, and all the ingredients involved are scale-invariant.

A rather more difficult problem relates to gear accuracy both as far as effecting backlash and index accuracy is concerned. The error involved in this should, of course, go down as "L". In our real world tolerances, however, do not go down linearly with the size of parts. Particularly in gears, which are manufactured according to AGMA (American Gear Manufacturer's Association) standards, tolerances do not decrease as fast as sizes. The effect of this will be discussed in connection with arm design.

4.3.2 Scaling of Tendons

Tendons are frequently used in manipulators for motion transmission purposes. They consist of either metal tape or aircraft type wire rope. In either case the favorable scaling as L^2 of structural members in tension applies, where our scaling laws call for L^3 scaling. One therefore gains in both strength and stiffness of tendons for scale factors $L > 1$.

The use of tendons involves guide and terminal pulleys around which tendons wrap. The stress due to this is $\propto Dw/Dp$, where Dp is the diameter of the pulley used and Dw is the diameter of the individual wires in the wire ropes or the thickness of the tape. This remains scale-invariant for linear scaling of these components as it should.

These scaling relationships will result in tendons designed to work with a scaled pulley diameter, but with diminishing tensile stresses.

A limitation in the use of wire rope will appear due to availability of rope in scaled down sizes.

4.3.3 Scaling of Bearings

As low friction in BFR manipulators is of extreme importance, all bearings in these devices are usually high quality ball bearings. This motivates us to understand the behavior of ball bearings under our scaling laws.

The limiting static capacity (P_o) of a ball bearing is known to be related to the ball diameter as follows:

$$P_o \propto ND^2 \quad ,$$

where N is the number of balls in the bearings and D their diameter. Since the first number can stay constant for an exactly scaled bearing P_o scales as L^2.

The static load carrying capacity P_o is an absolute maximum load under conditions of quiet and low friction running. It is essentially a limiting condition of brinelling of the balls in the bearing race.

The permissible load on a bearing at a given rate of rotation varies as speed$^{1/3}$. Due to our scaling laws of invariant angular velocities this results in an effective increased load capacity, which scales approximately as $L^{1.5}$.

While available working loads P_n on bearings seem to scale like $L^{1.5}$ required working loads in many cases will be larger than one would expect from L^3

scaling of forces. This results from the fact that one will take advantage of the increased relative capacity available from scaled gears and select smaller gears. Since the bearing loads due to gear action are essentially proportional to the tangential loads on the gears, the use of smaller than scaled gears will result in larger than scaled bearing loads for gear trains.

On the other hand, guide and terminal pulleys for tendon systems should have scaled pulley sizes and scaled tendon tension. Since the load due to this scales as L^3, bearing sizes will decrease faster than the scale factor.

Another concern is friction in ball bearings a parameter which should be minimized in any bilateral manipulator system. We are primarily interested in this parameter under no load conditions, as this determines the bilateral sensitivity of the arm. At larger load levels we are interested in the friction to payload ratio. In ball bearings we can distinguish four sources of friction:

1. Sliding friction due to balls sliding on separators.
2. Rolling friction due to deformation of balls and races.
3. Slip which may occur due to differences in curvature in the ball contact area.
4. Friction due to windage at high speeds.
5. Starting friction due to lubricant action.

The fourth factor is practially eliminated by the way we defined our scaling laws. The third factor is known to be small in bearings with 1 in. diameter bore and up. This behavior is thought to be maintained for small and very small bearings but due to measurement difficulties this has not been verified.

The contribution due to the first two sources has a complicated behavior but empirical tests show that a reasonable approximation results in a coefficient of friction model. That is, friction torque is proportional to load × (radius of balltrack) so that in a scaled bearing load friction torque goes as L^4 as it should.

However, starting friction is a problem. In any bearing not preloaded or fitted up too tightly it is essentially due to a transition from hydrostatic to hydrodynamic lubricant action. With any given lubricant it scales as the balltrack radius or as "L". The result of this slow scaling is that starting friction becomes an ever larger fraction of full load friction with reduction of scale and the transition from starting to load friction comes at a higher and higher fraction of full load.

But, since one will take advantage of higher than scaled bearing capacity for tendon pulleys (capacity goes like L^2 rather than L^3) in such applications, one can make starting friction behave like L^2. And since this is a torque which should scale like L^4 one is losing as the square of the scaling factor.

For scaling of gears, one would however tend to have starting friction scale as "L", if one takes full advantage of gear strength. The best compromise seems to be to take advantage of minimized gear size only at train output stages where gears tend to be largest and bearing friction is not multiplied by subsequent gear reduction. For earlier stages, gears should be underdesigned by making use of more common materials, possibly even plastics.

Another variation concerns preload. Preload is well known as a means of minimizing deflection of bearing shaft assemblies. It is, however, a constantly applied bearing load and accompanied by load friction. To reduce this one may have to use larger bearing spans in order to minimize preload requirements.

Another observation with regard to ball bearings concerns available size. This is best explained by means of an example. In BFR manipulator design one makes frequent use of articulated arm configuration where the arm structures are tubular. In many cases these tubular members are revolving around their own axis. Suitable bearings for this are so-called "thin section" bearings. For the shoulder of the "TOS" SM-2090 Manipulator these satisfactorily work out to be 2-5/8 in. diameter bore ¼ in. × ¼ in. cross section bearings. An $L = 1/3$ replica would require a 7/8 in. diameter bore bearing with 0.083 in. cross section. However, the best available bearings are 7/8 in. diameter bore with 0.125 in. × 0.156 in. cross section, a factor of 1.5 in height and 2 in width above scale.

This availability mismatch contributes towards the bearing overwhelming the arm configuration.

4.4 Scaling of Actuators

4.4.1 Scaling of Electric Motors

Requirements: parameters that should be maximized:

T: torque should scale $\lesssim L^4$

P: power should scale $\lesssim L^4$ (since angular velocity is scale-invariant)

Parameters that should be minimized:

$\dot{p} = \frac{T^2}{J_m}$, $\dot{p}$ should scale as $\lesssim L^3$,

J_m = rotor inertia,

T_m = motor torque

$\dot{p}$ = power rate

T_f: friction should scale as $\gtrsim L^4$.

Looking at permanent magnet (P.M.) motors and assuming constant rotor surface dissipation W_s, we get:

Available cooling are: A_w scales as L^2.

Wire diameter in winding: D_w scales as L^2.

Length of wire: h_w scales as L.

Rotor resistance: R_w scales as $h_w/D_w = L/L^2 = L^{-1}$.

For constant current densities: $S = 1/A_w$: I scales as L^2.

Dissipation W with S = constant, $W = I^2 R_W$ scales like $L^2 \times L^{-1} = L$.

But $A_w = I^2 R$ scales as L^2,

$\therefore$ I scales as $L^{3/2}$.

Voltage required to drive I through rotor is V_r. V_r scales as $L^{1/2}$, which means that wire insulation thickness requirements drop less fast than wire size. This is hard to assess, but empirically I scales as $L^{1.9}$ to $L^{2.3}$ rather than $L^{1.5}$. We will use $L^{2.1}$ scaling.

