USAFA-TR 92-1

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BUILDING AN EDUCATIONAL ROBOT ARM FOR UNDER $1,000

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FEB 1992

FINAL REPORT

DEAN OF THE FACULTY

UNITED STATES AIR FORCE ACADEMY

COLORADO SPRINGS, CO 80840

USAFA-TR-92-1

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28 JAN 92
Dated

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	20 Feb 92	Final

4. TITLE AND SUBTITLE
Building an Educational Robot Arm For Under $1,000

5. FUNDING NUMBERS
PR 303634

6. AUTHOR(S)
Kenneth A. Lillie, Capt, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Mathematical Sciences
United States Air Force Academy, Colorado 80840

8. PERFORMING ORGANIZATION REPORT NUMBER
USAFATR 92-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Frank J. Seiler Research Laboratory
United States Air Force Academy, Colorado 80840

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited
"A"

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Undergraduate research in robotics has blossomed in the last decade, primarily because of the wide diversity of disciplines involved, such as mathematics, computer science, electrical & mechanical engineering. The colleges and universities that have the best robotics programs have the largest budgets. Typical educational robots cost from $3,000 to $10,000. This particular project is specially aimed at producing an educational robot structural design for under $1,000, thereby making robotic research more accessible to the smaller schools. Foremost in the high-level design philosophy was the idea of making the architecture as "open" as possible--providing the widest possible dissemination of information. Secondly, the building materials had to be easily acquired within the continental United States, preferably by mail order or local purchase. The Preliminary Design included choosing the structural materials. A decision to use plastic for arm construction resulted from an appropriate trade-off study. Next, the most logical actuators were chosen, based on speed, size, and type. The Detailed Design included making specific choices for building materials, specific motors/gears, dimensions, range of motions, and end-effector design.

14. SUBJECT TERMS

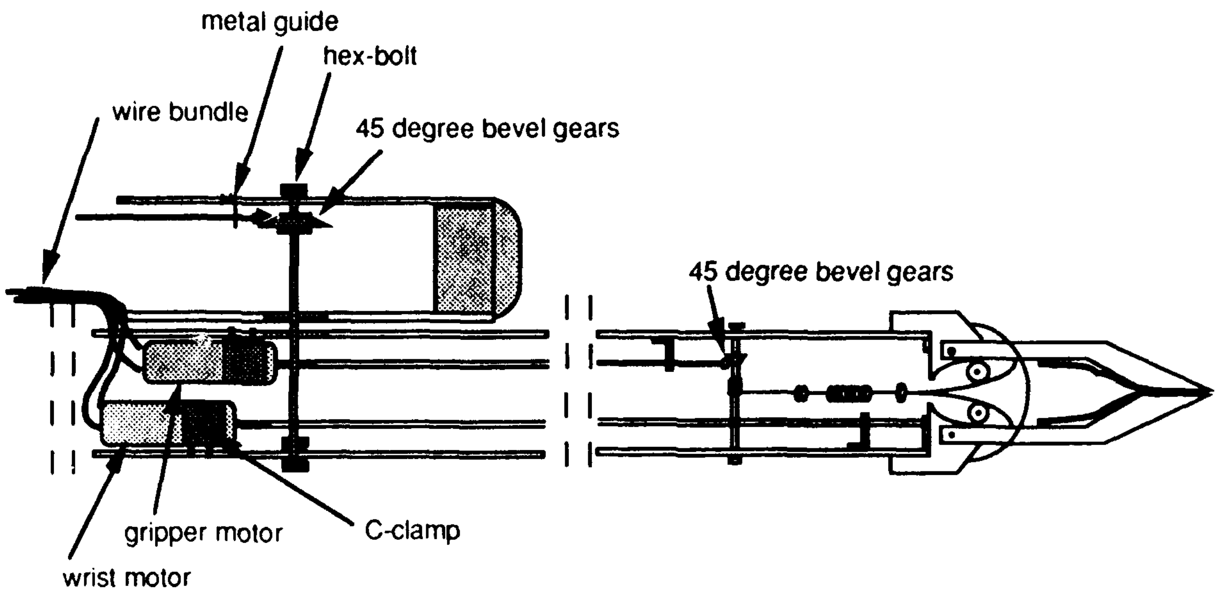
15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Building An Educational Robot Arm For Under $1,000

Part I: The Structural Design



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Building An Educational Robot Arm For Under $1,000

by Ken Lillie, Capt, USAF

PART I : The Structural Design

Introduction: Robotics is a field of study which incorporates many other fields of study, namely Electrical Engineering, Mechanical Engineering, Computer Science, Industrial Engineering, and Mathematics. Studying robotics at the undergraduate level helps the technical majors of these various fields take a few steps back and look at a macroscopic view of a complex system composed of several subsystems, all operating smoothly together. By studying the relationships between the various subsystems, the student learns to appreciate the difficulties that a Systems Engineer faces every day; the art of integration and balance.

The value of robotics for the future of America is evidenced by the tremendous increase in the use of robots in areas such as electronics and automotive manufacturing, and assembly/material handling in hazardous or harsh environments. The military is spending millions of dollars each year for robotics research, aimed at improving US productivity. Comparatively, the Japanese are not only the largest manufacturers of robots, but also the largest users of robots (Critchlow, p. 27); hence their very high productivity level.

How can the undergraduate student better prepare himself or herself to the future wave of automation, than to study an introductory course in robotics? And how better to learn about robots than to actually program them for specific tasks, watching how the intended program often differs from the actual program, as witnessed in the laboratory? But how do these students experience the hands-on approach to learning, without the necessary equipment, primarily the robots themselves? Many undergraduate schools and programs can't afford the high price of educational robots, typically costing from $3,000 to $10,000 per copy.

This report shows in part how an educational robot can be built for less than $1,000. Intrinsic is also the extensibility for vast modifications at reasonable costs. Consider the ramifications of building a mock-up of the Space Shuttle's Remote Manipulator System (RMS), or building a two-arm inter-dependent system, or building a bi-pedal locomotion machine, etc. The list goes on and on. The primary inhibitor is the lack of available information on robot arm design. There are hundreds of books on robotics and robot design, but very few that are serious for educators, or they go far beyond the educational level of undergraduate institutions.

