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Stiquito II and Tensipede: Two Easy–to-Build Nitinol–Propelled Robots

by

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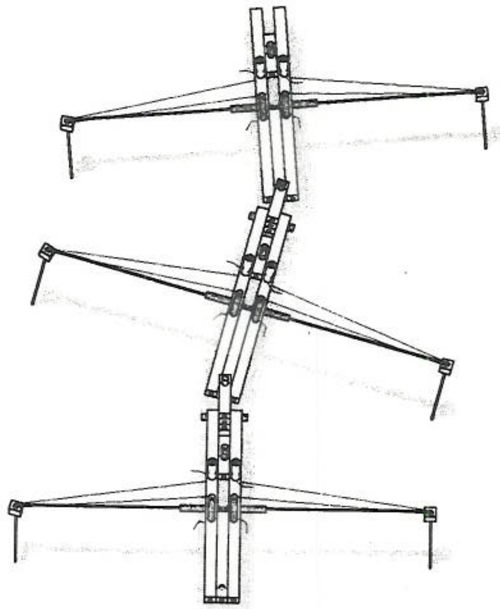

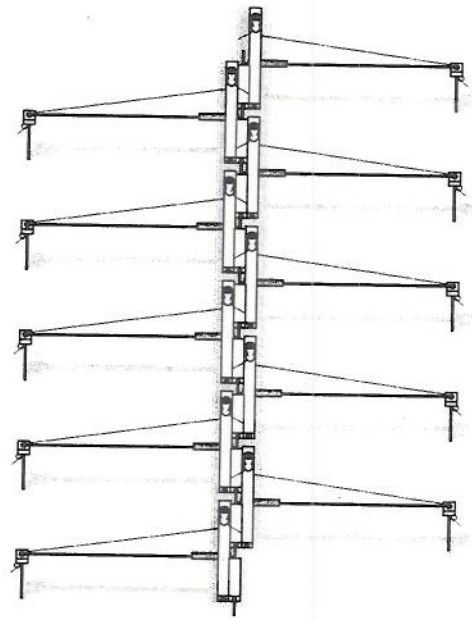

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Abstract

Stiquito II is an improved Stiquito: it is larger, modular, has an articulated body, two-degree-of-freedom legs, and carries more weight. Tensipede is a simple, modular robot centipede. Stiquito II and Tensipede are easier to build than Stiquito. Both are larger and easier to handle. The assembly sequences are simpler, and require only common, sturdy tools. A mistake typically affects only one module instead of the entire robot.

This technical report contains five major sections: a tutorial that introduces necessary skills as the reader builds a practice leg; the instructions to build Tensipede; the instructions to build Stiquito II; the instructions to build an interface to the parallel printer port on IBM PCs and compatible computers; and a programmer's guide with BASIC programs that demonstrate how to control each robot.

0. BUILDING STIQUITO II AND TENSIPEDE IS AS EASY AS 1-2-3

1. **Skim through the technical report** to familiarize yourself with its contents.
2. **Build the practice leg** to develop the skills you need to build either robot.
3. **Follow the instructions** to build either Stiquito II or Tensipede.

1. INTRODUCTION

Look for this helping hand. It will point to a hint to build a better robot.

1.1 A BRIEF HISTORY OF STIQUITO

Legged robots are typically large, complex, and expensive. These factors limited their use in research and education. Few universities could afford to construct robot centipedes, or 100 six-legged robots to study emergent cooperative behavior; even fewer could give each student in a robotics class his or her own walking robot.

The introduction of Stiquito in 1992 changed that. Stiquito was developed from a larger and more complex robot called "Sticky" because it looked like an insect commonly called a "walking stick." Sticky was very difficult to assemble and rather fragile, so a simpler design was sought. During this process multiple components were combined into single, robust, mechanical devices. The best example is Stiquito's leg, which carries the weight of the robot, acts as a leaf spring to provide bias force for the nitinol, and delivers the current that powers the nitinol actuator. A series of five small robots were eventually built that culminated in Stiquito.

Stiquito is a small, simple, and inexpensive six-legged robot that has been used as a research platform to study computational sensors, subsumption architectures, neural gait controllers, emergent behavior, and machine vision. Stiquito has also been used to teach science in primary, secondary, and high school curricula. As of 1994 more than 2500 Stiquitos have been distributed. However useful it has been during the past two years, hundreds of users have taken the time to point out the major flaws in the original design:

- it is hard to build, especially for young people or those not mechanically inclined,
- it requires costly, hard-to-find, or easy-to-break tools to assemble, and
- it cannot be easily adjusted to operate reliably.

These problems have been resolved, as far as is possible, in Stiquito II and Tensipede. These robots were developed to provide larger and more robust platforms for research at Indiana

University's Analog VLSI and Robotics Laboratory, and yet be easy enough to build that they could be used educationally. Even though both robots are made from simple modules, if you have never built models, assembled electronic circuits, or used hand tools to cut plastic, bend wire or drill small holes, I urge you to build the practice leg before attempting to build your robot. Care and patience are still needed to assemble a Stiquito II or a Tensipede, but it is easier than building the original Stiquito.

Educational use of Stiquitos depends on their low cost, so a great deal of attention was given to making the improved design inexpensive. As a result, the Stiquito II kit is the same price as the original kit and technical report. The Stiquito II kit with the parallel port interface parts and this technical report costs as much as two of the original Stiquito kits. The cost reduction is possible because less labor is required to pack the kit, and the manual controller, hook-up wires, and 9-volt battery connector have been eliminated.

1.2 A BRIEF COMMENT ON STIQUITO FROM THE AUTHOR

In nature Stiquito and Stiquito II would be greedy, blind, crippled, retarded ants. They consume electricity voraciously; they have no sensors or effectors (at least as as described in this technical report); their legs lack the numerous degrees of freedom of an ant; their controller, an IBM personal computer, is overwhelmingly large, clunky, and incapable compared to the ganglia that serve an ant (at least to accomplish an ant's tasks).

So why build Stiquitos?

Well, *I* build them because they are simple, they are fun, and they let me investigate robotics without getting a million-dollar grant. I build Stiquitos because I have yet to construct anything the size of an ant that has the capability of an ant. But...I'm working on it.

I encourage all readers of this report to improve on Stiquito, and assure you that if you build a better ant-like robot, I'll be standing in line to get one.

1.3 ABOUT THIS TECHNICAL REPORT

This technical report was written on a Macintosh SE computer with a Radius Accelerator and Radius Two-Page (monochrome) Display. Microsoft Word 4.0D was used for the text and page layout, and Canvas 3.0.6 was used to generate the illustrations. The illustrations are composed of objects from which a "virtual" robot was assembled. To preserve the accuracy of the figures, many are rendered as bitmaps.

The report is structured to help the beginning robot builder. After conducting numerous Stiquito workshops, and receiving more than 5,000 electronic mail messages about the robot and the first technical report (TR 363a), these steps were taken to improve the presentation:

- Large figures that illustrate the desired appearance of each major component are presented at the beginning of the section that describes how the component is built. This helps the builder understand the steps in the assembly process, and visualize the relationships between the parts and the finished component. The illustration of the component is repeated at reduced size to mark the end of the assembly. This helps partition the assembly process into related groups of steps.

- *Cues* — small pictures — are used to focus the builder's attention during each step of the assembly. Cues warn the builder in advance of common mistakes, point out critical steps in the assembly, identify which parts must be made precisely, or indicate when the assembly can tolerate a little sloppiness. Cues are my attempt to share my robot-building experience with the reader.

- The names of the parts have been chosen to emphasize the modularity of the design. While there is no need for complex part numberings — after all, Stiquito II is not a space shuttle — there is still a need to avoid cumbersome and lengthy descriptions of a specific (and usually very small!) part. All parts are made during the first steps in the assembly process. This seems to reduce stress among first-time builders by literally breaking the apparently-complicated assembly sequence into simple, tangible parts.

If you, the reader, encounter mistakes in this report, find a better way to assemble the robot, or develop an improved or new and innovative nitinol-actuated robot, I encourage you to either post your results to the stiquito newsgroup, **stiquito@xcf.berkeley.edu**, or send me electronic mail at **stiquito@cs.indiana.edu** or jwmills@cs.indiana.edu. The first two addresses listed are those that will receive reasonably prompt replies.

If you have a question, and have read the relevant parts of this report, post your question to the mailing list. There are many people who have successfully built Stiquitos out there, and they are typically friendly and willing to help you. So am I, but the volume of e-mail directed to me means that you risk having your messages go unanswered. Please post to the list!

2. COSTS, PARTS, AND MATERIALS

2.1 COST

The 1994 costs of Stiquito II kits in volume (500 or more) are listed:

1 ea	Stiquito II kit including technical report	$15
1 ea	Stiquito II kit, technical report, and parts for IBM PC parallel interface	$20

2.1.1 MATERIALS

Materials alone for a single robot cost about $17. Nitinol wire is available in a minimum length of one meter for $10. It is the most expensive part of the robot. The pro-rated cost of materials used to construct Stiquito II in volume (500 or more) is less: $10.96 each in 1994.

Amount	Cost	Part Number	Item
30 in	1.00	Plastruct ST-4	$^1/_8$" square ABS plastic rod
24 in	.50	K&S Engineering No. 117	$^1/_{16}$" o.d. copper tube
12 in	.30	K&S Engineering No. 102	$^1/_8$" o.d. aluminum tube
36 in	.15	K&S Engineering No. 501	.032" music wire
3 in	.01	n/a	28 ga copper wire ('telephone wire')
1500 mm	9.00	Dynalloy .004" Dia. 70°C	.004" (100μm) nitinol wire (*Flexinol®*)

The plastic stock is available from Plastruct, Inc. (tel. 818-912-7017), 1020 S. Wallace Place, City of Industry, CA, 91748. Plastruct offers a 30% educational discount to instructors and schools ordering on a purchase order. The aluminum tubing and music wire are available from K&S Engineering (tel. 312-586-8503), 6917 W. 59th Street, Chicago, IL, 60638. Hobby shops carry these products, also. Flexinol® can be ordered in lengths of one meter or more from Dynalloy, Inc. (714-476-1206), 18662 MacArthur Blvd, Suite #103, Irvine, CA, 92715; or from Mondo•Tronics, Inc. (415-455-9330), 524 San Anselmo Ave., #107-70, San Anselmo, CA, 94960. Mondo•Tronics, Inc. also sells Stiquito II kits.

2.1.2 TECHNICAL REPORT, ADDITIONAL PARTS, POSTAGE, ADMINISTRATIVE CHARGES

If you purchased a Stiquito II kit, your cost included these additional items or services:

Amount	Cost	Part Number	Item
1 ea	1.50	IU Technical Report 4xx	Instructions to build Stiquito II
1 ea	.27	n/a	Tyvek™ mailing envelope
1 ea	1.00	n/a	Postage (varies with destination)
1 ea	1.00	n/a	Labor (approximately)

If your kit contained the IBM PC and compatible computer parallel port interface the cost included:

Amount	Cost	Part Number	Item
1 ea	1.19	n/a	Printed circuit board
2 ea	1.20	DS2001	Darlington high-current driver
2 ea	1.44	74LS373N	Octal tri-state D flip-flop
1 ea	.18	G5102	5-element 1kΩ resistor network
1 ea	.80	225M-ND	DB-25 solder cup male connector
24 in	.38	HC09G-100-ND	9-wire gray ribbon cable

The interface electronics are available from Digi-Key, (800-344-4539), 701 Brooks Avenue South, P.O. Box 677, Thief River Falls, MN, 56701-0677, or other mail-order vendors. The printed circuit board is available from Indiana University, or can be made locally by copying the illustration shown in section 7.2 and using it as a mask to etch a copper-clad printed circuit board.

2.1.3 HOOK-UP WIRE NOT PROVIDED

To keep the cost of Stiquito down, the wire used to connect the robot to the interface card is not provided. Any thin wire, such as magnet wire or wire-wrap wire can be used. Both kinds of wire are readily available at radio and electronics supply stores, such as Radio Shack.