The permanent magnet field available should essentially scale invariant since the decrease in magnet thickness is compensated for by a reduction in gap size.

We then have:

T: torque $\propto I \times b \times$ radius $\times$ length.

T scales as $L^{2.1} \times 1 \times L \times L = L^{4.1}$.

As one can see, the continuous torque available from a motor falls off only slightly more slowly than requirements. Furthermore, the exact scaling rate seems to depend critically on the insulation quality for the wire used. However, manufacturing limitations on the wire tend to result in a minimum insulation thickness which is reached with small wire sizes. So that even the above rule seems to become invalid for scale factors $L < 1/5$.

The use of some of the new permanent magnet materials like Samarium Cobalt, which promise much improved energy products, does not seem to help either. These materials have a very narrow and high hysteresis curve in contradiction to the more square ones of the commonly used "alnico materials". This makes these new materials suitable for larger motors with large air gaps and quite unsuitable for miniature devices. The above is at least true for conventional motor design techniques.

In a wound rotor dc motor the field B is subject to the same current limitation as in a wound rotor. Torque in such motors tends to scale as $L^{4.4}$ to L^5.

Motor power scales less fast than the L^4 required by our time invariant scaling system. This results from the fact that shaft power is a direct function of available angular velocities which can increase with size reduction. However, this advantage is not terribly useful for a device scaled by time invariant rules, and therefore will not be discussed here.

Motor friction in P.M. motors has three main components of concern here. Brush friction, bearing friction and hysteresis friction for motors having iron in the rotor.

Bearing friction has been discussed in the last section. The effect of relatively increasing starting friction for reduced scale increases contribution of this from negligible to important.

Brush friction is a function of brush pressure and commutator radius. Brush pressure is a function of current carried which scales like $L^{2.1}$ as shown above. This makes brush friction scale as $L^{3.1}$ which is approximately verified from data on commercial motor families.

For motors having iron in their rotors, hysteresis friction is usually not negligible. The amount of friction torque from this is proportional to B and the size of the iron hysteresis loop both of which are scale invariant. It is also proportional to rotor radius and length each of which scale as L for a total hysteresis scaling of L^2.

We have then bearing and hysteresis frictions scaling as L^2 and brush friction scaling as $L^{3.1}$.

Another parameter that one would like to minimize in a BFR manipulator motor is motor rotor inertia. This should scale as L^3 to result in accelerations required by our scaling laws.

Since rotor inertia is proportional to $r^4 * l$, where r = rotor radius and l = rotor length, this parameter scales favorably as L^5.

What really should be examined is scaling of $\dot{p}$ or power rate as this removes the gear ratio parameter from the acceleration capability comparison. We will use power rates at continuous torque rating.

It can easily be shown that the reflected inertia from the motor at the output of a manipulator and expressed as a pseudomass m_o is given by $m_o = K_1^2/\dot{p}$, where K_1 = the arm lifting capacity when the arm is outstretched. This is useful in comparing arm component inertia to load inertia. Since K_1 scales as L^3, as does m_o, we have a $\dot{p}$ scale requirement at $L^6/L^3 = L^3$. In actually using T scaling as $L^{4.1}$ as above we have $\dot{p} = Tm^2/J_m$ scaling as $L^{8.2}/L^5 = L^{3.2}$. That is power rate falls off a little faster than desired. In view of the fact that the inertia effect due to all other components falls off faster than required this is probably partially if not totally compensated for.

4.4.2 Scaling of Stepping Motors

In a computer controlled robot arm one is tempted to introduce direct digital control which would lead one to the obvious examination of stepping motors. There are a considerable variety of stepping motor types all of which cannot be described and analyzed here. To simplify the task one asks what a useful first scale-down step might be. Without very detailed reasoning one would like to aim at scales of L = 1/3 or smaller. Using direct scaling from TOS SM-2090 Manipulator one would require a motor of about 1 $in.^3$ volume or smaller. We will therefore eliminate from consideration any stepping motor types which do not include at least a 3 $in.^3$ or smaller motor, among available models. Such preselection seems to leave only variable reluctance and premanent magnet stepping motors as possible candidates.

Both these types should scale exactly as permanent magnet dc motors. However, inherently stepping motors do not have the same power to volume ratio, or torque to volume ratios. Indeed, the smallest stepping motor one could discover is too large by about a factor of two for down scaling to L = 1/3.

Other drawbacks of stepping motors are that they are not inherently bilateral. This might not turn out to be a drawback, but from our present viewpoint chosing bilateral mechanism is an advantage. Some further remarks on bilateralism will be found in section 6.4.

4.4.3 Scaling Hydraulic Actuators

Hydraulic actuators are repeatedly proposed as ideal actuators for manipulators. For large manipulators with scales $L \succ 2.5$ their distinct advantage in force to mass ratio tends to overcome the characteristic high compliance, actuator friction and system tendency to leak.

For small scale applications actuator force scales favorably as L^2 and energy content scales as L^3 as it should. However, seal friction scales only as "L" so that it becomes predominant for small actuators.

Compliance actually improves with small scale. It can be shown easily that actuator deflection under load is given by:

$$dl = \frac{1}{E_v} SM\,dP \quad ,$$

where dl = deflection under load; s = required stroke; E_v = bulk modulus of fluid; P = fluid pressure; M = mechanical advantage. So that:

$$dl \text{ scales like: } \frac{L \times L^3}{L^2} = L^2 \quad .$$

Since E_v is for all intents and purposes a constant for all fluids and since dl is to be minimized, a low pressure system is indicated. But system pressure and mechanical advantage cannot be reduced indefinitely if one would like to maintain a miniature system, and also prevent vapor evolution in the fluid. Under these conditions a low compliance is hard to obtain.

Furthermore, servo control valves for very small systems are not available as unavoidable leakage rates in the small valve passages approach full flow rates, thus resulting in loss of flow modulation. Also the smallest available servo valve (which has too much flow by a factor of about 10^2) are already extremely sensitive to particle contamination. Development of substantially smaller valves would constitute a major development effort.

For the above reasons and others, hydraulic actuators and controls do not seem attractive solutions for mini-robot arms.

A possible exception is terminal device actuation. Compliance requirements for this is not as high as for other motions and a hydraulic link through bellows and flexible tubes might be attractive. This would simply link shoulder proximate electrical motors to the actual terminal device.

4.5 Scaling of Force Transducers

There are a great variety of ways to measure forces; all of which actually measure the deflection or strain in a more or less stiff springs or deflection member. The scaling of at least two devices have to be examined:

a. The deflection member.

b. The transducer measuring strain or deflection.

The deflection member may be a beam or a torsion bar. From section 4.2 we know that in both of these members the stress and therefore the strain scales as L, while the deflection scales as L^2. Therefore, no problem is to be expected from this type of deflection member.

Somewhat more difficult is the scaling of the deflection or strain measuring transducers. Deflection measuring transducers are essentially position transducers with small motion ranges which do become somewhat smaller with decreased motion range requirements. But improved resolution and accuracy brings with it the size increase typical of all position transducers. Since the allowable stress is limited by metal hysteresis considerations, the associated reduced deflection makes deflection measuring transducers less attractive.