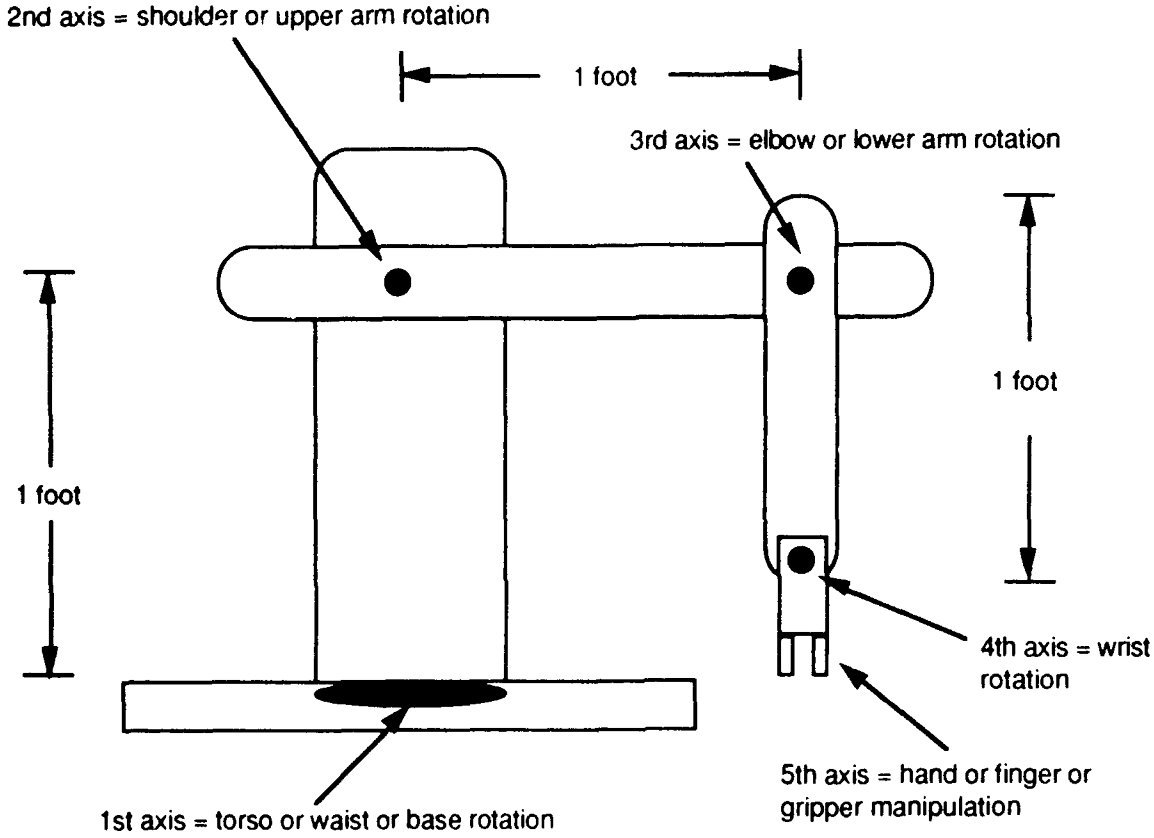

Figure 1: Original Robot Concept

Hopefully, this report will open up whole new possibilities for smaller colleges and universities to either build their own educational robots, or to extend these principles to even newer and more sophisticated prototypes of future machines. Education, many times, is hampered by the unavailability of low-cost yet valuable equipment and their designs. This simple design is only a first step towards opening up the closed-architecture of educational robots, so prevalent today.

I. Design Constraints - these are self-imposed up front to make the design task easier and more well-defined.

- The finished design should cost less than $1,000 to build.

-- This includes: the structure, motors/actuators, power supply, controller, PC interface, gears, pulleys, and other hardware.

- The overall size of the robot should be less than 3 feet high and have a radius of operation less than 2 feet.

- The number of degrees of freedom is 5 including: base rotation, upper-arm (or shoulder) rotation, lower-arm (or elbow) rotation, wrist rotation, and gripper (or finger) manipulation (all 5 joints are revolute).

- The speed of the arm should be less than 0.5 foot/second, for safety reasons.

- The equipment should be easily acquireable anywhere in the United States, either by mail order or local purchase, including:

-- Frame Structure as individual components.

-- Power supply, controller, and interface as complete units.

- The initial precision of the robot will be low, so that only routine inexact movements will be expected.

II. Preliminary Design (General Design)

- Choosing the structural materials - once the above design constraints were applied, the initial design focus centered on choosing potential materials out of which to build the body or structure of the robot. Below is a list of trade offs between various structural construction materials. As you can see, the obvious choice at the outset was the PVC/ABS plastic, not commonly found on current educational robots.

Material	Weight	Mfg Ease	Avail	Cost	Aesth	Score
wood	neg (0)	null (3)	pos (5)	pos (5)	neg (0)	13
plastic	pos (5)	pos (5)	pos (5)	pos (5)	pos (5)	25
aluminum	null (3)	neg (0)	neg (0)	neg (0)	pos (5)	8
steel	neg (0)	neg (0)	null (3)	null (3)	null (3)	9
sheet metal	neg (0)	null (3)	pos (5)	null (3)	null (3)	14
composites	pos (5)	neg (0)	null (3)	neg (0)	pos (5)	13