3. TOOLS AND RULES

3.1 TOOLS

The following tools are **required** to build Stiquito II:

- needlenose pliers
- wire cutters
- rubber bands (used to clamp parts, and grip objects with pliers without holding them)
- small hobby knife (X-Acto™ type)
- pin vise with 1/16" drill bit
- 320 grit fine sandpaper
- model cement (methyl ethyl ketone; also contained in waterbed patch cement)
- two AA batteries and holder

The following tools are **optional**:

- locking forceps (hemostats)
- ruler marked in millimeters (optional because illustrations are drawn life-size)
- c-clamps (instead of rubber bands)
- Dremel Moto-Tool with 1/16" drill bit

3.2 GROUND RULES

Look for these *cues* (small pictures) as you follow the instructions to build your robot. They will warn you in advance of mistakes you shouldn't make, point out critical steps, identify which parts must be made precisely, or tell you when a little sloppiness is OK.

Cue	Meaning
✓	**Do** take the action indicated. No particular precision is required.
×	**Don't** do this! It is a mistake.
💧	**Apply plastic cement** to the part surfaces marked with a heavy dotted line (▪▪▪▪▪▪▪▪).
⊟	**Work as carefully as you can.** The dimensions are critical. Stay within 0.5 mm or less of the required measurement.
⌶	**Some variation is allowed.** The dimensions are not critical. Stay within one or two millimeters of the specified measurement.
●	**A tight fit is necessary.** A loose or sloppy fit will prevent your robot from working well, and may keep it from working at all.
◉	**A loose or sloppy fit is OK.** Your robot will work fine if the fit is not tight.

PRECAUTIONS

✓ Always follow the manufacturer's instructions when using a tool.

✓ Wear safety glasses to avoid injury to your eyes from broken tools, or pieces of plastic or metal that may fly away at high velocity as a result of cutting or sawing. Be especially careful when cutting music wire with wire cutters (the cut wire can be forced into your finger, for example).

✓ Use motorized tools such as Dremel Moto-tools carefully. Motorized tools are not needed to construct Stiquito, although they are helpful.

✓ Use a piece of pressboard, dense cardboard, or wood to protect your work surface.

× **Avoid inhaling the fumes of model cement.**

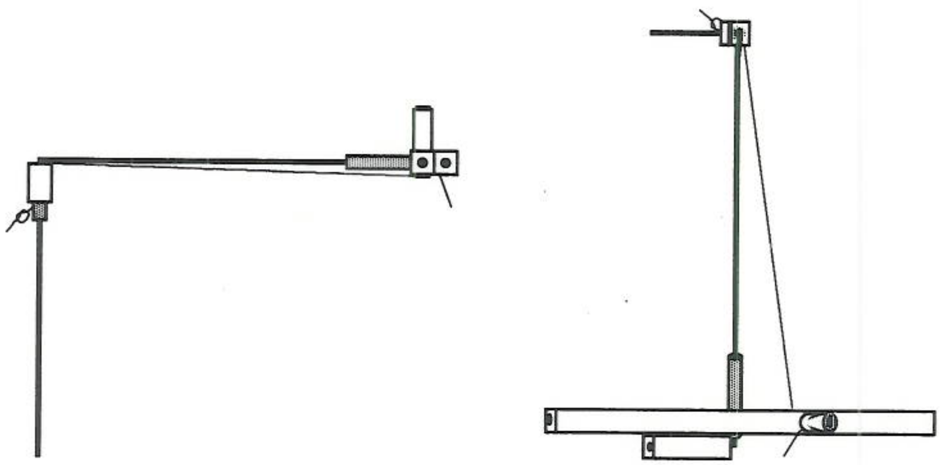
✓ Work in a well-ventilated area.

4. PRACTICE LEG

You can **improve the quality of your robot** by building this practice leg first.

This section introduces the skills to build either robot as you build a nitinol-actuated leg. The kit includes extra material to build the leg, and allow for mistakes building Stiquito II or Tensipede.

This is what the completed leg will look like from the front and the top.



Let's begin now.

Keep track of your progress by **crossing off each step as you complete it.** Mark through the little picture to the left of each step with a highlighter or colored marker to show that you have finished it.

4.1 MEASURE AND CUT PARTS

The first two skills you will learn are used to make parts from the raw materials provided in the kit.

4.1.1 MEASURING

A ruler is optional because critical illustrations that provide dimensions are drawn to scale. Use these illustrations to measure your parts, locate holes, etc.

"Measure twice, cut once" to prevent most mistakes. If you choose not to use the illustrations, use any metric ruler marked in millimeters. Look directly down at the ruler so that your measurement is not affected by your viewing angle. Mark the location by scoring the tube or rod lightly with the knife.

4.1.2 CUTTING PLASTIC ROD AND METAL TUBING

Before cutting, check that your fingers are not in the way of your knife, and that a slip of the knife will not damage anything nearby. Direct the knife away from yourself to avoid injury. Cut tubing and plastic rod by scoring it firmly around the outside of the tube or rod. Score plastic rod by rocking the knife back and forth on each side, working your way around all four sides. Score tubing by slowly rolling the tubing under the knife while pressing down on it firmly. After scoring the tube or rod, bend it back and forth gently to snap it at the score.

4.1.3 CUTTING MUSIC WIRE

Cut music wire with wire cutters. Use heavy duty wire cutters if you have them, otherwise cut the wire near the bottom of the cutters (**not** at the tip, where the wire cutters are more easily damaged). Be careful, as the cut wire may shoot away from the cutters. Hold the wire along its length, **not** by its end, or the cut wire may be forced into your finger.

Now measure and cut the following parts for each assembly. The 'cues' in the part column tell you how carefully to make each part.

4.1.4 LEG SEGMENT

qty	length	material	part	illustration
1	50 mm	$^1/_4$" ST-4 plastic rod	☐ leg rod	
1	10 mm	$^1/_4$" ST-4 plastic rod	☐ leg holder	
1	100 mm	.032" steel music wire	☐ leg	(see below ↓)
1	10 mm	$^1/_{16}$" o.d. copper tube	☐ leg bushing	

4.1.5 ACTUATOR

qty	length	material	part	illustration
1	75 mm	.004" 70°C nitinol wire	☐ actuator wire	(see below ↓)
1	5 mm	$^1/_4$" ST-4 plastic rod	☐ knee clamp holder	
2	8 mm	$^1/_{16}$" o.d. copper tube	☐ actuator clamp	
1	5 mm	$^1/_8$" o.d. aluminum tube	☐ outer clamp	

4.2 PREPARE THE LEG ROD

Drilling and deburring are needed to make holes to hold actuators and legs.

4.2.1 DRILLING

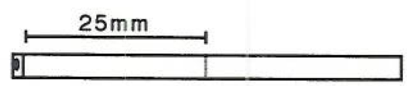
Mark the location of holes by lightly scoring the plastic body segment. Start the hole by twisting the point of the knife blade back-and-forth at the location of the hole. This makes a shallow hole to hold the drill bit in place. Brace the part on a sheet of scrap wood or plastic to protect the work surface. Hold the pin vise perpendicularly to the part when drilling, and twist the bit back-and-forth with a short-but-firm motion, applying moderate downward pressure. If the drill bit sticks, pull it out then begin again. Be careful not to drill through the material used to brace the part. After making the hole, twist the bit in it as you slide the bit into and out of the hole. This will ensure that the hole is the correct diameter, cylindrical, and smooth inside. Blow into the hole to remove any scraps of material left inside.

4.2.2 DEBURRING

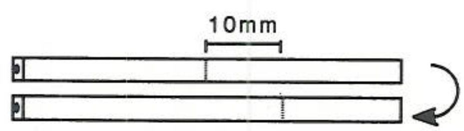
Cutting and drilling may leave rough edges ("burrs") on some parts. Remove the burrs by sanding the rough edge with fine sandpaper (320 grit), by trimming the burr with a small knife, or by lightly abrading the part with a drill bit held in a pin vise. Leaving burrs on parts, especially clamps, may cause the nitinol actuators to break. Parts that are press-fitted may bend or break during assembly if not deburred.

Now prepare the leg rod.

- Measure 25 mm from one end of the leg rod. This is the location of the leg hole.

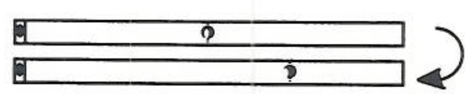


- ✓ Mark the location of the leg hole by lightly scoring it with the knife. This also defines the top of the leg rod.
- Measure 10 mm further to the right of the center of the leg rod, then turn the rod on its side. The actuator hole is located here, on the side of the leg rod.



- ✓ Mark the location of the actuator hole by lightly scoring the leg rod with the knife.
- ✓ Start the leg hole and actuator hole by twisting the tip of the knife back and forth in the middle of the leg rod at each score.

- Each hole should be centered in the width of the leg rod (the middle of the score).
- Drill the leg hole and the actuator hole.



- ✓ Debur and clean out any scrap by blowing through the holes, and running the drill bit in and out through the holes.

4.3 BEND THE LEG

Bending music wire makes joints that retain the leg and the actuator wires.

4.3.1 BENDING

All bends in the music wire are 90° angles. Use a pair of needlenose pliers and hold the music wire near the joint of the pliers (at the thick part) to get a good grip as you make the bend. Don't straighten out the wire if a bend isn't quite perfect. Adjust the bend by twisting it. Leave it alone if it is almost at 90° unless a later step in assembly requires a better bend.

Now bend the leg.

☐ Bend the leg in a sharp 90° bend...

☐ ... about 5 mm from one end.

4.4 ATTACH THE LEG AND LEG HOLDER TO THE LEG ROD

Tubing must be smoothed out after it is cut and before it is inserted into the plastic rod. This allows the tubing to be easily press-fitted without enlarging the hole into which it is inserted.

4.4.1 SWAGING

Roll the ends of cut tubing back and forth over the top of the work surface while pressing on them with a hard flat object, like the back of a metal ruler. This will remove the 'lip' that is left after the tubing has been scored and snapped apart, and that prevents it from being press-fitted easily.

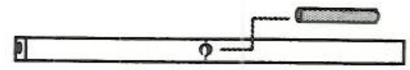
4.4.2 PRESS-FITTING TUBING INTO PLASTIC ROD

Push firmly but carefully to insert the tubing into plastic rod. Press-fitting does not require excessive pressure. If you push hard and nothing happens, debur the part and hole, and swage the tubing again. The tubing should not fall out of the hole holding it; if it does, the hole is too large. Discard the part with the hole and make a new one.

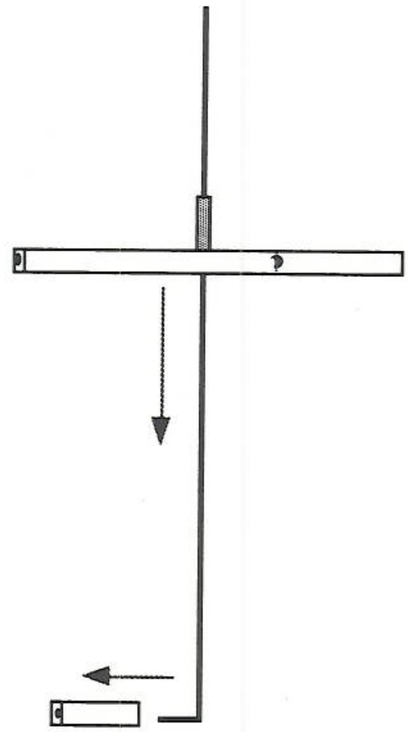
4.4.3 GLUING

Pieces of plastic rod are glued together to fabricate larger components like body segments and c-joints. Model cement is used to bond plastic parts to each other. Do not use too much cement or the plastic may "melt." Let the plastic get tacky before pressing parts together. Hold parts together for 15 seconds to bond them, then clamp the assembly and let it dry at least two hours before cutting or drilling it.