While the above remarks are in general true of strain gauges too, the latter are very small devices, particularly the solid state variety, which also has higher output and resolution.

In manipulators solid state strain gauge force transducers have first been used in the Brookhaven arm in 1965. They were successful then, and the technology has been improved since. When transducers based on these are scaled down, a favorably decreased compliance contribution occurs if they are designed to invariant strain levels.

Even though solid state strain gauges are small, a size will be reached when scale-down limitations will have to be faced. It is then possible to unite the deflection member and strain gauge by making the former out of solid single crystal silicone which is appropriately doped and provided with leads. This will eliminate almost all hysteresis effects. The deflection element will be a single crystal with presumably no hysteresis and the effect due to gauge mounting is eliminated as well. The exact limitations of this method must be studied further.

In the terminal device one would like to have an array of tactile sensor in addition to the force sensors with wide dynamic range, these could presumably be bistate devices. Since their introduction by Bliss,[13] these have traditionally been home-made and require further study to elucidate their scaling characteristics.

4.6 Scaling of Position Transducers

Position transducer requirements for robot arms are rather different than for BFR manipulators. For the latter, the term accuracy is not well defined, one is rather interested in transducer smoothness and resolution as continuous correction from the manual manipulator operator exists. As one rescales a robot arm the accuracy of position achievable is related directly to transducer linearity. Since this accuracy should scale like "L" just like the arm size the required position transducer turns out to be scale-independent.

However, virtually every type of position transducer known increases in best available linearity output smoothness and resolution with size increase only. Since our scaling requirements require smaller transducers these, apparently can only be obtained at the expense of reduction in available accuracy.

A variety of techniques exists which allows us to maintain accuracy for modest down-scaling. Beyond that, either means have to be found to accommodate large position transducers or one must relax the accuracy requirements and replace them with different programming methods as will be discussed later.

5. MINI-ROBOT DESIGN

By looking at manipulator derived robot arm design we concluded that open loop and unilateral design techniques are satisfactory for fairly large programmed transfer devices. However, for robot arms equipped with properly utilized force sensing systems, better dynamic performance than is possible to achieve with joint proximate actuator location is required. For larger, higher capacity arms use of hydraulic actuators might result in nearly tolerable dynamic performance. Electrical actuators are nearly optimal in the neighborhood of unity scale, but even there it is hard to obtain really adequate dynamic performance.

For mini-arms, joint proximate mounting of actuators, becomes increasingly difficult. Hydraulic actuators, at least in conventional form, are not usable and the unfavorable scaling of electric motors as well as the scarcity of really small ones bring about a rapid deterioration of arm aspect ratio and dynamic performance. This is amplified by torque resolution problems of unbalanced joints, so that the design and performance of even a half scale arm along these lines becomes exceedingly unattractive.

However, tendon technology, coupled with counterbalance techniques, as used in modern BFR manipulator design, allows at least respectable dynamic performance over a wide range of sizes. Furthermore, placing of actuators near the arm shoulder allows one to keep arm aspect ratio in reasonable bounds. While motors do not scale any more favorably due to tendon design their placement is such that usefulness is extended to smaller scales. Proper counterbalancing techniques allow all motors to be the same size with much reduced torque resolution problems. Arms with scale of ¼ to 1/5 seem to be possible with tendon technology and working on an even smaller scale (approximately 1/20) seems possible with some deviations from direct scaling. However, for work with much smaller scales other design approaches have to be developed.

There are a number of advantages in using scaled down manipulator technology for initial work in the mini- and micro-robot arm field:

I. Work on mini- and micro-robot arms is in its infancy, therefore experience with work in this regime would be welcome before one departs on an extensive program of complete innovative activity.

II. Work with force sensing AI robot arms is also just beginning. One must expect at least some surprises, which cannot be foreseen now, to influence arm requirements.

III. Both above considerations make it attractive to obtain a well performing arm without too much effort. The mechanism derived from manipulators, while somewhat complex are well understood and familiar (at least to BFR manipulator designers). This will result in great time savings in the design-development and prototype building sequence while assuring adequate performance.

IV. Work in the new regime involves aspects of dexterity which were not involved in previous AI work. To that end a scaled down arm based on BFR manipulator technology allows highly dexterous manual control for check out and exploratory purpurposes.

The last point might bear some discussion.

When one attempts to make a transition from development work on open loop manipulator systems to similar work with BFR manipulators it does not suffice to acquire the rather broader technology base for the latter. Rather, it is more essential, that a complete change of attitude with respect to the meaning and goals of manipulation be acquired. In terms of open loop manipulators one tends to think of manipulation strictly as a positioning problem in a geometrical world, where the effects of gravity, the dynamics of masses and the frictional constraints of task configurations are at best regarded as minor perturbations. Effective work with BFR devices shows us that in the majority of tasks the geometrical positional problem of object placing is only one element in the task sequence to be accomplished, an element that is frequently rather minor.

In working with BFR manipulators we have learned that any but the simplest manipulator tasks require complete control of all pertinent parameters with due regard to their task specific hierarchy.

A clue to the nature of manipulation was obtained by this author on recording force and position transducer readings while developing tasks for a "dexterity quotient" test system with the Brookhaven manipulator. (The Brookhaven manipulator is still the only one existing which is capable of this.) A simple analysis of these initial and unfortunately incomplete recordings shows that all too frequently manipulation is but a series of well controlled collisions which are even dominant in plain visual positioning operations.

We believe that the above information is pertinent to the choice of at least initial force sensing AI robot arms. In the past in AI robotry some force sensing has been added to arms as an afterthought and was used as an aid to the system which is based on a positional solution to the mechanistic elements of the tasks. This approach grossly under-utilizes the potential power of an adequate force sensing system. The proper utilization appears to involve a drastic change of attitude on the part of the programmer toward the mechanics of task accomplishment, a change somewhat analogous to that involved in utilization of force reflection in manipulators.

The intended meaning here might be more easily clarified by an example:

One is given a force sensing, hand-eye AI robot system and the generalized task of placing dowels in tightly fitting holes. The reaction of the hand-eye-computer system which one would like to achieve can be likened to the following:

Let us see what we can learn about this situation by exerting small forces with the end of this oblong object in the vicinity of the round region? It becomes quite obvious that to achieve this kind of result, programming attitude changes must go rather deeper than the routines involved in the more mechanistic aspects of task accomplishment.

There might possibly be a number of ways of familiarizing the programming staff with the various aspects involved. A proven way, however, to do this consists in planned experimentation with a BFR manipulator system of adequate performance. Preferably such system should have its manipulator work in a similar size domain as the chosen mini- or micro-robot arm. As was shown in the section on manipulators, BFR systems of adequate performance are not "off the shelf" hardware, certainly not with scaled down output. However, as it turns out, much of the same technology used for building a mini-robot arm with adequate performance has already been used in ongoing developments of unity scale manipulators and is compatible with the proposed design. This then reduces acquisition of a manual control mode device to some additional hardware acquisition of relatively modest cost, and with only minor interface development problems.

The above considerations are one more reason for favoring the design chosen.