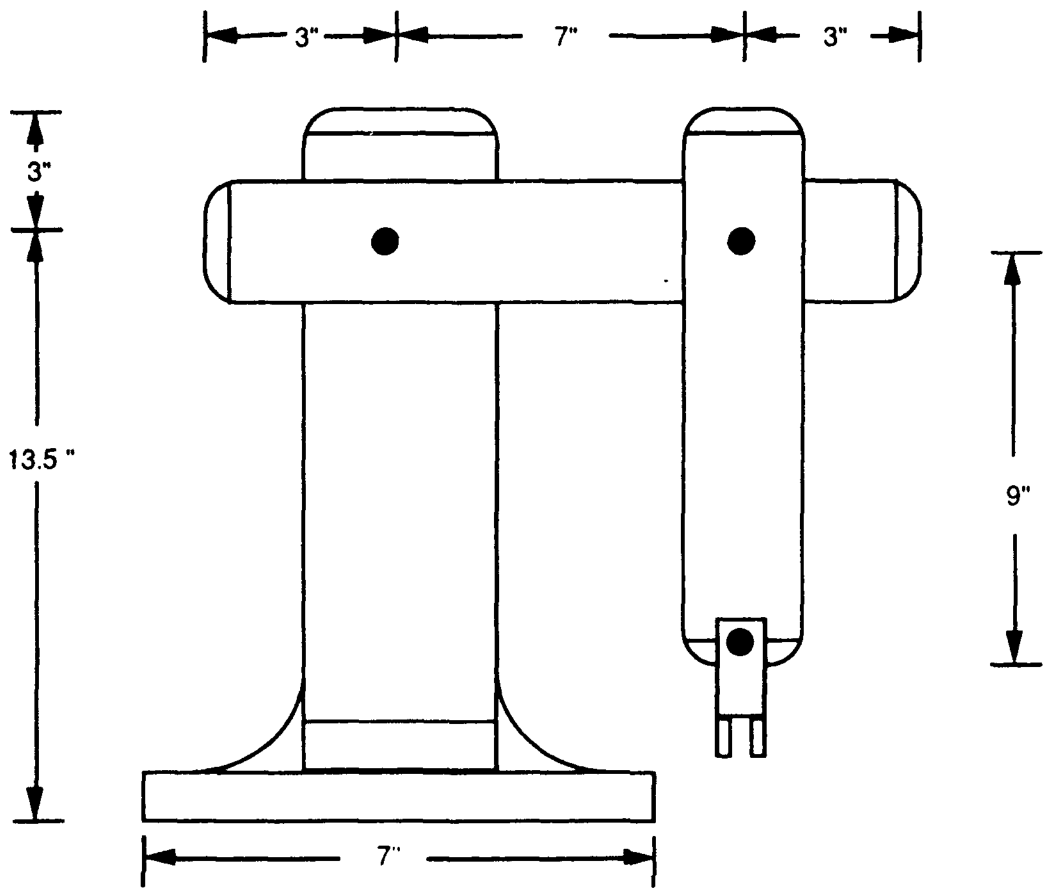

Figure 2: Second Robot Concept

Assigning point values for the ratings in parentheses, some attributes may have slightly more overall weight in the decision-making process, but with this type of low-cost design project the above figures will suffice. The higher the score, the better the rating of the material.

The PVC/ABS plastic received the highest rating, however, it depends heavily on who is the judge, especially for aesthetic reasons. It also depends largely on the equipment available to help in the building process. For instance, pragmatically the composites material is off-limits, simply because of the difficulty in handling carbon fibers, fiberglass, resins, ovens, etc. Materials like titanium may be very desireable for very-precise and expensive projects, but this building material was not even considered as a possibility.

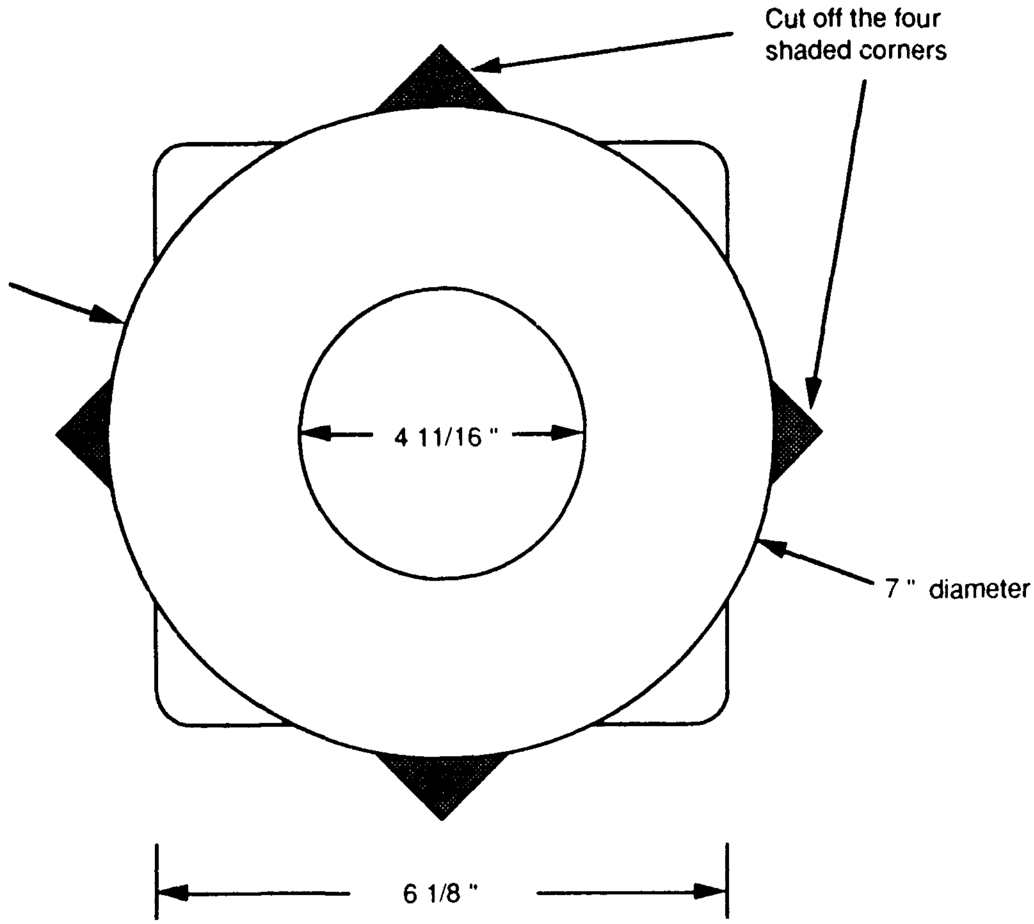

Figure 3: Top View of Lazy Susan

Another factor, not considered above, is that of uniqueness. Considerable intrigue in using a new material played a major part in the decision to use the plastic.

What about the customary tradeoffs using specifications like payload weight, precision, speed, reach, and stiffness? Well, these play a somewhat secondary role when it comes to doing educational tasks like moving lightweight wooden blocks, assembling rather easy-to-build objects, etc.

- Possible PVC/ABS Plastic Components - hardware stores generally carry a fairly wide selection of plastic pipes, commonly used for plumbing and low-strength construction members. Here is a partial list of components considered most likely to be used in this robot design (total cost of all these is under $20.00 for lengths under 13 inches):

Torso and Base Components

3 inch (ID) Crestline White PVC pipe
3.5 inch (ID) Crestline White & Black PVC collar/baseplate
3 inch (ID) Crestline Black PVC collar with threaded end
3 inch (OD) Crestline Black PVC endcap

Lower and Upper Arm Components

1.5 inch (ID) Crestline Black PVC pipe
1.875 inch (ID) Crestline Black PVC endcap
1.875 inch (ID) Crestline Black PVC collar with threaded end
1.875 inch (OD) Crestline Black PVC endcap
1 inch (ID) Crestline Gray ABS pipe, threaded on both ends
1 inch (ID) Crestline White PVC endcap
1 inch (ID) Crestline White PVC collar

At this point in the design process we have narrowed the structural selection down to the approximate size, shape, material, number of joints, and weight.

- Possible Structural Configuration - once the plastic tubular framework was selected as the optimum structural material, the next logical step is looking at various robot arm configurations. The two fundamental configuration categories are revolute (rotational) joints and prismatic (sliding) joints. Since prismatic joints generally involve more sophisticated and heavier hardware, the choice was to go with 5 revolute joints.

Since practically all five-axis revolute-joint robots have the same general appearance, we went with the generic design in Figure 1.