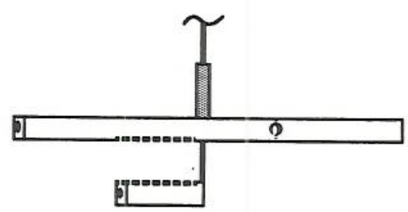
Now attach the leg and leg holder to the leg rod.



- ✓ Swage the leg bushing.
- ● Insert the leg bushing into the leg hole.
- ● Insert the long length of the leg into the leg bushing.
- ● Insert the short 5 mm length of the leg into the hole in either end of the leg holder.
- ✓ Push the leg rod along the leg until it touches the leg holder.
- × Do **not** continue if the leg rod and the leg holder aren't parallel. The bend in the leg is not 90°. Pull the leg out of the leg rod and the leg holder, adjust the bend, then insert the leg and try again.

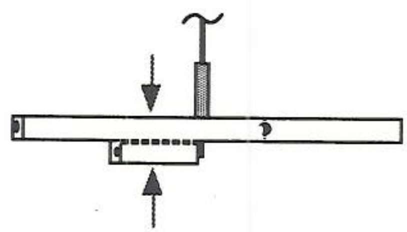


- Pull the leg rod and the leg holder apart about 10 mm, and...
- ...apply plastic cement to the inner face of the leg rod and the leg holder.
- ✓ Let the glue get tacky, then push the leg rod and the leg holder back together.



- Align the leg rod with the leg holder so they are in the same plane.
- Lightly apply some plastic cement along the joints between the body segment sides and the leg pair holder. No gap should be visible. The joint should be even and smooth.

- ✓ Clamp the leg assembly.



Let the leg assembly dry for **at least** two hours. OK, when you make the leg assembly you can get away with waiting just 15 minutes. But don't make a habit of it.

4.5 ATTACH THE NITINOL ACTUATOR

The parts of the nitinol actuator must fit tightly without any 'play,' or the nitinol will waste most of its force taking up the slack due to sloppy assembly. Take extra care during these steps.

4.5.1 ATTACHING ACTUATOR CLAMP TO PLASTIC ROD

This is the same as press-fitting tubing into the plastic rod.

4.5.2 REAMING OUT THE KNEE CLAMP HOLDER

Reaming is the same as drilling, but is used to enlarge an existing hole. Reaming is used to enlarge the hole in the center of the ST-4 plastic rod so that it is large enough to hold the actuator clamp.

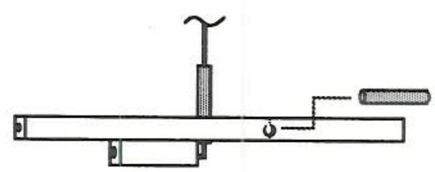
4.5.3 CLAMPING NITINOL

Smooth and swage the ends of the copper actuator clamps to avoid breaking the nitinol. Apply tension to the nitinol using the locking forceps or needlenose pliers whose handles have been wrapped tightly with several rubber bands. Keep the nitinol taut until it is held tightly between the outer wall of the actuator holder and the inner side of either the aluminum outer clamp or the plastic knee clamp holder. You can remove the outer clamp and retighten the nitinol if necessary.

Now attach the nitinol actuator to the leg rod and the leg.

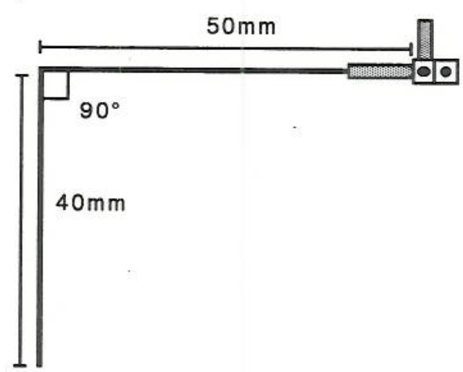
✓ Swage the actuator clamp.

● Insert the actuator clamp into the actuator hole.

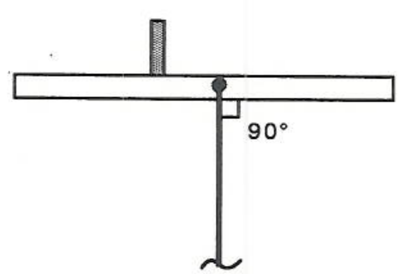


☐ Bend the free end of the leg down in a sharp 90° bend, toward the side of the leg rod **opposite** the actuator clamp...

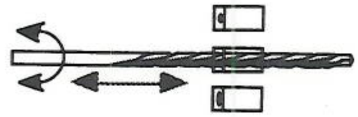
☐ ... about 50 mm from the leg rod. This will leave about 40 mm from the knee to the foot.



☐ Twist the free end of the leg right or left until it makes a 90° angle with the leg rod when viewed from the side.



☐ Use the drill to ream out (enlarge) the hole that runs through the center of the knee clamp holder.

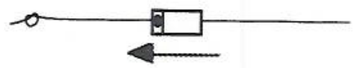


✓ Grasp the knee clamp holder with the needlenose pliers so that the drill bit does not slip.

✓ Ream the entire length of the hole.

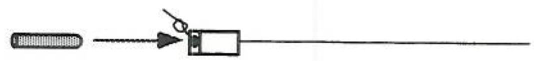
☐ Tie an overhand knot in the nitinol actuator and pull it finger-tight so it is about 3 mm from one end of the nitinol actuator.

● Insert the free end of the actuator into the knee clamp holder and slide the knee clamp holder to the knot.



✓ Swage the actuator clamp.

● Press the actuator clamp into the knee clamp holder at the hole nearest the knot.

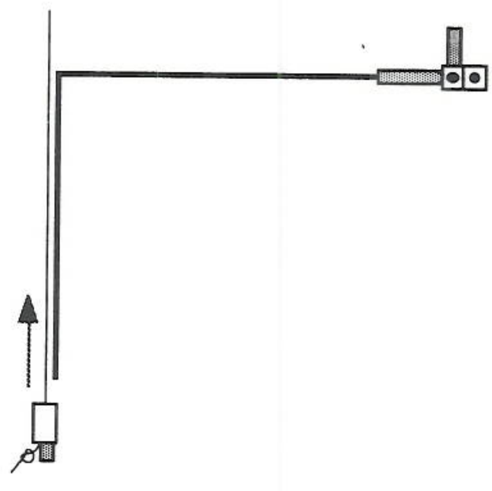


✓ Push it all the way through the knee clamp holder. The actuator clamp will protrude from the end of the knee clamp holder.

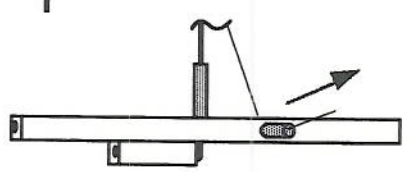
× Do **not** let the nitinol actuator cross over the end of the actuator clamp, or it will be cut off.

× Do **not** use excessive force to press-fit the actuator clamp, or the nitinol will break now, or after a few activation cycles. If it is difficult to press-fit the actuator clamp into the knee clamp holder, ream out the knee clamp holder again and swage the ends of the actuator clamp.

● Slide the knee clamp assembly onto the end of the leg. The free end of the nitinol actuator must exit the knee clamp assembly facing **toward** the actuator clamp.



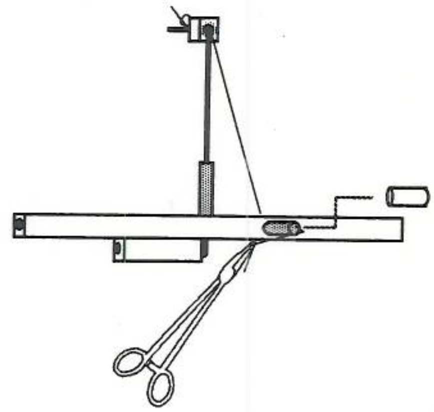
● Now thread the free end of the nitinol actuator through the flush end of the actuator clamp and out its top.



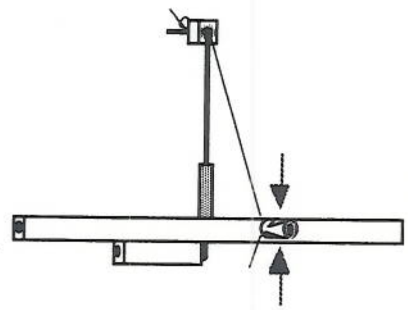
✓ Grip the free end of the actuator with the locking forceps and let it hang freely to provide tension to the actuator.

● Press-fit the aluminum outer clamp over the nitinol and the actuator clamp. It is a snug fit.

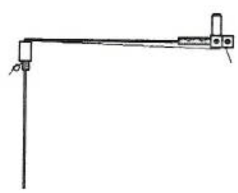
✗ Do **not** use excessive force to press-fit the outer clamp, or the nitinol will break. If it is difficult to press-fit the outer clamp, ream out the inside ends slightly with the knife.

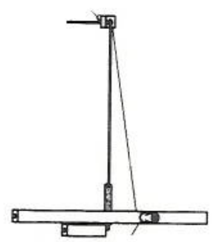


⊓ Use the wire cutters to **gently** crimp the outer clamp about halfway down its length so that the nitinol actuator is held tightly.



The completed leg will look like this from the front and the top (reduced size illustration).



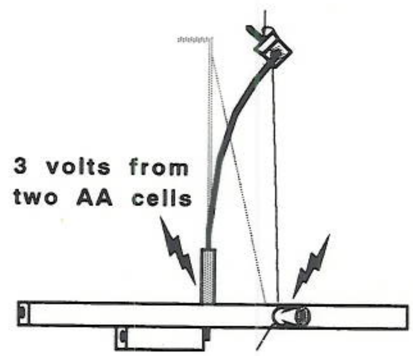


✓ Apply 3 volts from the two AA cells at the points indicated, and your leg should bend toward the actuator clamp.

✗ Do **not** use more than 3 volts, or the nitinol actuator will snap.

✗ Do **not** apply power to two points close together on the nitinol wire, or the nitinol actuator will overheat, and melt or break.

✗ Do **not** touch a heated nitinol wire. You could burn yourself.



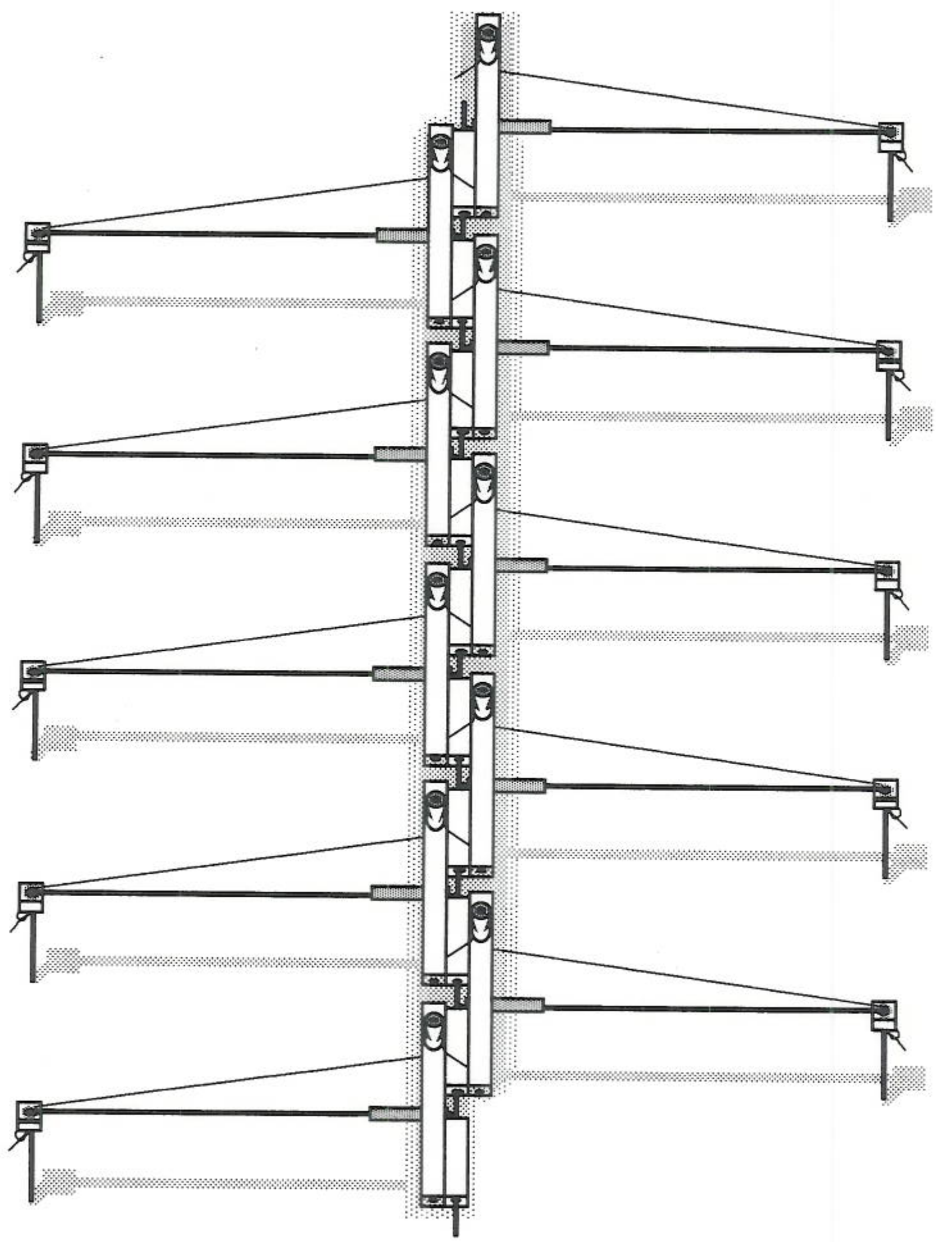
Congratulations! You have successfully built the practice leg. **Take a break**, then you can continue by building either Stiquito II or Tensipede.