5.1 The Proposed Design

The proposed arm design is illustrated in drawing AIR-5001. It accomplishes the following basic objectives:

I. A sufficiently small arm size (8" total length) to make the project interesting, achieved through use of tendon technology.

II. A completely self-counterbalanced design allowing the use of full motor torque resolution for all degrees of freedom.

III. An exact tendon joint articulation compensation system, which is coordinated with the counterbalance system.

IV. Exceptionally low compliance in both the structural and motion transfer systems. Error due to worst case full load deflection is of the order of position accuracy due to transducer linearities.

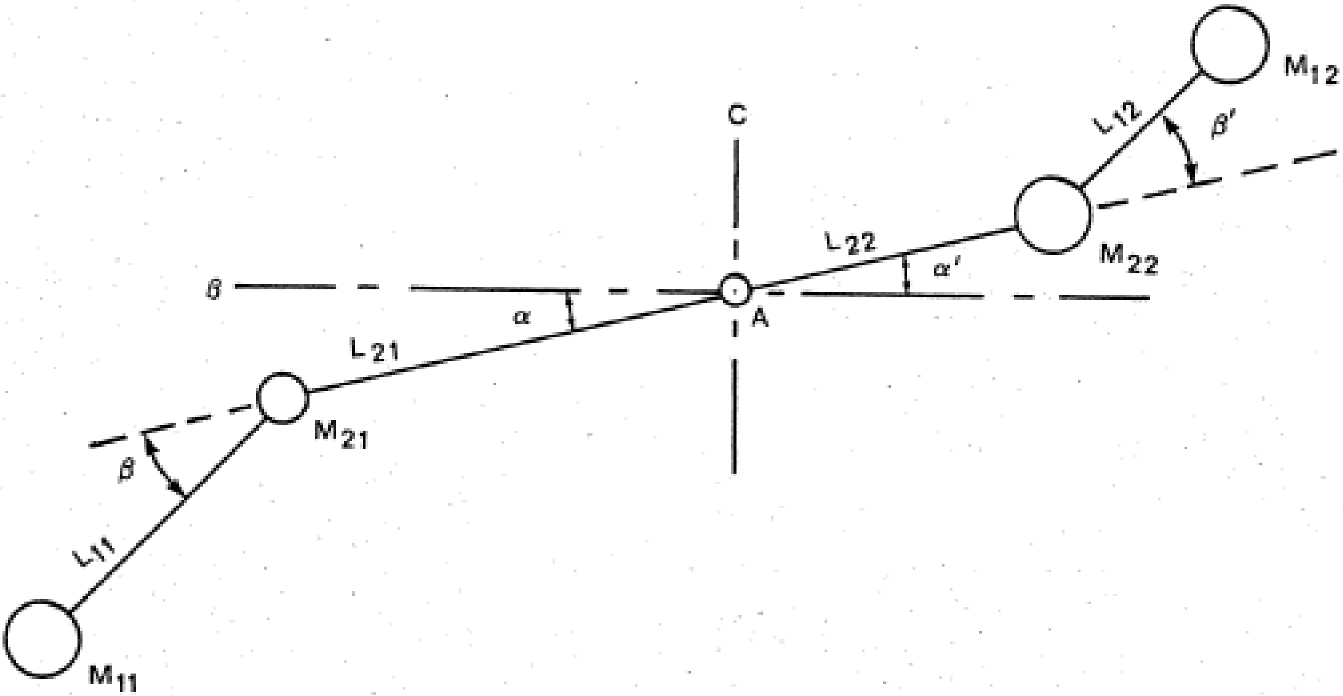
V. Compatibility with a fully bilateral manual control arm system already well advanced in its development.

The proposed design is possibly not as small a scale as this technology would allow. It was chosen as a reasonable compromise between the desire to achieve a significant scale reduction and the need to verify the scaling rules and problem approach.

5.2 Selection of Kinematic Arrangement

5.2.1 Counterbalance Arrangement

To show that the counterbalance arrangement is in principle exact for all possible motion of the upper and lower arms we first confine ourselves to the planar argument with equivalent point masses representing the arm masses involved.



To obtain balance in a gravitational field one must satisfy the following relationships where $\alpha = \alpha'$ and $\beta = \beta'$ are design constraints.

$$m_{12}(L_{12}\cos\beta' + L_{22}\cos\alpha') + m_{22}(L_{22}\cos\alpha) =$$

$$m_{11}(L_{11}\cos\beta + L_{21}\cos\alpha) + m_{21}(L_{21}\cos\alpha) \qquad \text{(a)}$$

$$m_{12}(L_{12}\cos\beta') = m_{11}(L_{11}\cos\beta) \qquad \text{(b)}$$

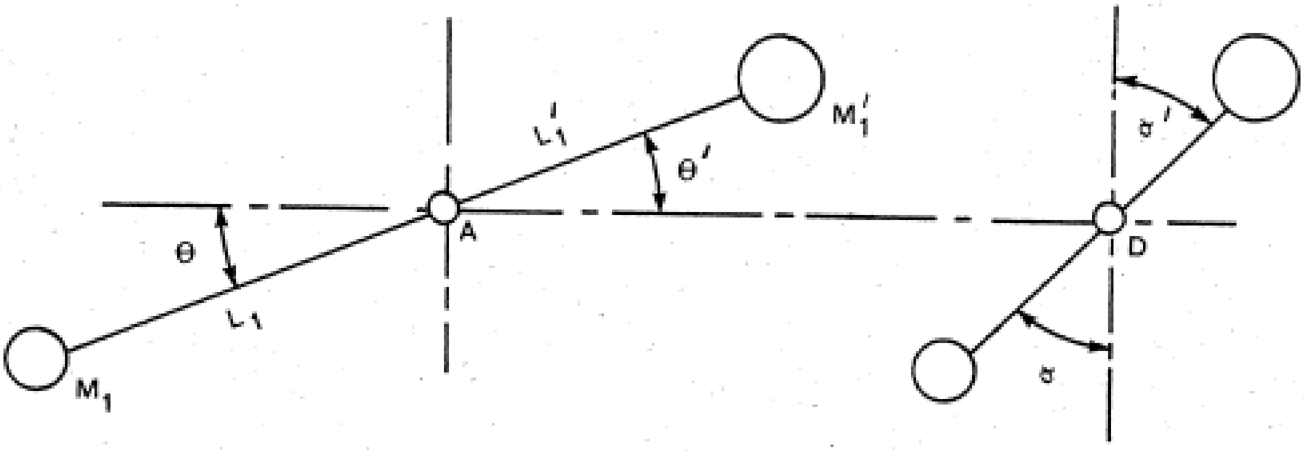
from the above for $\alpha = \alpha'$ and $\beta = \beta'$ we get for all α and β:

$$m_{12}L_{12} = m_{11}\ L_{11}$$

$$(m_{12} + m_{22})\ L_{22} = (m_{11} + m_{21})\ L_{21}$$

as requirements for planar balance. It is obvious that these requirements are also satisfied for rotation around the "c" axis.