- Choosing the size, speed, and type of driver motors (or actuators) :

-- type : for an inexpensive, medium-sized, lightweight robot, without a requirement to lift heavy loads at high speeds, the need for pneumatic or hydraulic actuators was rejected. Stepper motors have some advantages and disadvantages. They don't require an encoder and servo-control system in order to achieve precise positioning, but they are more expensive than dc electric motors, they are rather slow starting and moving, and they typically jump steps and so you lose positioning control. High-torque motors are rather expensive and are much heavier than dc electric motors. Ac induction motors are becoming more popular, but size and current availablility and data led to their rejection. Solenoids and exotic actuators are seldom used in robots, hence their rejection.

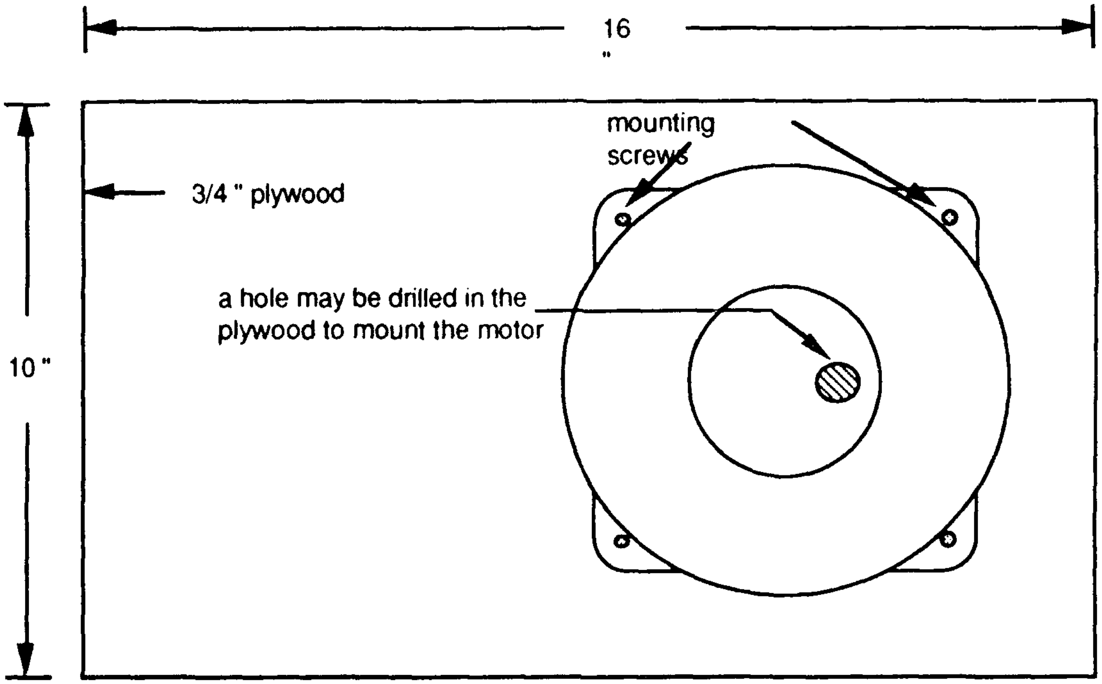

Figure 4: Top View of the plywood platform

The only type of actuator remaining is the dc electric motor. These have the advantage of being readily available, inexpensive, a wide variety of selections, and they come in small, lighweight sizes.

-- <u>Size</u> : one of the elements of robot design is the aesthetics or visual appearance of the machine. It was determined at the outset that if possible, all actuators would be mounted inside the arms so that the external appearance would not be cluttered with wines, moving parts and distracting units bolted onto the outside. With this in mind, there are obvious size limitations on the actuators. If the torso is built with the 3 inch (ID) pipe, then that limits the size of the actuator to less than 3 inches in diameter, if mounted internally.

Similarly, the upper and lower arms would generally get smaller and smaller, posing more space restrictions as we go out toward the end-effector (hand).

-- Speed : the following table lists common speeds found on typical educational robots:

Joint	Speed
Base	2 RPM
Upper Arm	2 RPM
Lower Arm	2 RPM
Wrist	13 RPM
Gripper	1 inch/second

These will be used as the baseline figures during the detail design phase.

- Choosing the end-effector - because this entails an in depth knowledge of the design of the lower arm and wrist, we'll wait until the detail design to discuss it. The only pre-conceived design is that the gripper will undoubtedly have two symmetrical fingers that pinch together evenly for grasping and releasing objects.

III. Detailed Design (Specific Design)

- Choosing the specific structural materials - from the preliminary design for the material choices and the size of the actuators, the logical choices for the structure configuration are shown in Figure 2.

Originally, the preliminary design showed a smaller diameter pipe for the lower arm, however, because of the need to put the actuators on the inside of the tube, the inside diameter needed to be at least 1.5 inches, as will be shown later.

The lengths of these structures is somewhat arbitrary. Since the overall dimensions were stated up front as approximately 3 feet in height and a working radius of 2 feet, the natural tendency was to keep the arms as long as possible, trying to stay fairly close to these desired lengths. With some trial and error, the final dimensions were as shown on the figure above. These may vary somewhat with little effect on the robot's performance. The general guidelines here were optimized balance and reach of the end-effector.

The placement of the joints at 3 inches from the endcaps was another trial and error arrangement that worked nicely for the counterbalance effect--the actuators placed inside the 3 inch ends of the lower arm sufficed, but for the upper arm the single actuator weight wasn't enough, so it was mounted on the outside of the endcap (for an increased lever arm) and an additional lead counterweight was added as well.