5. TENSIPEDE: A ROBOT CENTIPEDE BASED ON THE PRACTICE LEG

Your kit contains enough material to **build either Tensipede or Stiquito II but not both!** You must choose which robot you want to build.

You can build a number of interesting robots based on the practice leg. As an example, here is the design for Tensipede, a ten-legged robot centipede that high-school junior John Dankanich of Hammond, Indiana, assembled and tested during his summer internship at Indiana University's Analog VLSI and Robotics Laboratory.

If you work carefully, your finished Tensipede will look like this:



Start by making the required number of parts to build 10 legs that use a shorter leg rod.

5.1 LEG SEGMENT

qty	length	material	part	illustration
10	25 mm	$^1/_4$" ST-4 plastic rod	☐ leg rod	
10	10 mm	$^1/_4$" ST-4 plastic rod	☐ leg holder	
10	100 mm	.032" steel music wire	☐ leg	(see below ↓)
10	10 mm	$^1/_{16}$" o.d. copper tube	☐ leg bushing	

5.2 ACTUATOR

qty	length	material	part	illustration
10	75 mm	.004" 70°C nitinol wire	☐ actuator wire	(see below ↓)
10	5 mm	$^1/_4$" ST-4 plastic rod	☐ knee clamp holder	
20	8 mm	$^1/_{16}$" o.d. copper tube	☐ actuator clamp	
10	5 mm	$^1/_8$" o.d. aluminum tube	☐ outer clamp	

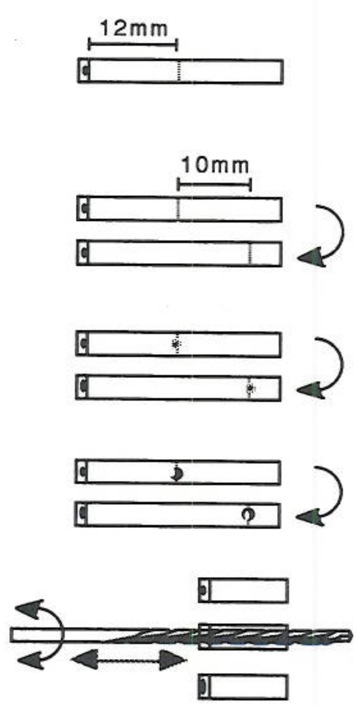
5.3 SPINE

qty	length	material	part	illustration
1	150 mm	.032" steel music wire	☐ spine	(see below ↓)

5.4 MAKE FIVE LEGS

Note the changes: the leg rod is shorter, and the leg holder must be reamed out to hold the spine.

- ☐ Measure 12 mm from one end of the leg rod. This is the location of the leg hole.
- ✓ Mark the location of the leg hole by lightly scoring it with the knife.
- ☐ Measure 10 mm further to the right on the leg rod, then turn the rod on its side. The actuator hole is located on the side of the leg rod.
- ✓ Mark the location of the actuator hole by lightly scoring the leg rod with the knife.
- ✓ Start the leg hole and actuator hole by twisting the tip of the knife back and forth in the middle of the leg rod at each score.
- ☐ Each hole should be centered in the width of the leg rod (the middle of the score).
- ☐ Drill the leg hole and the actuator hole.
- ☐ Use the drill to ream out (enlarge) the hole that runs through the center of the leg holder.
- ✓ Debur and clean out any scrap.



✓ Make five (5) legs with the shorter 25 mm leg rod.

✓ **All other parts are the same as for the practice leg.**

✓ **Follow the instructions to make the practice leg.**

✓ When you are through, your five legs should look like this from the top.

5.5 MAKE FIVE MIRROR-IMAGE LEGS

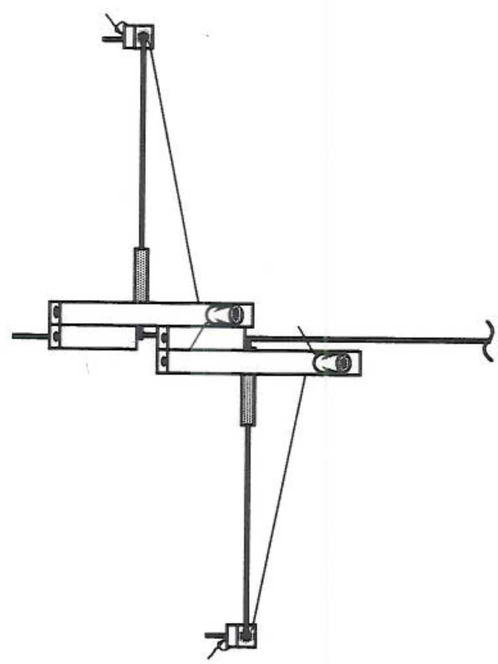
✓ Make five (5) legs with the shorter leg rod that are **mirror images** of the first five.

✓ When you are through, your five mirror-image legs should look like this from the top.

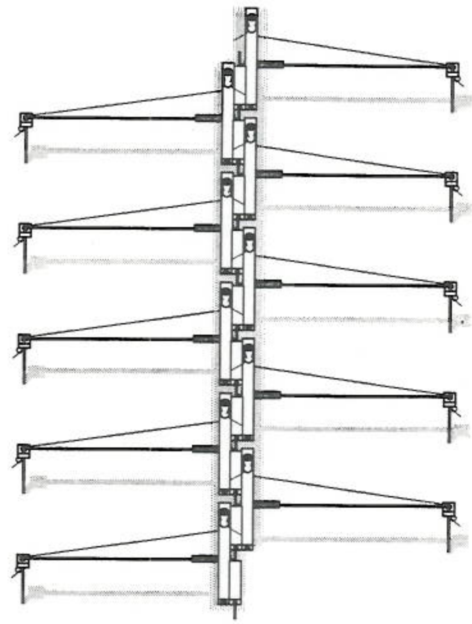
× Do **not** make them the identical to the first five legs or your Tensipede will only be able to walk in circles (unless you do some tricky programming).

5.6 ATTACH LEGS TO A SPINE

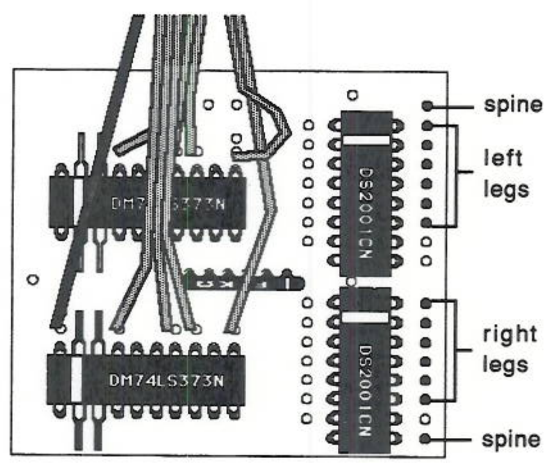
◉ Thread the legs onto the spine through the leg holders, alternately attaching a leg and a mirror-image leg until all legs are attached to the spine.



When complete, your Tensipede should look like this (reduced size illustration).



5.7 FINISH BY WIRING THE TENSIPEDE TO THE CONTROLLER



✓ Build the PC interface described in Section 7.

✓ Wire the Tensipede to the controller. Attach the spine to the positive (leg+) power source. The actuator clamps on the leg rods are attached to the Darlington drivers' outputs.

✓ Write a BASIC program to make the Tensipede walk (see example in section 8).

✕ Do **not** activate more than than three legs on each side simultaneously. The Darlington drivers can sink about 700 mA, enough to drive only three legs on each side at once. If more are simultaneously activated, the legs will not move to their full extent.

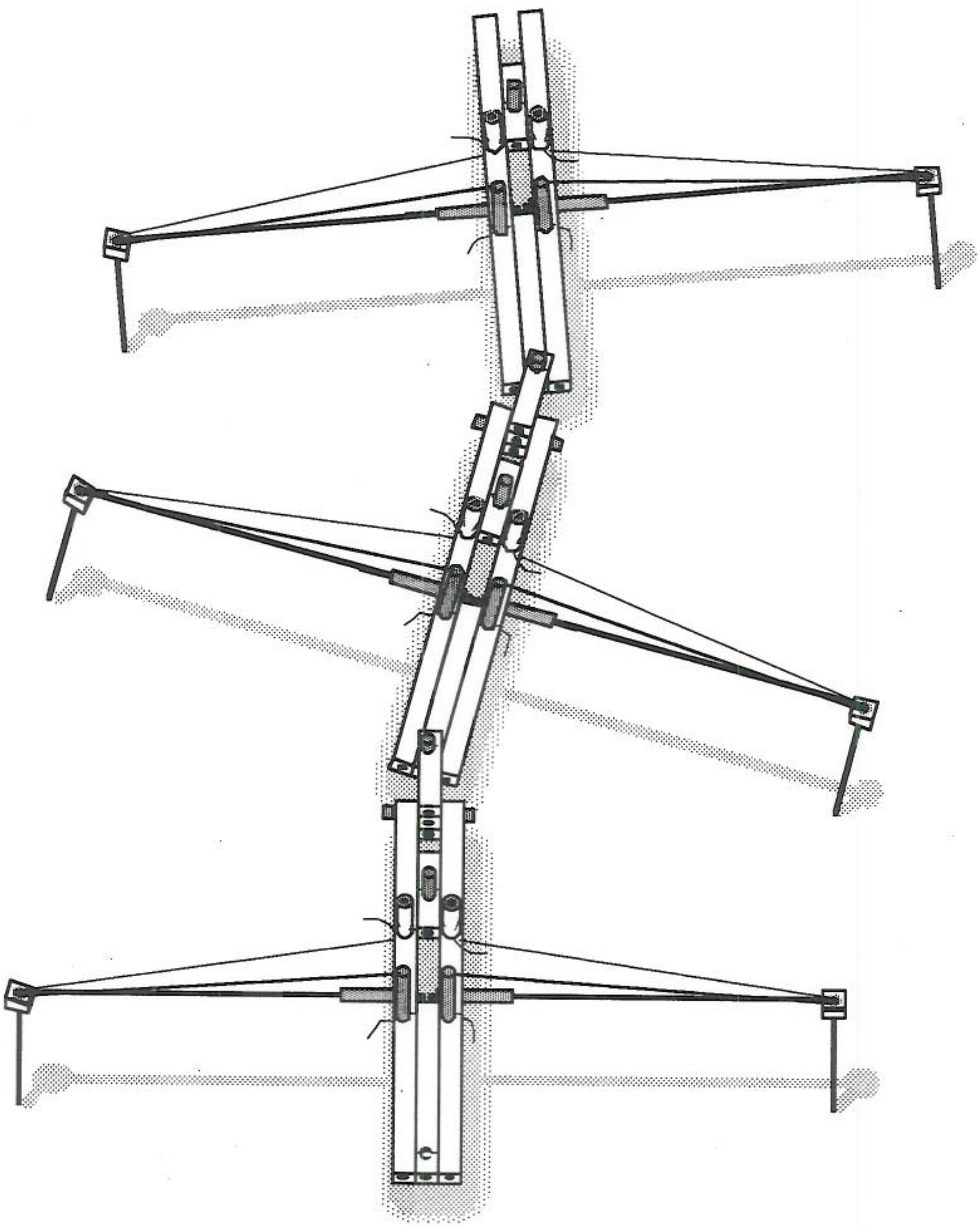
Tensipede can carry a large payload. You may want to put a single chip controller, like a PIC 1600 or a BASIC Stamp on the robot, along with batteries and driver circuits for the nitinol actuators. However, **Tensipede doesn't turn very well.** You may want to try designing an articulated joint in the middle of the robot to allow it to turn more easily. For example, a small spring could be used to connect a spine made in two pieces.