For examination of the third possible rotation around the "D" axis one replaces the planar system with its equivalent:



where, $m_1L_1 = m_{11}(L_{11} + L_{21}) + m_{21}(L_{21})$

$$m_1'\ L_1' = m_{12}(L_{12} + L_{22}) + m_{22}(L_{22}) \tag{c}$$

we then have:

$$m_1L_1\ \sin\theta \sin\gamma = m_1'L_1'\ \sin\theta' \sin\gamma'$$

and since $m_1'\ L_1' = m_1L$ and $\theta = \theta'$ by transformation of c, we get as remaining requirement $\gamma = \gamma'$.

In the actual mechanism $\gamma = \gamma'$, and $\alpha = \alpha'$ is satisfied by the one piece upper arm. A connecting rod was chosen to maintain $\beta = \beta'$.

5.2.2. Tendon Compensation

Having already introduced the constraint of $\beta = \beta'$ to obtain counterbalancing, a satisfactory solution for the tendon compensation of the elbow exists which utilizes this arrangement.

The basic problem of tendon compensation consists in keeping tendon length between actuator pulley and motion output pulley unchanged due to intermediate joint motion. As guide pulleys must exist at each intermediate joint to keep tendons under tension, the problem is reduced to compensation for change in length due to change in the angle of wrap of the guide pulley. In our case, this is easily accomplished by using equal size guide pulleys at the elbow joint and counterbalance joint, but wrap the tendon in opposite directions. This keeps the sum of the wrap angles a constant and therefore tendon length unaffected.

An additional pulley or two per cable path are required to accomplish the reverse wrap at the counterbalance joint. These pulleys can also be utilized to pretension tendons to the required degree.

Once these two problems have been satisfactorily solved, the wrist drive motors can be conveniently placed in the counterbalance mass, thus eliminating addition of extraneous weight for this purpose.

5.2.3 Arrangement of Degrees of Freedom

Drawing AIR-5001 shows an elbow convex confiruration. This is made necessary by the choice of wrist arrangement. The wrist kinematic arrangement is identical to that used in virtually all existing BFR manipulators both mechanical or servo. It is probably the simplest arrangement possible for obtaining wrist action from tendon motion. It involves a simple differential action for the pitch and roll motions. When both differential input pulleys rotate in the same direction at the same speed, the differential adds these motions and pure pitch results, or an (A + B) operation. Similarly, pure roll results from a (A - B) operation. Combined motion can be obtained from linear combinations of these two. These simple operations should not involve programming difficulties.

As a result of yaw motion the tendons for pitch and roll must twist in the tube. Surprisingly this can be done with impunity and with very little position error in pitch ($\simeq$ 0.0007" for the worst case). This small error is achieved by having the effect subtract in the differential at a sacrifice of about 0.006" error in roll.

The disadvantage of the above arrangement is that a motion singularility exists when the roll axis is parallel to yaw axis. As simple priority logic can resolve the resulting redundancy, this means that for position near the singularity the arm has effectively only five degrees of freedom.

To avoid this situation pitch motion is restricted to

As the assumption is that the preferred working position for the terminal device is parallel to the main working surface, this results in an elbow convex attitude of the arm.

An elbow concave attitude either requires another more elaborate wrist arrangement or a "terminal device down" preferred position.

Linear motions and other articulated motion arrangement have not been discussed here as new counterbalance and tendon compensation geometrics must be developed for them.

5.3 Position Accuracy and Position Transducers

Since the proposed arm is initially to be used with traditional programming with its emphasis on positional accuracy, position transducers must be selected with care.

The scaling problem of position transducers have been pointed out above. As can be seen from AIR 5001 , even the smallest available transducers are quite large for this arm. Small transducers are however not available in the highest linearity ratings. Therefore the following compromise has been arrived at for this arm:

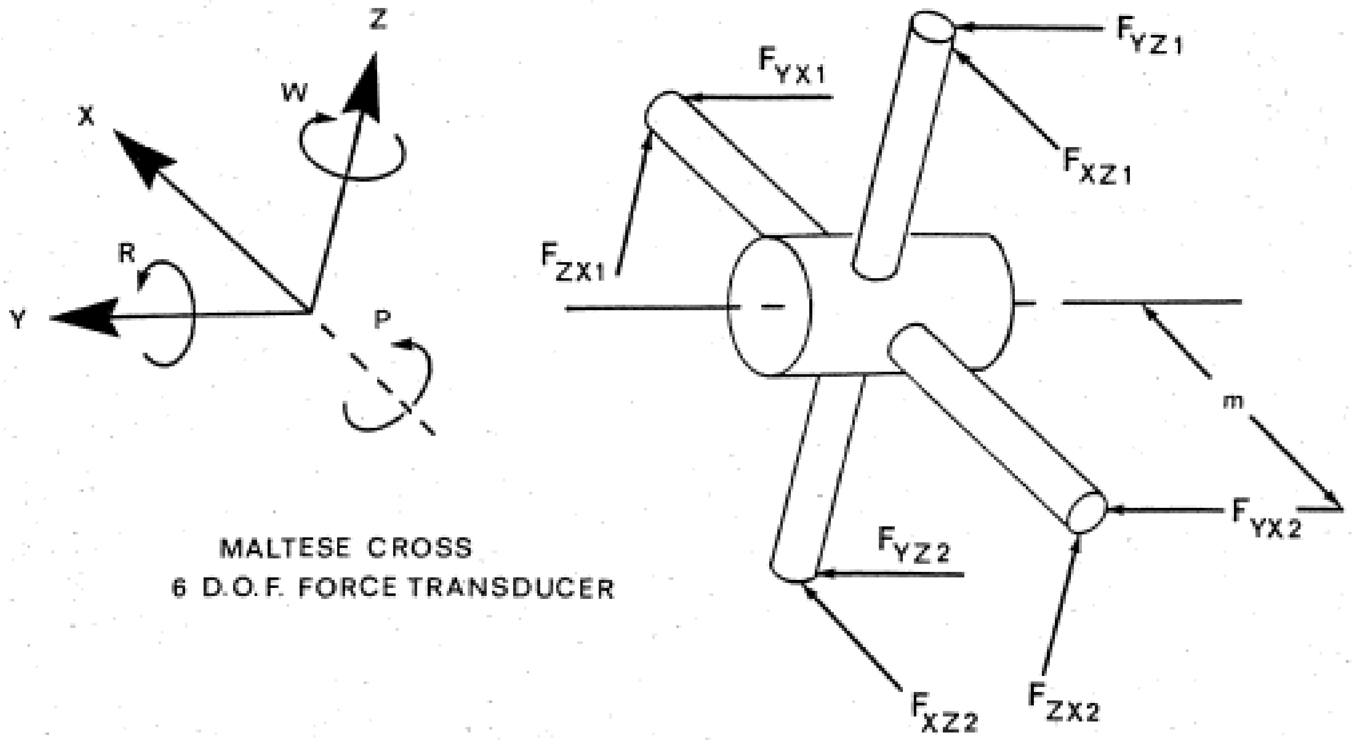
For x, y, and z motions 1-7/16 diameter conducting plastic potentiometers will be used either geared or as elements as shown for the x motion on AIR-5001 . These should be available with 0.05% linearity. In the counterweight mass no room for such large transducers can be made available. Consequently ½" diameter potentiometers which recently have become available in 0.15% linearity will be used.