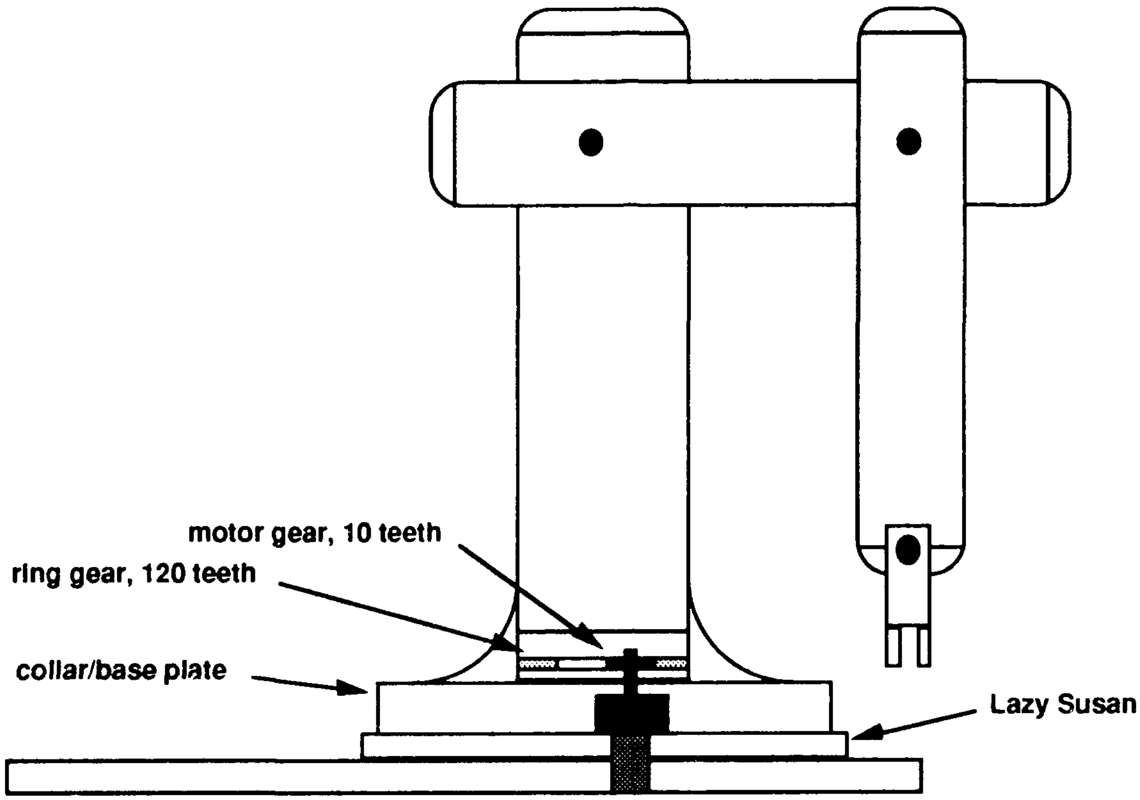

Figure 5: #1 Joint side view showing ring gear

- Base [Rotation] Joint (#1) - this first joint allows the arm to rotate about a vertical axis, giving the arm a much larger working envelope. To circumvent wire-wrap problems we simply limited the range of motion to 350 degrees by using a mechanical stop. By using brushes or similar devices, this joint could potentially be free to rotate completely around (360^0).

A modified Lazy Susan (turntable) is mounted on a 3/4 inch piece of plywood. As can be seen in Figure 3, the corners of the Lazy Susan have been cut off so that the collar/base plate will mount flush with the top rotating surface without the metal 'ears' protruding out. Use tin-snips, sheet metal shears, a hacksaw, or any other appropriate tool to cut off the excess sheet metal. Figure

4 shows the approximate placement of the modified Lazy Susan on the plywood platform.

Figure 5 shows a side view of the platform, the Lazy Susan, the collar/base plate, the base actuator, the ring gear, the drive gear, and the robot arm.

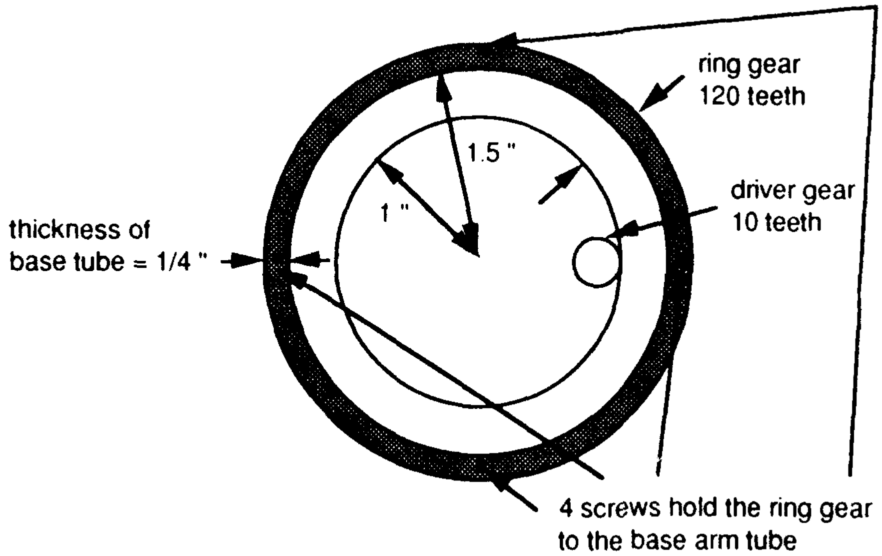

Figure 6: Joint #1 showing ring gear mount

Figure 6 shows how the ring gear is mounted to the bottom of the base tube with four screws, prior to the tube being inserted into the collar/base plate. The ring gear has an outside diameter of 3.5 inches, an inside diameter of 2 inches, and 120 teeth. The driver gear has 10 teeth, for a gear ratio of 12/1. To make a solid mount for the driver motor, a hole can be drilled vertically in the 3/4 inch plywood so that the motor fits snugly inside the hole. Screws should also be used to hold the motor more securely to the plywood. The motor wires should be routed either above or below the plywood, but in either case a small groove channelled in the wood suffices. Leave enough room to route all the other wires through this groove as well [wires to the other actuators, sensors, etc.].