6. STIQUITO II: A HEXAPOD WITH A MODULAR ARTICULATED BODY

Stiquito II is a larger Stiquito with an articulated body that is designed to move freely, allowing the robot to walk up and down shallow stairs, climb small inclines, negotiate rough terrain, and turn to avoid obstacles, all without explicitly being programmed to do so.

Read the instructions through completely before you start to assemble Stiquito II. Check that you have all the materials and tools needed before you start. Plan to spend about four to eight hours (or an equal amount of time in several shorter sessions) building Stiquito II.

If you work carefully, your finished Stiquito II will look like this.



6.1 MEASURE AND CUT PARTS

Measure and cut the following parts for each assembly from the materials indicated:

6.1.1 BODY SEGMENT

qty	length	material	part	illustration
6	50 mm	1/4" ST-4 plastic rod	side	
3	23 mm	1/4" ST-4 plastic rod	leg pair holder	
3	10 mm	1/4" ST-4 plastic rod	power bus holder	
6	100 mm	.032" steel music wire	leg	(see below ↓)
6	10 mm	1/16" o.d. copper tube	leg bushing	

6.1.2 C-JOINT

qty	length	material	part	illustration
4	10 mm	1/4" ST-4 plastic rod	top/bottom side	
2	5 mm	1/4" ST-4 plastic rod	inner side	
4	15 mm	1/16" o.d. copper tube	axle	

6.1.3 ACTUATORS

qty	length	material	part	illustration
6	150 mm	.004" 70°C nitinol wire	actuator wire	(see below ↓)
6	5 mm	1/4" ST-4 plastic rod	knee clamp holder	
6	8 mm	1/16" o.d. copper tube	knee clamp	
6	8 mm	1/16" o.d. copper tube	horizontal clamp	
6	15 mm	1/16" o.d. copper tube	vertical clamp	
6	5 mm	1/8" o.d. aluminum tube	outer clamp	

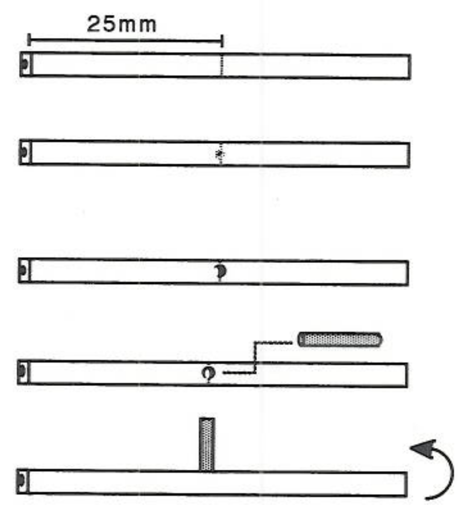
6.1.4 POWER BUS

qty	length	material	part	illustration
3	8 mm	1/16" o.d. copper tube	receptacle	
3	25 mm	28 ga copper wire	wire	

6.2 MAKE THREE BODY SEGMENTS

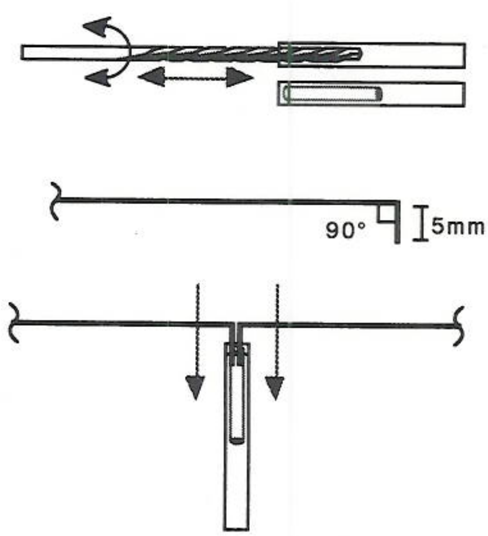
A body segment looks like this (shown slightly reduced in size so that both legs can be seen).

6.2.1 MAKE SIX BODY SEGMENT SIDES



- ☐ Measure 25 mm to the center of each body segment side.
- ✓ Mark the center by lightly scoring it with the knife.
- ✓ Start the leg bushing holes by twisting the tip of the knife back and forth in the middle of the body segment side at the score.
- ☐ The hole should be centered in the width of the body segment side (the middle of the score).
- ☐ Drill the leg bushing holes.
- ✓ Debur and clean out scrap.
- ● Insert the leg bushings into the leg bushing holes.

6.2.2 MAKE THREE LEG PAIRS



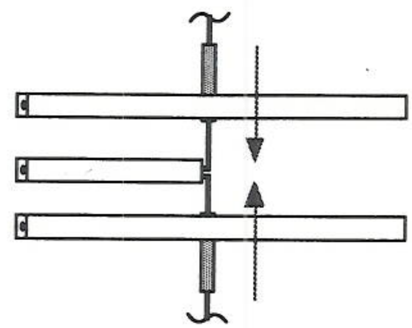
- ☐ Enlarge the hole in one end of each leg pair holder by grasping the leg pair holder with the pliers and reaming (drilling out) the hole with the 1/16" drill bit...
- ☐ ...to a depth of about 1/2".
- ☐ Bend each leg in a sharp 90° bend...
- ☐ ... about 5 mm from one end.
- ● Insert the short 5 mm length of two legs into the enlarged hole in the leg pair holder.

- Adjust the legs until they are aligned along the diameter of the enlarged hole in the leg pair holder, viewed from the end.

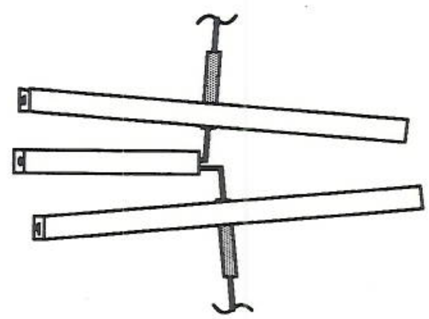
- × Do **not** allow the legs to get off-center. If this happens you will not be able to align the body segment with the leg pair holder, preventing it from being glued securely.

6.2.3 ATTACH TWO BODY SEGMENT SIDES TO EACH LEG PAIR

- Insert the long length of the legs into the leg bushings.
- ✓ Push the body segment sides along the legs until they touch the leg pair holder.



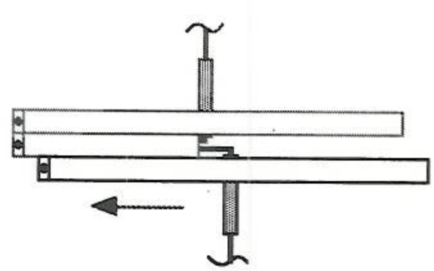
- × Do **not** continue if the body segment sides and the leg pair holder aren't parallel. The bend in one or both legs is not 90°. Pull the legs out of the leg pair holder, adjust the bend, then insert the legs and try again.



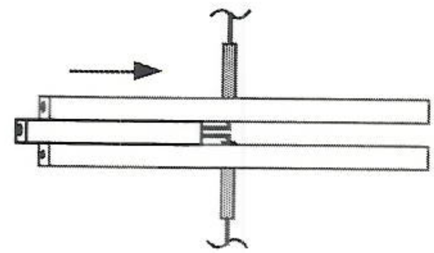
- Align the body segment sides with the leg pair holder so they are in the same plane.

- × Do **not** continue if the body segment sides and the leg pair holder won't line up in the same plane. The legs are misaligned in the enlarged hole in the leg pair holder. Twist the leg pair holder until the legs are opposite each other.

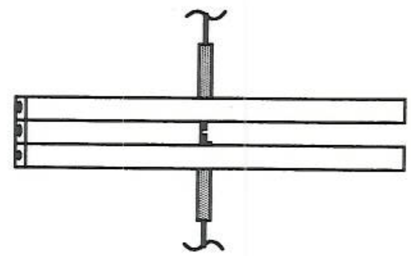
- Align the legs so they are opposite each other. You may need to slide one or both of the body segment sides forward or backward.



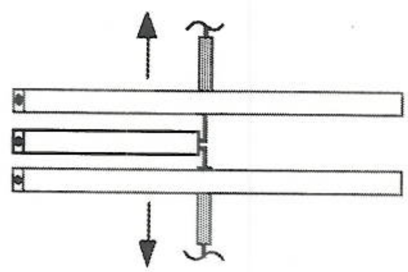
Align the body segment sides and the leg pair holder so their ends are even. You may need to slide the leg pair holder forward or backward.



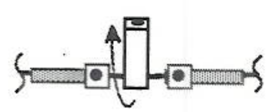
✓ When aligned, the body segment should look like this.



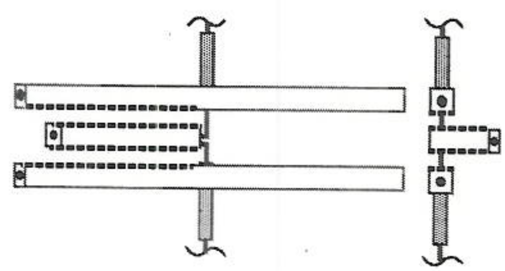
Pull the body segment sides apart slightly, then grasp the body segment by the body segment sides...



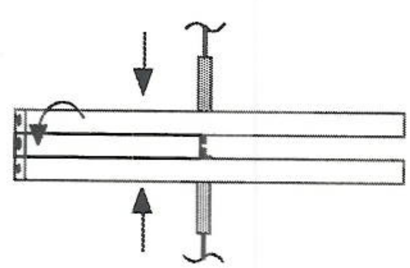
✓ ...and rotate the leg pair holder upward and outward.



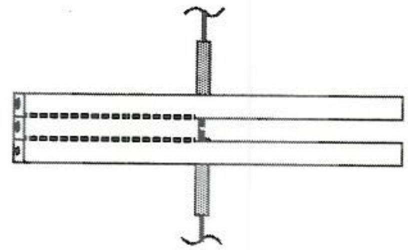
Continuing to hold the body segment, apply plastic cement to the inner face of each body segment side and the outer two faces of the leg pair holder.



Let the glue get tacky, then rotate the leg pair holder back into alignment with the body segment sides and push the body segment sides against the leg pair holder.



Lightly apply some plastic cement along the joints between the body segment sides and the leg pair holder. No gap should be visible. The joint should be even and smooth.