The larger position error due to this will affect only the wrist motions, which because of the smaller moment arms, does not reduce overall accuracy that drastically. The derivation of the complete error function for the entire arm is beyond this study. However, a quite accurate approximation method for this familiar geometry yields a very worst case accuracy error of 0.015". By very worst case we mean that all possible error sources combine in the worst possible way, something which is statistically rather unlikely.

If higher accuracy is desired one would have to resort to mapping the transducer nonlinearities and storing correction tables in the computer.

5.4 Force Transducers

No design proposal for the force transducer interface is offered at this point. The volume assigned to the transducer on AIR 5001 is sufficient to introduce a 6 D.O.F. transducer



MALTESE CROSS
6 D.O.F. FORCE TRANSDUCER

As shown in the sketch this configuration consists of four orthogonal deflection bars, each having strain gauge sets on two sides. As there are six D. O. F. for eight strain sensors we must expect an assymetric transformation matrix. This latter can be shown to be::

$$\begin{vmatrix} -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 \\ 0 & -1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m & 0 & -m & 0 \\ -m & m & m & -m & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m & 0 & -m \end{vmatrix} \times \begin{vmatrix} f_{xz1} \\ f_{zx1} \\ f_{xz2} \\ f_{zx2} \\ f_{yz1} \\ f_{yx1} \\ f_{yz2} \\ f_{yx2} \end{vmatrix} = \begin{vmatrix} F_x \\ F_y \\ F_z \\ M_p \\ M_r \\ M_w \end{vmatrix}$$

It is apparent that all strain sensors must fulfill a dual function as each term is appearing in the expression for exactly two force or torque components. Since no restrictions on superposition of forces of torques may be imposed for manipulation, this reduces available sensitivity by a factor of two. One is also over constrained in choosing parameter "m" which further reduces available sensitivity.

On top of this the strain bars must be terminated at their outer ends by sliding and rotating joints and their associated hysteresis.

Looking at the lower half of the transformation matrix one sees that the dual function of sensors, over constraint of parameter "m" and requirement of sliding joints is eliminated if the same configuration is used for a 3 D.O.F. torque transducer. Similarly a 3 D.O.F. force transducer can result by replacing rotating joints with sliding ones.

The above discussion suffices to conclude that the "Maltese Cross" configuration is probably far from optimal. Hopefully with more study an improved configuration can be found. Contacts with commercial force transducer specialists has been established to make existing expertise and technology available to the solution of this problem.

5.5 Actuators

Much of the dynamic advantages if the tendon design can be undone if one chooses motors which do not have sufficiently low inertia to allow a truly bilateral behavior of the robot arm. To that end an Inland "inch square" motor model NT-0716 has been chosen. This choice results in a load inertia at 1 g acceleration referred to the arm loading point of nearly 20% of full capacity, over 3/4 of this is due to motor inertia. While this is excellent compared to what is possible with joint proximate actuator techniques, it is just barely tolerable for the proposed operating conditions. However, since our scaling laws call for L scaling of acceleration, 1 g acceleration would correspond to an excessively high acceleration of ^{3} g of a unity scaled arm, and such high accelerations are not necessary. This result was to be expected from the scaling laws as defined. Another contributor to a relatively high no load inertia is the 6 D.O.F. force transducers placed very near the output end of the arm.

The inertial contribution due to the motor could be reduced by a factor of four if use is made offull motor torque capability and gear ratio adjusted accordingly. However, this would reduce available motor duty cycle at full load from 100% to 25%, which is not really a viable approach as the thermal time constant of the above motor is only about 15 seconds. Addition of a brake would just add considerable bulk to arm and mask the problem, but not solve it.

Another consequence of motor scaling laws results in friction torque contribution of about 10% of full torque capability. That means that for loads up to 10% of maximum bilateral behavior can only be obtained by closing a loop from the force sensor through the computer control system. This will be elaborated on below.

5.6 Choice of Tendons

Miniature wire rope was chosen for the tendons, primarily because a usable size, in very flexible construction, has very recently been made available. The wire rope allows rather lower compliance than a tape design with similar arm aspect ratio. The high degree of stiffness has been achieved by using a fairly large gear ratio between the differential and the lower tendon pulleys. This requires multiple turns at the tendon input and output pulleys which would lead to serious position error with a tape system. With the wire rope, deflection due to tendons of the terminal device in pitch at full load is about 0.002 in. The disadvantage of wire rope tendons consists of somewhat higher friction. However, in this scale this effect turns out to be small compared to the friction contribution of the motor.

5.7 Terminal Devices

A further restriction on force transducer placement calls for insensitivity to tendon actuation tension. With a six D.O.F. transducer placed at the wrist T.D. interface, only the T.D. tendons will be affected.

Assuming a "Maltese Cross" configuration one would get a false "F_y" force indication due to T.D. actuation, the magnitude of which can however be calculated from the T.D. motor current. This approach would require strengthening the F_y bars thus further reducing force transducer sensitivity. To avoid this, a hydraulic link is proposed for the T.D. The terminal device can tolerate the somewhat higher compliance associated with this.

A further advantage of the hydraulic link is that much less fussy tendon compensation is required for such link making addition of further T.D. motions possible at a later date.

A large number of single and multi-D.O.F. terminal device configurations are known. These are however rich in mechanical detail and more suitably dealt with after more feedback from the AI group has been obtained. Further work and selection can then be performed.

The intention is to have T.D.'s removable and interchangeable in a reasonably quick lab operation (30 - 60 minutes) without requiring oil disconnects. T.D. changing under computer control seems possible but is probably best left to later stages if it is required at all.

It is intended to equip all T.D.'s with touch sensor arrays. These should be bistate devices sensitive to about 2% of full force yet capable of enduring full force repeatedly without damage. A potentially attractive new device for this appears to be a force switchable diode which is proprietary with Innovation Labs, Inc. A sensitivity of 5 - 10 gm at a size of 0.060-in. diameter and 0.20-in. length seem possible but production is at the moment limited to 3/8-diameter devices. This, as well as alternate ideas, require further investigation.

5.8 Control System

The control system for the mini- or micro-arm does not seem to pose any particular problems. It seems best to contain all control logic and compensation in the digital computer where it is capable of being modified by software. Control of each motor would then be accomplished by a digitally controlled current driver.

A somewhat different problem arises due to the characteristics of the motor chosen. Even under modified input conditions this motor is capable of excessive speed and has also a rather large amount of ripple torque. The combination of these characteristics could lead to problems at slow speeds. The exact degree of this behavior cannot be predicted. It is therefore advisable to build an actuator breadboard,if smooth, slow running cannot be achieved on the latter, ripple torque reduction by a factor of 20 or 30 can be achieved by placing a single analog servo loop around each motor. This loop requires no additional transducers.