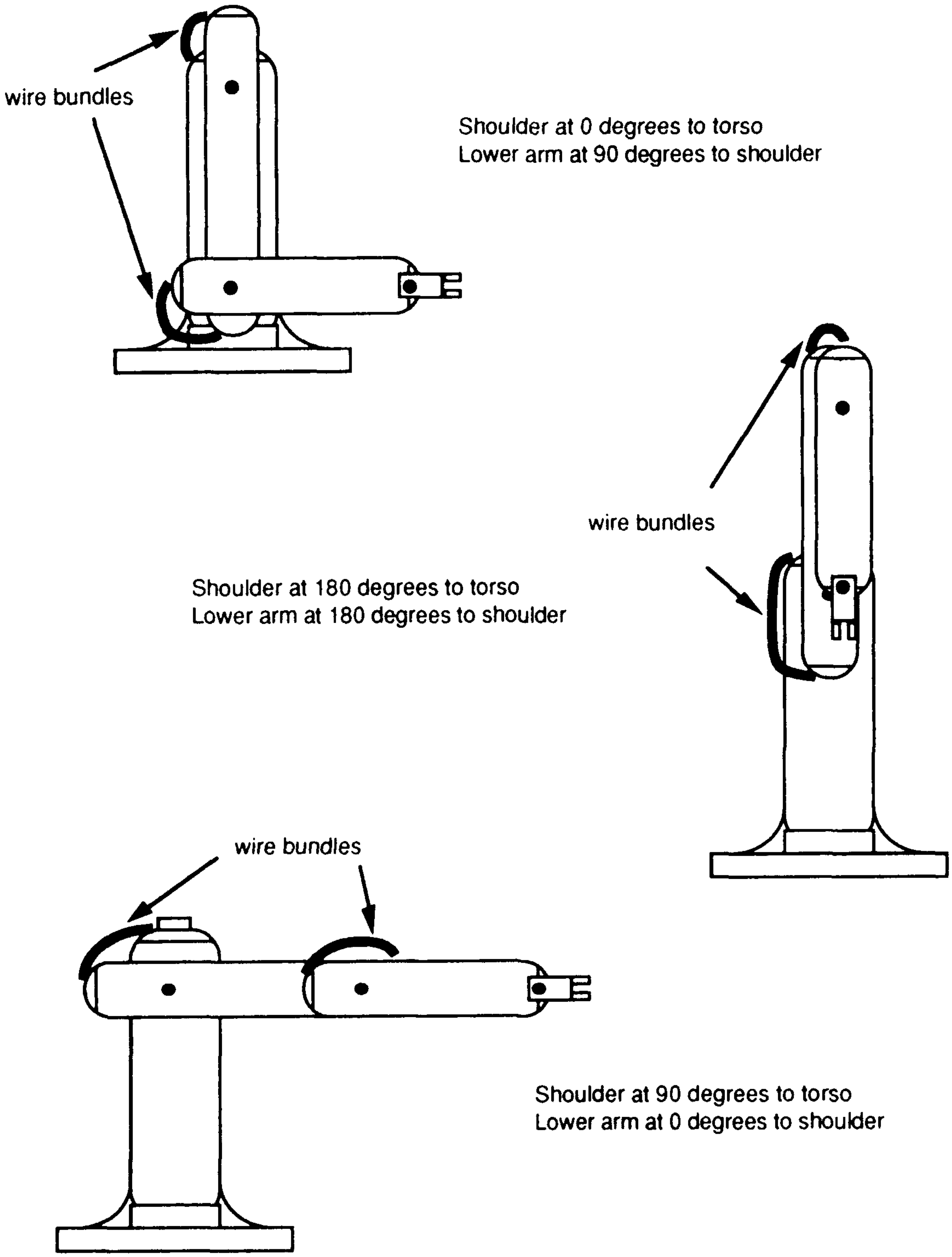

Figure 7: Shoulder & lower arm range of motions

- Calculations for the base (joint #1) gearing
  - Desired base speed = 2 RPM
  - Reversible motor with high torque and gear reduction
  - Small enough to fit between the Lazy Susan and the ring gear
  - A drive gear with 10 teeth (common) and a shaft speed of 24 RPM for motor G-35,116, the ring gear requires 120 teeth, as follows:

$$\frac{24 \text{ RPM (Motor)}}{2 \text{ RPM (arm)}} = 12 \text{ (gear ratio)}$$

$$x/10 = 12$$

$$x = 120 \text{ (teeth for ring gear)}$$

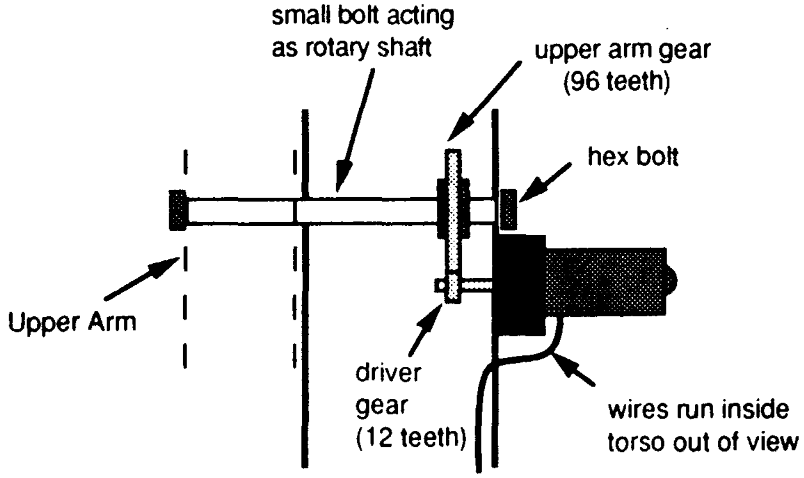

Figure 8: Side View of Joint #2 acutator

- Upper Arm/Torso Joint (#2) - this joint is akin to the shoulder joint on a person, except in this case the upper arm range of motion will be from 0° to 180° (see Figure 7).

Also shown in Figure 7 is the range of motions for the lower arm, and the various positions of the wire bundles.

The #2 joint actuator was mounted externally for two reasons. The motor mounting holes were oriented for just such a configuration and the exposed motor shaft made a better site for locating optical or magnetic encoders, rather than mounting them internally (see Figure 8).

Figure 9 shows the side view of the #2 joint, emphasizing the placement of a filed-off flat washer, installed for rigidity and smooth operation. By filing off the top and bottom of the washer and heating it with a Bunsen burner (or similar device), it can be melted into the plastic at the joint for a secure, stable platform, which the hex-bolt axle will be fastened to on the upper arm with lock washers.

Figure 10 shows a top view of the upper arm/torso joint, indicating the placement of the other pieces of hardware. The only flat washer that necessarily needs to be filed off is the one that is locked tight to the hexbolt shaft.

The way this joint operates is that the hex-bolt turns freely within the larger torso pipe, but is secured to the upper arm pipe. Therefore, when the motor (fastened to the torso) drive gear turns the output gear (fastened to the hexbolt by two lock nuts), the shaft rotates relative to the torso, and with it turns the upper arm.

- Calculations for #2 joint gearing
  - Desired upper arm rotation speed = 2 RPM
  - Reversible motor with high torque and gear reduction
  - A drive gear with 12 teeth and a shaft speed of 16 RPM for motor G-35,116; the output gear requires 96 teeth, as follows:

$$\frac{16 \text{ RPM (Motor)}}{2 \text{ RPM (arm)}} = 8 \text{ (gear ratio)}$$

$$x/12 = 8$$

$$x = 96 \text{ (teeth for output gear)}$$

- Upper arm/lower arm joint (#3) - this joint is akin to the human elbow, except that for the robot arm the range of motion is greater, or a full 180^0 (versus about 160^0 for most people). See Figure 7 for a depiction of the range of motion for this joint.

Figure 11 shows joint #3, as well as many details for joints #4 and #5. As stated earlier, the actuator for this joint is mounted on the proximal endcap to act as ballast and to reduce the weight out on the distal end of the upper arm (close to the lower arm). Figure 11 also shows how a thin, lightweight metal rod is used as a drive shaft from the #3 joint actuator to the set of 45^0 bevel gears, located at the #3 joint itself. To connect the drive motor shaft to the drive shaft a small section of 'heat shrink' plastic tubing will work well. This material can be found in most electronic stores and shrinks like a clamp when heated by a match or hot-air gun.