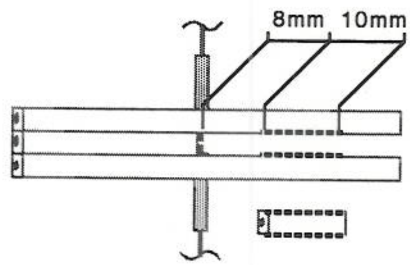


Apply plastic cement...

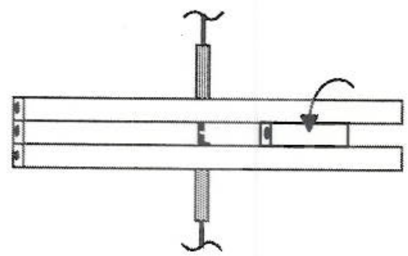
...to 10 mm of each inner face of each body segment side...

...starting 8 mm back from the center of the leg bushing...

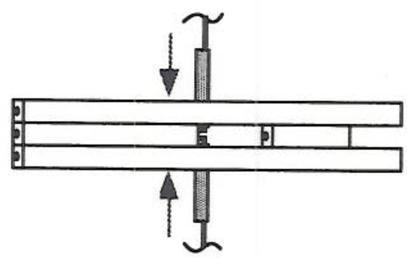
...and to the two outer faces of the power bus holder.



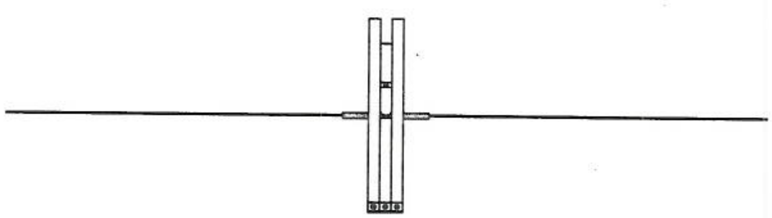
Insert the power bus holder and align it in the same plane as the body segment sides.



✓ Clamp the body segment just forward of the leg bushings.



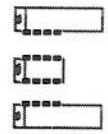
A body segment looks like this (reduced size illustration).



Let the body segment dry for **at least** two hours. Build the remaining body segments if you have not yet done so, or continue to the next section and assemble the c-joints.

6.3 ASSEMBLE TWO C-JOINTS

Apply plastic cement...



...to 5 mm at one end of each inner face of the c-joint top and bottom sides.

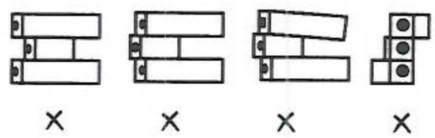
Apply plastic cement to the two outer faces of the c-joint inner side.

✓ Make the c-joint by attaching the top and bottom sides to the c-joint inner side.

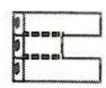
Align the c-joint top and bottom sides with the c-joint inner side so all lie in the same plane.

Align the c-joint top and bottom sides with the c-joint inner side so their ends are even.

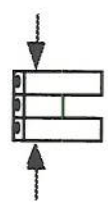
× Do **not** continue if the c-joint is crooked. Press the c-joint against a flat surface to align it. Break it apart and re-glue it if necessary.



Lightly apply some plastic cement along the joints between the c-joint top and bottom sides and the c-joint inner side. The joint should be even and smooth.



✓ Clamp the c-joint.



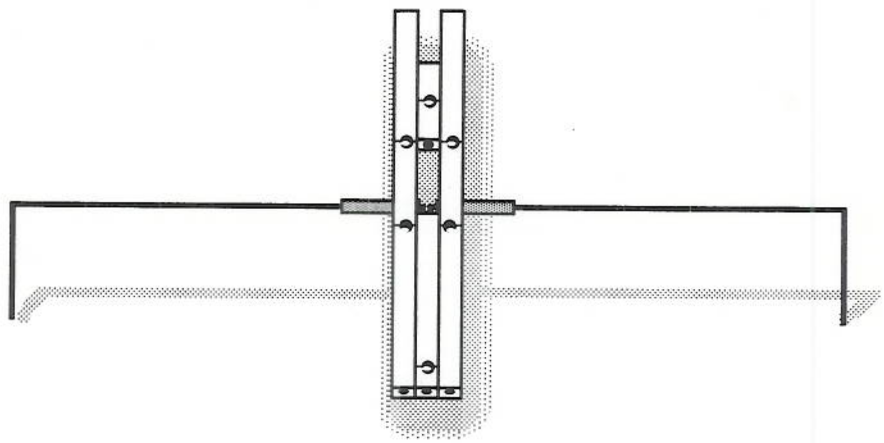
A c-joint looks like this.

Assemble the other c-joint, then let both c-joints dry for **at least** two hours. It is a good time to **take a break** if you have completed the body segments and c-joints, and are waiting for them to dry.

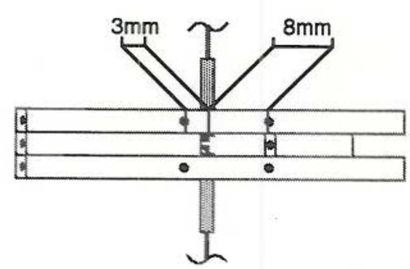
6.4 DRILL HOLES AND BEND LEGS ON EACH BODY SEGMENT

Do **not** continue until the glue holding the body segments and c-joints is dry. If you drill holes in the body segments or c-joints before the glue is dry, you will probably pull their component plastic rods apart.

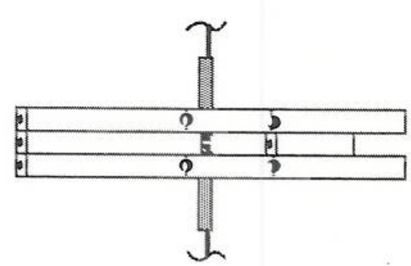
A body segment with actuator and axle holes drilled in it, and the legs bent downward, should look like this viewed from the top front.



6.4.1 DRILL FOUR ACTUATOR CLAMP HOLES IN EACH BODY SEGMENT

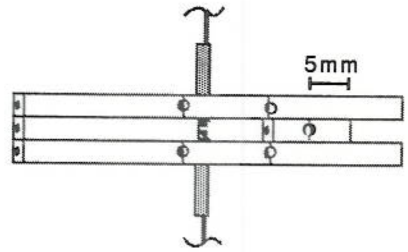


- ☐ Center all holes along the width of the ST-4 plastic rod.
- ☐ Locate the vertical clamp holes 3 mm in front of the center of the leg pair bushing. Start one hole in each body segment side.
- ☐ Locate the horizontal clamp holes 8 mm in back of the center of the leg pair bushing. Start one hole in each body segment side.



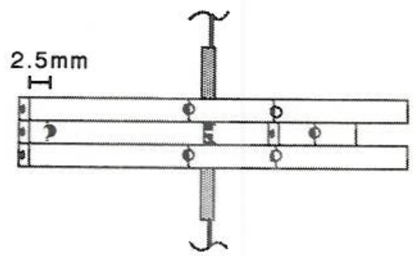
- ☐ Carefully drill these holes. They must be vertical, cylindrical, and $^1/_{16}$" in diameter.
- ✕ Do **not** make the holes larger than $^1/_{16}$" or the actuators and power bus receptacle will not fit tightly (the actuators are press-fitted ●). It is very easy to make the holes too large, crooked, conical, elliptical, or otherwise non-cylindrical if a motorized drill is used carelessly.
- ✓ Debur and clean out scrap by blowing through the hole.

6.4.2 DRILL ONE POWER BUS RECEPTACLE HOLE IN EACH BODY SEGMENT



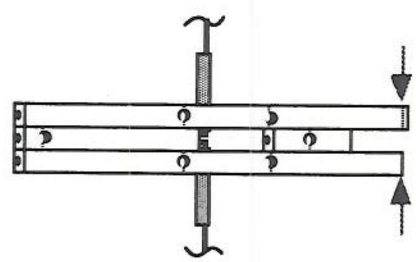
- ☐ Locate the power bus hole about 5 mm from the end of the body segment power bus holder (in the middle).
- ☐ Center the hole along the width of the ST-4 plastic rod.
- ☐ Carefully drill the hole. It must be vertical, cylindrical, and $^1/_{16}$" in diameter.
- ✕ Do **not** make the hole larger than $^1/_{16}$" or the power bus receptacle will not fit tightly.
- ✓ Debur and clean out scrap.

6.4.3 DRILL ONE VERTICAL AXLE HOLE IN EACH BODY SEGMENT

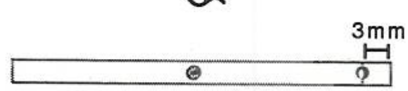


- ☐ Locate the body segment vertical axle hole 2.5 mm from the end of the body segment farthest from the power bus holder.
- ☐ Center the hole along the width of the ST-4 plastic rod.
- ✓ Use the knife to start the hole in the leg pair holder.
- ☐ Carefully drill the vertical axle hole.
- ✓ Debur and clean out scrap.

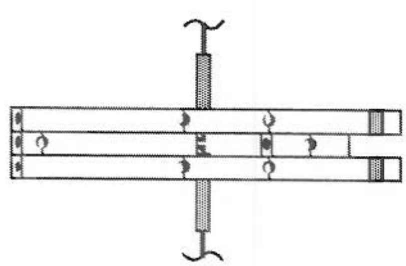
6.4.4 DRILL ONE HORIZONTAL AXLE HOLE ON EACH SIDE OF EACH BODY SEGMENT



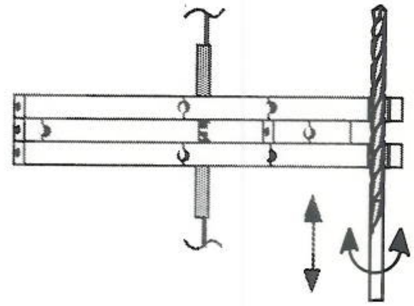
- ☐ Trim the ends of the body segment sides nearest the power bus holder so they are even.



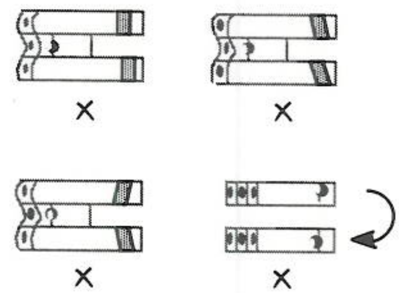
- ☐ Locate the horizontal axle holes at the rear of the body segment. Measure 3 mm from the end of each body segment side and mark with a score on the **side**, not the top, of **each** body segment side.
- ☐ Center each hole along the width of the ST-4 plastic rod.
- ✓ Start each hole with the knife.
- ☐ Carefully drill each horizontal axle hole.
- ✓ Debur and clean out scrap.



✓ Test the holes by inserting a drill bit through both of them, and rotating it. If you cannot do this easily, then...



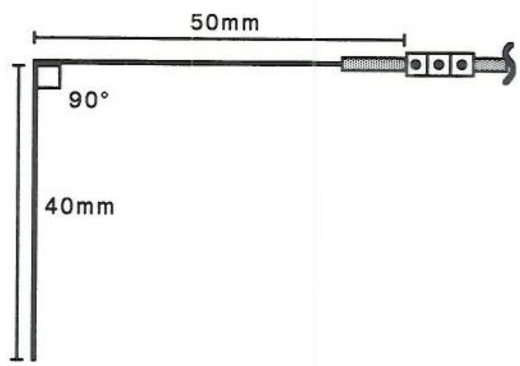
× ...do **not** use the body segment because the holes are not **opposite each other** or do not **lie on the same axis.** The axle will be difficult or impossible to insert, or will bind if inserted and prevent the joint from moving smoothly and freely. Discard it and make another.



6.4.5 BEND LEGS ON EACH EACH BODY SEGMENT

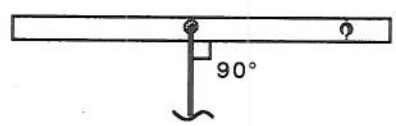
☐ Bend the free end of either the right or left leg down in a sharp 90° bend...