5.9 Required Development

The proposed mini-arm design is a first step intended to furnish a viable, well operating and reliable AI mini-robot arm for desktop use. The arm is sufficiently bilateral to allow exploratory work on programming techniques that will fully utilize its force sensing characteristics. Furthermore even this early in the design economics of fabrication have been kept in mind. The design makes almost exclusive use of catalogue motors, transducers, gears, cables, bearings, and other hardware, assuring not only ease of fabrication but also maintainability. The steps necessary to reduce this to operating hardware are as follows:

I. Design and specification review by the users from the AI laboratory. The proposed design was developed with relatively little feedback from the user community. In the report an attempt was made to cover at least briefly most of the topics that seem important. However, the likelihood is great that some requirements have been misunderstood or missed altogether. Interface requirements must

II. Explore problem areas by means of appropriate models, breadboards or detail design studies. Such areas include: force transducers, position transducer accuracy, motor ripple, terminal device configuration, hydraulic links, wrist differential configuration, and others.

III. Modify design according to results from steps I and II.

IV. Detail design. Repeat steps I to III as required by any problem areas arising.

V. All above steps continuously include analysis of producibility, reliability, and maintainability of design. Where applicable, value analysis of components is performed.

VI. Detail design is reviewed by design group and user groups, and remaining deficiencies are corrected.

VII. Fabrication and testing of prototype. If steps I and VI are properly executed, relatively few surprises should occur in this step.

VIII. Performance review. This step is intended to define all the lessons one learned during the first few steps (there are likely to be quite a number). These should be applied to future devices.

6. FUTURE DEVICES

During the brief study a number of ideas and questions have come up which might be of interest to future developments.

6.1 First Order Micro-Arm

This can be built by making simple modifications in the proposed design. If all motions in the mini-arm are reduced by about a factor of six and position transducer geared accordingly one can obtain an arm having about a 1-in. cube working volume and an accuracy capability of about 0.001 without stored correction tables. As can be seen the error is reduced faster than the motion range reduction. This, of course, is due to the fact that an articulated arm with small angular excursions more nearly approximates a linear motion arm and has reduced error cascading. This approach is sometimes called a quasi-linear motion arrangement.

A geared design for all position transducers is to be preferred for this purpose as it facilitiates building mini- and micro-arm to nearly the same pattern except for the transducer gearing. We would have an arm which would have about 1/18 motion scaling even though its size is no smaller than 1/3 scale arm. From our scaling laws, force requirements for such micro-arm would be about 2.5 gm which would be in the neighborhood of the friction levels. However, about a 2 to 3 oz. capacity with the use of smaller European motors, but otherwise the same structure as the 1/3 scale mini-arm would be a good compromise. Full load deflection with such capacity would be small compared to the accuracy (about 0.0004 in.).

It must be understood that the 1/18 scale micro-arm requires highly precise transducer gearing. Otherwise gearing index errors might become larger than transducer linearity errors. This gives us warning that this technique of obtaining large scale reductions cannot be amplified indefinitely.

6.2 Further Reductions in Size

Looking at the scaling rules one must conclude that progress in the direction of smaller and smaller arms can only be continued if new approaches are being sought. The unfavorable scaling of conventional motors, bearings, and position transducers, among others makes this a necessity.

One should, however, not conclude that one has reached any fundamental limitations. We know that at least biological systems range over an excess of three orders of magnitude in size and show marked improvement of force to mass ratio at the low end of the scale. Certainly as long as our information processing and storage is external to our micro-arm system some way should exist to go to considerably smaller scales then were discussed so far. Unfortunately, the above considerations do not give us a clue to what technological approaches to take.

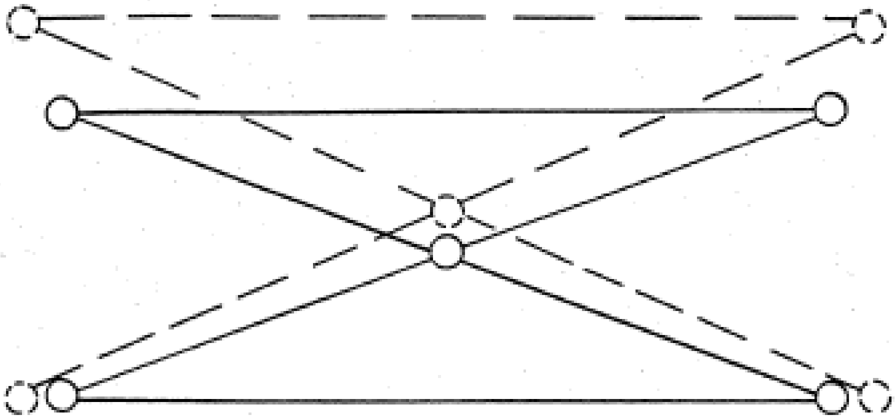
The exercise with the first order micro-arm above would indicate that one does not necessarily have to require an overall decrease of device size as one reduces motion range and force capability. Indeed there are a number of precedents to a trend of an increase of device size with reduction in working scale. The field of imaging devices might serve as an example. We might think of comparing a low powered microscope to the highest resolution electron microscope. More drasticall the largest particle accelerator (which is nothing but an imaging device) requires a 10^5 increase in linear dimension in order to obtain about 10^{20} increase in resolution.

6.3 New Actuators

It seems that electric motors scale down so badly because they have been invented to answer unity or larger scale motion problems. When addressing ourselves to mechanical scale reduction we automatically think "electric motor" since we have been thoroughly accustomed to their use for mechanization purposes. The fact seems to be that electric motors, which are rather complex devices, should be left to do the work in the larger scales, for which they have been invented. Intuitively one would expect to find much simpler actuators for smaller scales, if one were clever enough to see them.

Some promising actuator effects for small scale work seem to be magnetostriction piezoelectric effects and thermal expansion. All of these and any others that might be uncovered should be examined for suitability to this application.

Thermal expansion has been used repeatedly for devices requiring very fine motion. A number of effective configurations using solids are known. This author had occasion to examine the bimetallic triangular configuration, and found that for $L < 1/50$ frequency response becomes reasonable. The configuration is shown below. The diagonal bar have higher expansivity than the horizontal ones. When heated expansion (dashed line position) occurs.



Also of particular interest seems to be the wax motor of lowly automotive thermostat origin. This motor makes use of the rather high change in volume of certain waxes associated with a change from a molten to a solid state. For this reason it does not lend itself to continuous analog control but is more useful as a bistate device. This suggests an interesting arrangement yielding a true digital motor. If one has a number of chambers in series with strokes proportional to successive powers of two, or more conveniently, arranged in a grey code sequence, one would have a true digital actuator which with a mere indication of the status of each chamber, would give us an absolute position reading of the same resolution as that of the motor. Velocity and acceleration can be controlled by regulating the counting rates.

Such motors look attractive, but require small size if one would like to have some frequency response. Nevertheless a condiderable number of problems exist, not the least of which is the matter of precision. Each chamber must have a stroke precision of d/2n, where d is stroke of the smallest chamber, and n is the number of chambers. Such precision requirements exist for all digitally driven motion arrangements as for instance a variety of "Orms". Unless this can be provided there seems little point in pursuing such a scheme.

It is interesting to note that this as well as all the actuators mentioned above are length changers. Also none of them are inherently bilateral.

6.4 Is Bilateralism Necessary?

As we have seen above all the candidates for new small scale actuators are length changers and not inherently bilateral. The first is by no means a disadvantage as an examination of existing techniques shows much adaptation to rotary position changers. This adaptation can be reversed without difficulty for use with length changers. For many configurations length changers are a distinct advantage.