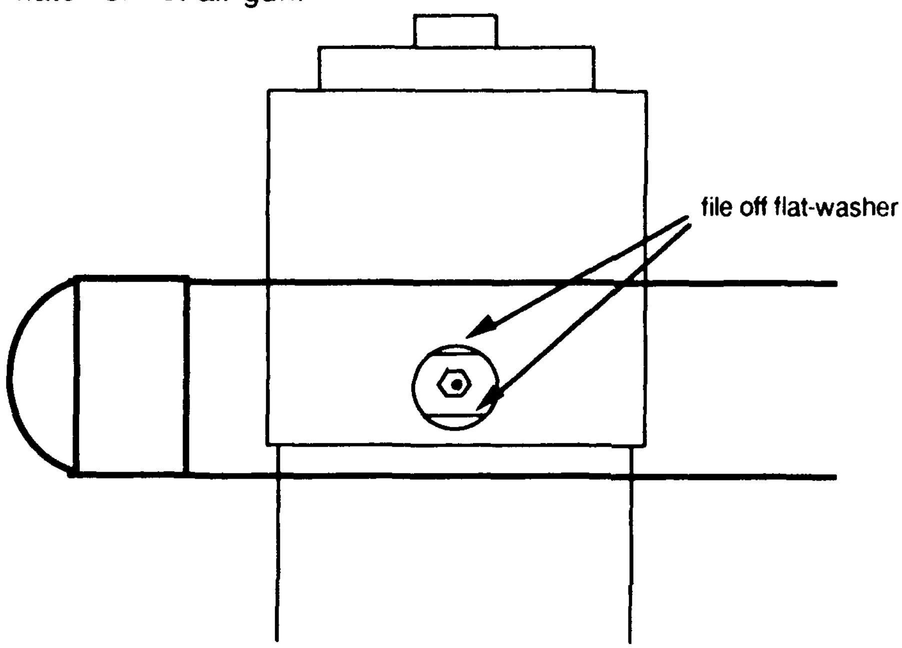

Figure 9: Side View of Joint #2 showing mounting washer

A similar setup, as in joint #2, was employed to fasten the hex-bolt to the lower arm (using lock washers).

- <u>Calculations for #3 joint gearing</u>
    - Desired lower arm rotation speed = 2 RPM
    - Reversible motor with high torque and gear reduction
    - A drive gear (45^0 bevel) with 12 teeth and a shaft speed of 16 RPM for motor G-35,116; the output gear (45^0 bevel) requires 96 teeth, as follows:

$$\frac{\text{16 RPM (Motor)}}{\text{2 RPM (arm)}} = 8 \text{ (gear ratio)}$$

$$x/12 = 8$$

$$x = 96 \text{ (teeth for output bevel gear)}$$

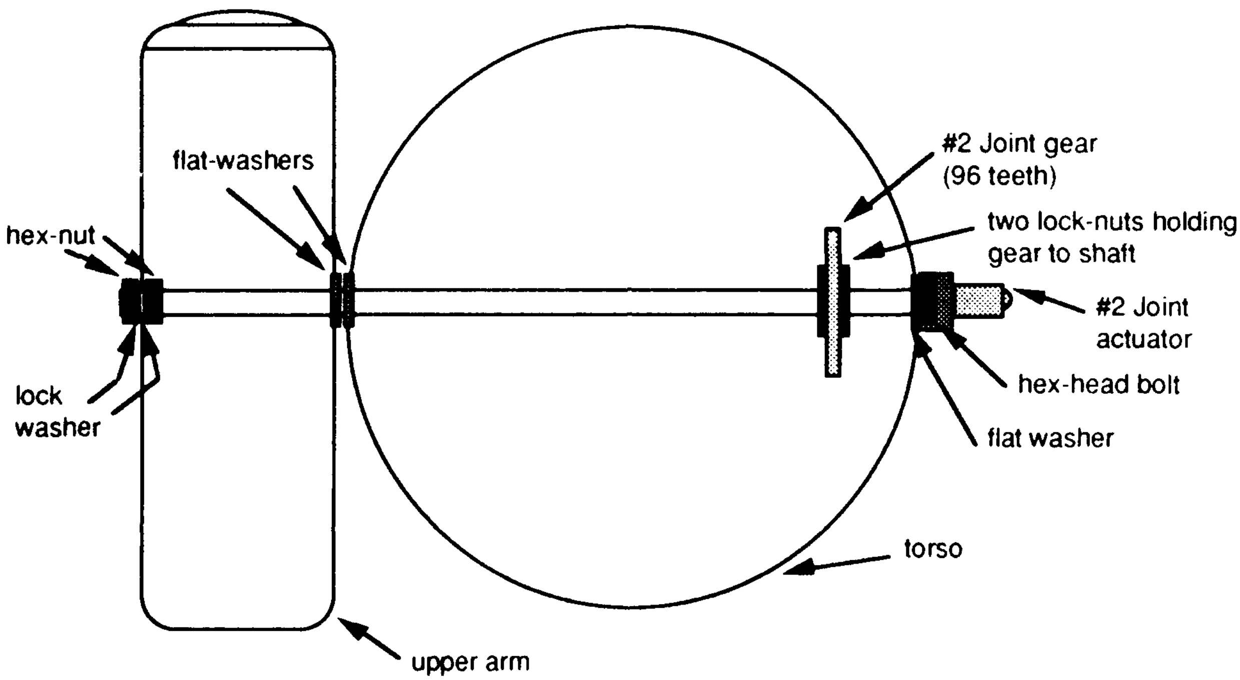

Figure 10: Top View of Joint #2 showing parts layout

- Wrist Rotation Joint (#4) - this joint is akin to the human wrist joint except in this case the robot wrist has no rotational restrictions, it can rotate a full 360^0 and beyond, while the human wrist rarely goes over 270^0 (see Figures 11 and 12).

Figure 11 shows how actuator #4 is located at the proximal end of the lower arm, along with actuator #5, primarily for counterbalance purposes. Actuator #4 uses the same type of setup that was used by actuator #3 in that it uses a thin rod drive shaft from the actuator to the wrist ring gear (similar in appearance to the base ring gear). The actuator is held in place by a C-clamp fastened to the inside of the lower arm.

Figure 12 indicates the location of the ring gear, with its 112 teeth. The driver gear has 6 teeth and both gears are made of lightweight plastic to cut down on weight and because they bear small loads.