☐ ... about 50 mm from the leg rod. This will leave about 40 mm from the knee to the foot.

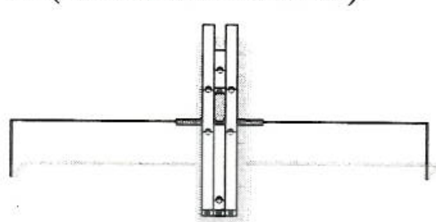


☐ Twist the free end of the leg right or left until it makes a 90° angle with the body segment when viewed from the side.

✓ Repeat for the other leg.



A body segment with actuator and axle holes drilled in it, and the legs bent downward, should look like this viewed from the top front (reduced size illustration).

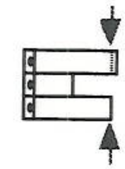


Body segments are **interchangeable.** If you have had trouble drilling the axle holes, you may be able to switch body segments to get a configuration that will work.

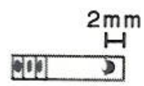
6.5 DRILL AXLE HOLES IN EACH C-JOINT

6.5.1 DRILL TWO VERTICAL AXLE HOLES IN EACH C-JOINT

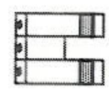
☐ Trim the ends of the c-joint top/bottom sides at the open end of the c-joint so they are even.



☐ Locate the c-joint vertical axle holes at the open end of the c-joint 2 mm from the end of each c-joint top/bottom side



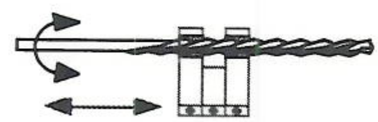
☐ Center all holes along the width of the ST-4 plastic rod.



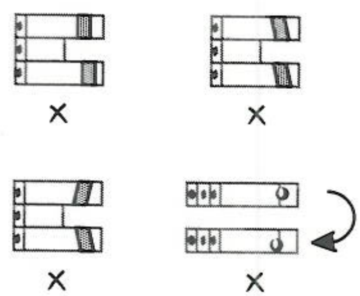
☐ Carefully drill each vertical axle hole.

✓ Debur and clean out scrap.

✓ Test the holes by inserting a drill bit through both of them, and rotating it. If you cannot do this easily, then...

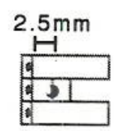


✓ ...do **not** use the c-joint because the holes are not **opposite each other** or do not lie **on the same axis**. Discard it and make another.



6.5.2 DRILL ONE HORIZONTAL AXLE HOLE IN EACH C-JOINT

☐ Locate the c-joint horizontal axle hole 2.5 mm from the closed end of the c-joint.

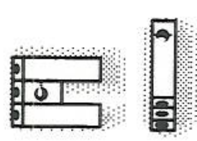


☐ Center the hole along the width of the c-joint inner side, then use the knife to start the hole.

☐ Carefully drill the c-joint horizontal axle hole.

✓ Debur and clean out scrap.

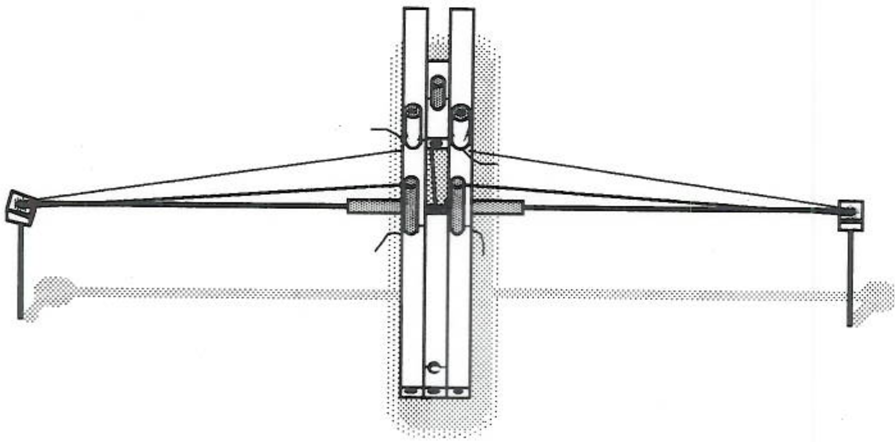
The finished c-joints look like this.



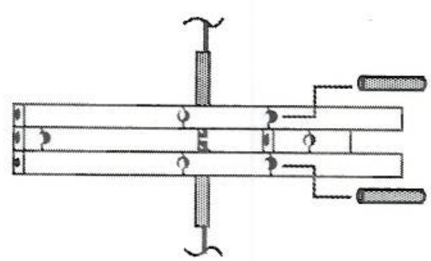
Now is a good time to **take a break.**

6.6 ATTACH ACTUATORS AND POWER BUS TO EACH BODY SEGMENT

A finished body segment will look like this when the actuators and the power bus have been attached.



6.6.1 ATTACH TWO HORIZONTAL CLAMPS TO EACH BODY SEGMENT

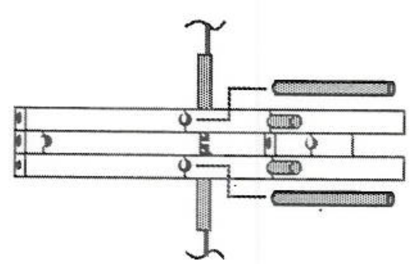


✓ Swage the horizontal clamps.

● Insert each horizontal clamp into the horizontal clamp hole until it is flush with the bottom of the body segment.

□ If the horizontal clamp is loose, remove it and crimp it gently approximately midway along the section that fits into the body segment. This will usually provide enough pressure to ensure a tight fit.

6.6.2 ATTACH TWO VERTICAL CLAMPS TO EACH BODY SEGMENT



✓ Swage the vertical clamps.

● Insert each vertical clamp into the vertical clamp hole...

□ ...until it protrudes 5 mm from the bottom of the body segment.

□ If the vertical clamp is loose, remove it and crimp it gently midway along the section that fits into the body segment. This will usually provide enough pressure to ensure a tight fit.

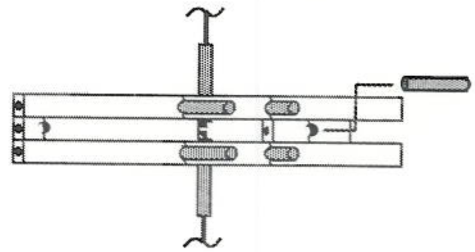
Do **not** use the body segment if the horizontal or vertical clamps cannot be made to fit tightly. The nitinol actuators will work poorly, or not at all. Discard the body segment and make another, being careful to drill the holes exactly $^1/_{16}$" in diameter. If you used a motorized drill the first time, try using a pin vise to hold the bit, and drill the holes manually. **Take care that the holes are not too large, crooked, conical, elliptical, or otherwise non-cylindrical.**

6.6.3 ATTACH ONE POWER BUS TO EACH BODY SEGMENT

✓ Swage the power bus receptacle.

● Insert the power bus receptacle into the power bus receptacle hole...

⊟ ...until it protrudes about 5 mm from the bottom of the body segment.

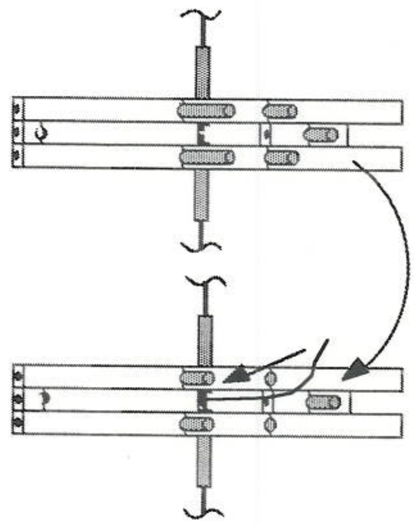


✓ Turn the body segment over.

✓ Strip the insulation from the power bus wire.

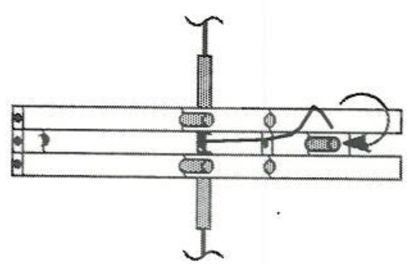
● Force the power bus wire into the leg pair holder...

⊟ ...about 10 mm. It must be a tight fit to make good electrical contact with the legs.

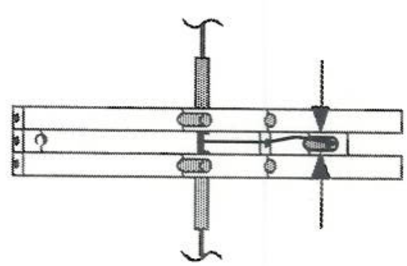


⊟ Bend the power bus wire up about 4 mm.

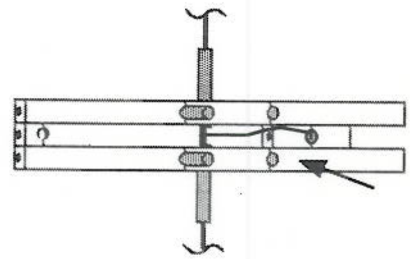
◉ Insert the bent length of the power bus wire into the power bus receptacle.



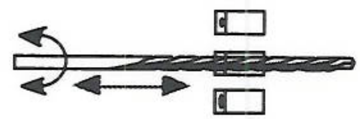
✓ Firmly crimp the power bus receptacle to make a good electrical connection with the power bus wire.



- From the bottom side of the body segment, push the power bus receptacle into the body segment. It should be flush with the bottom of the body segment.
- If the power bus receptacle is loose, remove it and crimp it gently midway along the section that fits into the body segment.

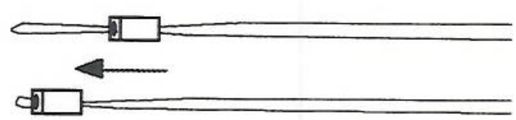


6.6.4 MAKE SIX KNEE CLAMP ASSEMBLIES

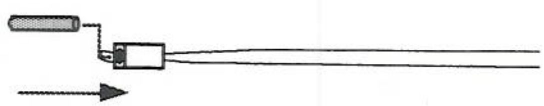


- Grasp the knee clamp holder with the needlenose pliers so that the drill bit does not slip.
- Use the drill to ream out the hole that runs through the center of the knee clamp holder.
- Ream the entire length of the hole.

- Bend the nitinol actuator in half but...
- ...do **not** crimp it at the bend.



- Insert the free ends of of the actuator into the knee clamp holder and push the knee clamp holder toward the bend...
- ...until the bend protrudes about 2 to 3 mm.

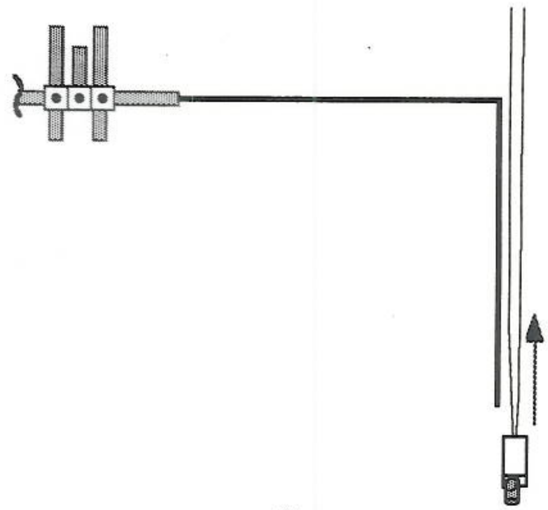


- Swage the actuator clamp.
- Press the actuator clamp into the knee clamp holder at the hole where the bend protrudes.
- Do **not** use excessive force to press-fit the actuator clamp, or the nitinol will break now, or after a few activation cycles. If it is difficult to press-fit the actuator clamp into the knee clamp holder, remove the actuator, ream out the knee clamp holder again and swage the ends of the actuator clamp.