More serious is the question of bilateralism. Bilateral devices have been advocated here as they have proved quite effective in taking advantage of force sensing potential. Other methods have been suggested but they suffer from a lack of fundamental understanding of the problem and have proved relatively ineffective.

One would however be surprised if it turned out the BFR scheme is the only possible scheme or even the best scheme to utilize force sensing in a computer controlled arm. This is important, as apparently all known actuator schemes for small scale work are not inherently bilateral. Should it turn out that this is a fundamental characteristic, one would want to find alternate but equally effective methods of utilizing the force sensing capability of the arm. It is hoped that with progress in the use of force sensing robot arms this question can be dealt with in more detail.

6.5 The Problem of Bearings

For smaller scale arms, bearings will become a problem due to their high starting friction and scarce availability. Jewel bearings are not an answer either as they do not allow sufficiently large bearing loads relative to their size. The use of flexures might be the answer as they scale well and the modest spring constants associated with them can easily be compensated for. Indeed, most sophisticated micropositioners built today make use of flexure bearings in one way or another.

Flexure bearings for fairly large angular excursions can be designed but they do not tend to be small. For small angular excursions (about $\pm 10^{\circ}$) simple flexures can be very effective. This leads to the use of quasi-linear motion arrangements which requires only small angular excursions for the upper motions. The angular motions of yaw, pitch and roll do not seem to be reduced in angular range requirements with smaller scale. In the proposed first order micro-arm the angular pitch, yaw and roll motion range has been cut as the desired task of working on microcircuits allows it and available imaging devices for $L = 1/18$ do not have enough depth of field to accommodate larger angular ranges. But it is not clear that this shortcut can be taken in general.

6.6 Linkage Devices

A number of problems that have crystallized point toward nonanthropomorphic configurations and possibly complete parallel motion configurations as suggested by Prof. Minsky.[14]

We call these linkage devices since analogy to three-dimensional linkages suggests a possible systematic approach to the synthesis and analysis of this family configuration. It is very possible that numerical linkage synthesis, a somewhat esoteric branch of kinematics, can be adapted to examine, analyze and modify these very interesting configurations to yield something useful. Should this turn out to be so, significant contributions can be expected from graduate students, provided one can find faculty members interested in the problem.

SUMMARY AND RECOMMENDATIONS

We have examined in a preliminary manner the problem of building force sensing mini-robot arms. We have concluded that one can scale down up to a factor of about five by utilizing existing BFR manipulator technology. By slight limitation of general purpose utility, scale factors of about 1/20 seem possible. BFR technology also suggests some approaches toward full utilization of the force sensing potential. For further research and data accumulation a preliminary design of 1/3 scale general purpose mini-arm has been worked out. It is recommended that an arm along these general lines be developed and constructed. The same design allows also the construction of a micro-arm working in a 1/18 scale. This somewhat specialized arm results from minor modifications of the mini-arm.

It is further recommended that a manual control input device be constructed for the purpose of familiarization and exploration of effective control approaches for the force sensing mini-robot arm.

Some possible useful ideas toward the building of later generations of mini- and micro-robot arms are also discussed briefly.

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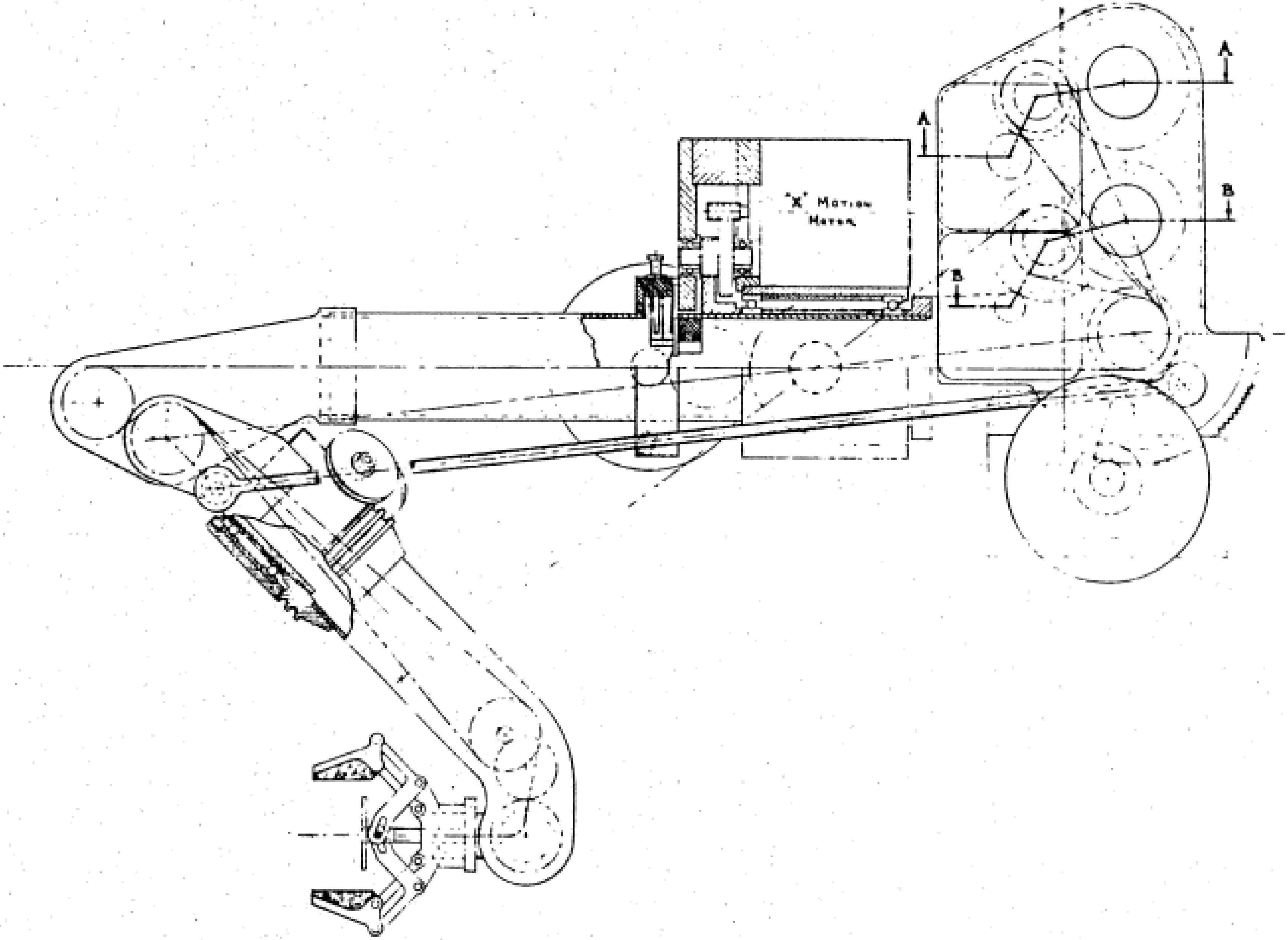

"X" MOTION MOTOR
A
A
B
B