- Calculations for #4 joint gearing
    - Desired wrist rotation speed = 13 RPM
    - Reversible motor with low torque and no gear reduction
    - A drive gear with 6 teeth and a shaft speed of 250 RPM for motor # R-20; the output gear requires 112 teeth, as follows:

$$\frac{250 \text{ RPM (Motor)}}{13 \text{ RPM (arm)}} = 18.67 \text{ (gear ratio)}$$

$$x/6 = 18.67$$

$$x = 112 \text{ (teeth for output gear)}$$

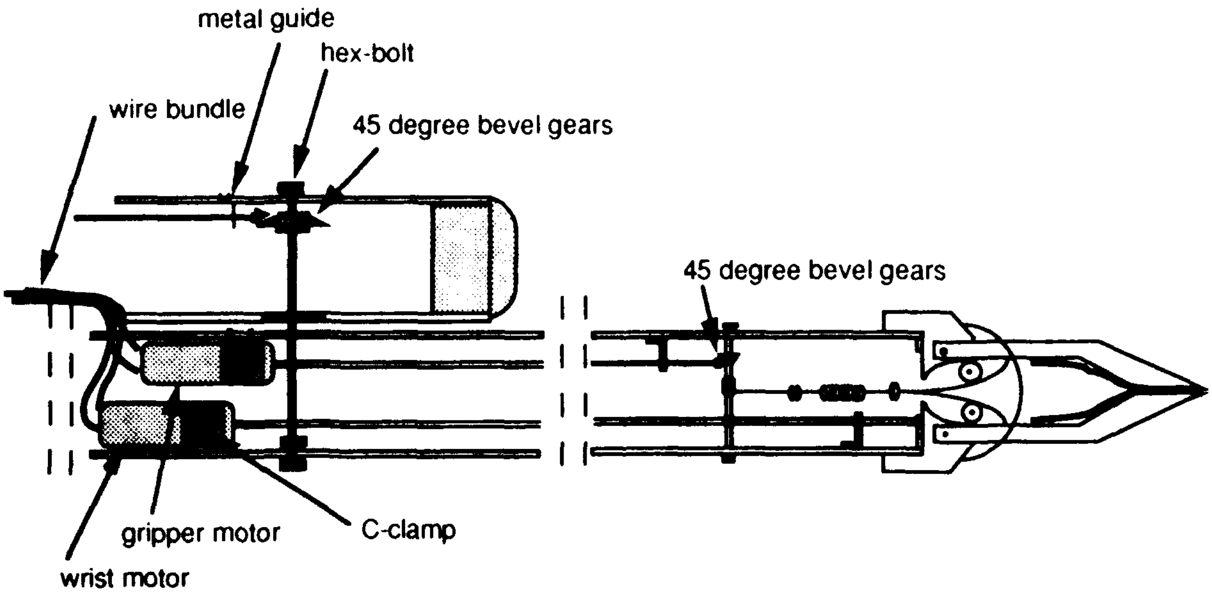

Figure 11: #3 Joint showing internal connections

- Gripper Joint (#5) - this joint is akin to the human hand except that the gripper has only two fingers, and they aren't composed of individually smaller joints like the human hand. Each gripper finger rotates at one focal point and is set up to remain at a fixed position anywhere between closed (0^0) and fully open (60^0), unless opened by force manually to remove or insert items during testing (see Figure 12).

The two torsion springs act to keep the grippers open, while the opposing closing force is supplied by acutator #5 (located close to actuator #4, see Figure 11), and the tension spring attached to a fishing line, which, in turn, is attached to a hex-head bolt. The whole gripper mechanism acts much like a motor-driven fishing reel, except that the movement of the gripper probably isn't fast enough to catch a fish.

The actuator is set up very much like actuator #3, utilizing the same drive shaft mechanism and 45^0 bevel gears. Because the wrist can rotate beyond 360^0, fishing line swivels are inserted on both sides of the tension spring to prevent any excess knotting on the fishing line itself. Many small robots have similar gripper designs.

In lieu of designing and building a prototype end-effector, there are many commercially available ones that are very sophisticated, yet fairly inexpensive.

- Calculations for #3 Joint gearing
    - Desired gripper closing/opening speed = 1 inch/second
        [translating to a fishing line speed of 0.5 inch/second
    - Free-spinning bolt diameter = 1/16 inch [circumference = 0.2 in.]

(1 Rev/0.2 in)(0.5 in/sec)(60 sec/min) = 150 RPM @ free-spinning bolt
        [yields a gear ratio of 250/150 = 1.7
    - If input bevel gear has 10 teeth then the output bevel gear needs 17 teeth (16 or 18 will suffice).

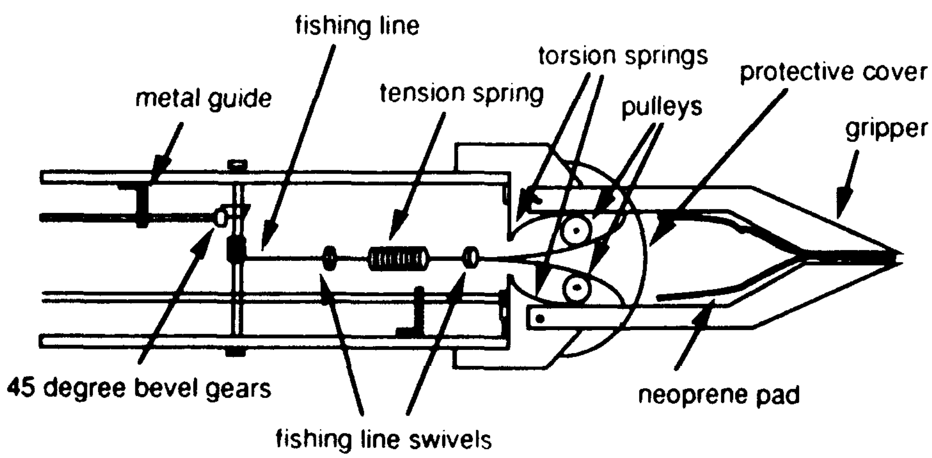

Figure 12: Joints #4 & #5 showing internal connections

IV. Conclusions - Part I of this report is that of the structural design. The follow-on reports will cover such topics as the electronics design, and the computer interface design. Hopefully, this report will enable colleges and universities to expand their present robotics programs, either by building many educational robots and starting robot labs, or by building new prototype research robots which have never been built before. Students with very little robotic experience can build their own robots for special projects. The possibilities are endless.

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Schiavone, J. J., "Super Armatron: An Inexpensive, Microprocessor-Controlled Robot Arm", Robotics Age, 6 (Jan 1984), 20-28.

Equipment Sources

Small Motors [# R-20]-------All Electronics Corp., P.O. Box 567, Van Nuys, CA 91408

Gears, pulleys-------Boston Gear, 14 Hayward St., Quincy, MA 02171

Geared Motors [G-35,116/Lazy Susan]-------Edmund Scientific Co., 101 E. Gloucester Pike, Barrington, NJ 08007-1380

PVC Pipes/bolts, nuts, washers, etc.-------Hugh M. Woods [or any large hardware store]

Springs-------Radio Shack stores [located in major cities everywhere]

Fishing line, swivels, weights-------Sporting goods stores [in general]