- When it is finished, a small loop of nitinol will protrude from the knee clamp holder. The actuator clamp will be flush with the other end of the knee clamp holder.
- Note that the nitinol is held between the knee clamp and the knee clamp holder.
- The nitinol does **not** run through the knee clamp holder.

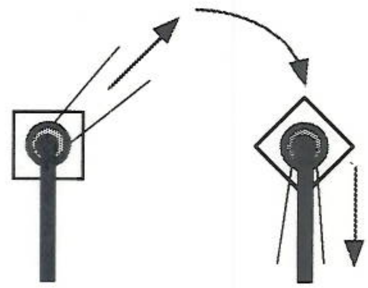
6.6.5 ATTACH TWO HORIZONTAL-VERTICAL ACTUATORS TO EACH BODY SEGMENT

◉ Slide the knee clamp assembly onto the end of the leg. The free ends of the nitinol actuator must exit the knee clamp assembly facing toward the **top** of the body segment.

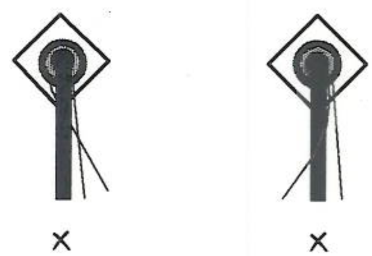


✓ Push knee clamp all the way to the knee.

✓ The knee clamp should rotate freely on the leg.

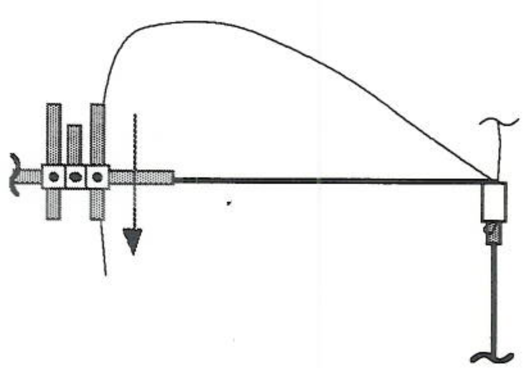


✓ Pull outward on the actuator wires, then, while pulling outward, change the direction of pull so that the actuators pull towards the body segment. The knee clamp holder may not be square with respect to the body, but that is OK.



× The actuator wires must **not** be crossed.

× The actuator wires must **not** cross over the leg, they should instead be free on either side of the leg.



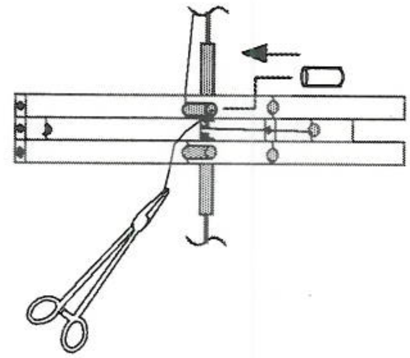
◉ Now thread the free end of the frontmost nitinol actuator through the top of the vertical clamp and out the bottom.

✓ Grip the free end of the actuator with the locking forceps and let it hang to provide tension to the actuator.

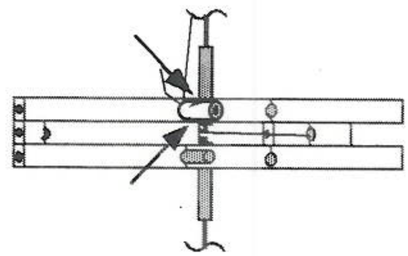
● Press-fit the aluminum outer clamp over the nitinol and the actuator clamp. It is a snug fit.

✓ The nitinol is clamped on the **bottom** of the robot.

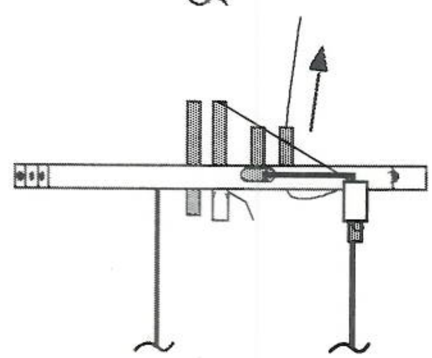
✗ Do **not** use excessive force to press-fit the outer clamp. If it is difficult to press-fit the outer clamp, ream out the inside ends slightly.



Use the wire cutters to **gently** crimp the outer clamp about halfway down its length so that the nitinol actuator is held tightly.



◉ Now thread the free end of the other nitinol actuator through the **bottom** of the horizontal clamp and out the top.

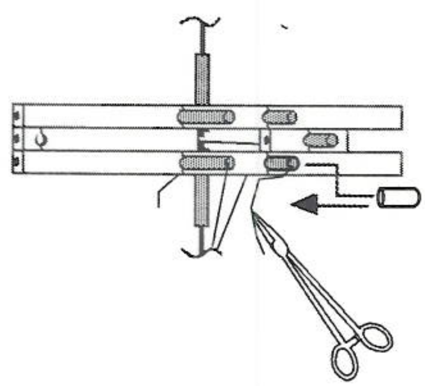


✓ Grip the free end of the actuator with the locking forceps and let it hang freely to provide tension to the actuator.

● Press-fit the aluminum outer clamp over the nitinol and the actuator clamp. It is a snug fit.

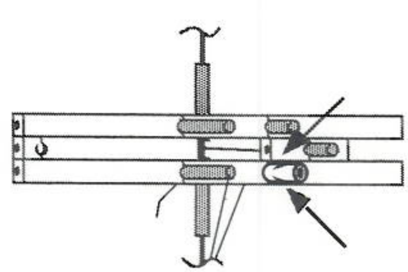
✓ The nitinol is clamped on the **top** of the robot.

✗ Do **not** use excessive force to press-fit the outer clamp, or the nitinol will break. If it is difficult to press-fit the outer clamp, ream out the inside ends slightly with the knife.

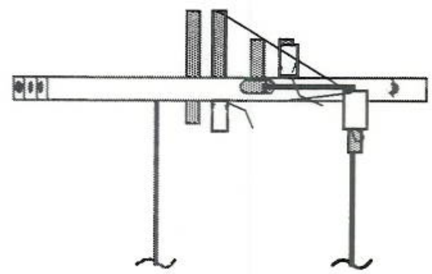


Use the wire cutters to **gently** crimp the outer clamp about halfway down its length so that the nitinol actuator is held tightly.

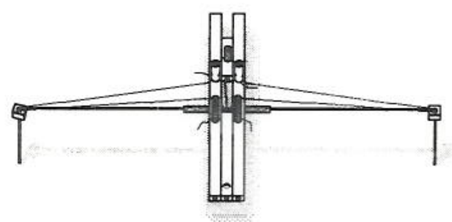
✓ Repeat for the actuator on the other side of the body segment.



- ✓ A single finished horizontal-vertical actuator looks like this from the side.
- ✓ Now attach the actuators to each of the remaining body segments.

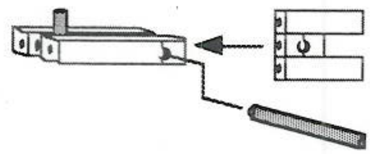


A body segment with the actuators and the power bus attached looks like this (reduced size illustration).



You can **test the actuators** on each body segment by applying power across the power bus and each actuator clamp. Nitinol is not directional, so it does not matter at this time if the power bus is positive or negative (later we will make the power bus positive because the driver circuit on the interface card pulls the actuator signal to ground).

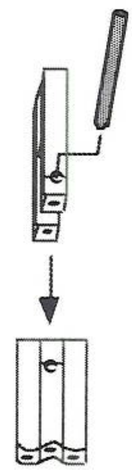
6.7 PIN THE THREE BODY SEGMENTS AND TWO C-JOINTS TOGETHER



✓ Insert a c-joint to the rear of a body segment...

◉ ...then pin it in place by inserting an axle through the horizontal axle holes in the body segment and the c-joint.

✓ Repeat for the other c-joint and one of the remaining two body segments.

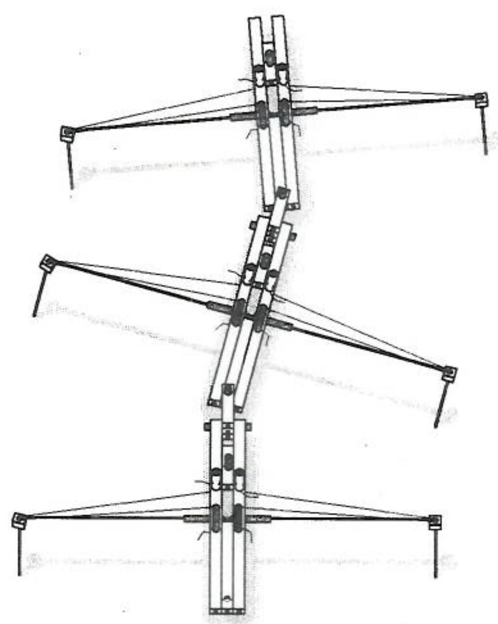


✓ Insert the front end of a body segment into the open end of a c-joint...

◉ ...then pin it in place by inserting an axle through the vertical axle holes in the c-joint and the body segment.

✓ Repeat for the other body segment + c-joint assembly and the remaining body segment.

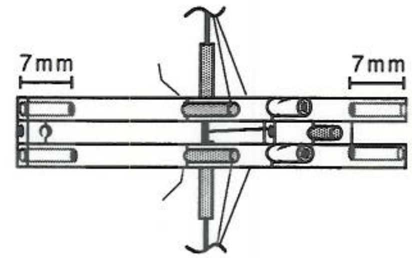
Your finished Stiquito II should look like this (reduced size illustration).



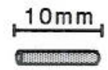
Congratulations! Your Stiquito II is complete! Now is a good time to **take a break**. Build the IBM PC and compatible computer parallel port interface later.

6.8 A USEFUL VARIATION: THE RIGID STIQUITO II

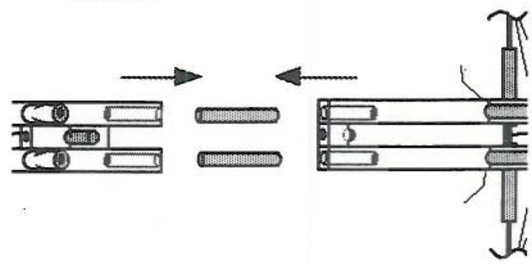
- Use the drill bit to ream out each end of the the hole that runs through the center of each body segment side to a depth of about 7mm.
- ✓ Repeat for each body segment.



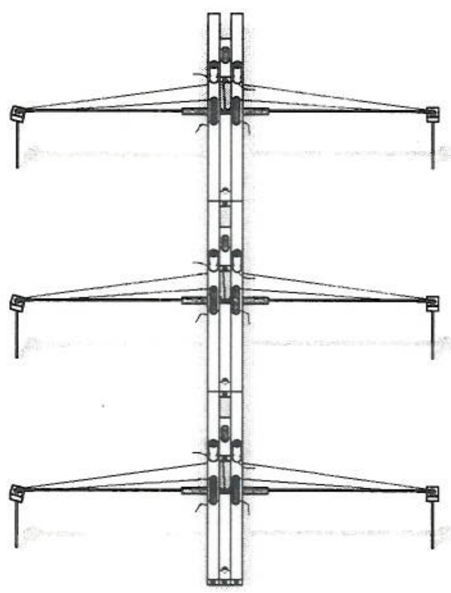
- Cut four 10mm body segment pins out of $^{1}/_{16}$" o.d. copper tube.



- ● Pin the body segments together with body segment pins, using two at each joint between body segments.
- × The c-joints are **not** used in this version.



Your finished **rigid** Stiquito II should look like this (reduced size illustration).



The rigid version can carry a miniboard attached underneath the body. Use a c-joint to connect two rigid Stiquito IIs. One can carry a miniboard, the other can carry rechargeable nickel-cadmium batteries to power the miniboard and the robot. Attach a "solar cell sail" to the top of each segment to recharge the batteries and you are ready to send the **Stiquito II Rover** to Mars!

Well, maybe NASA would prefer that you try it out on a gravel driveway first.

7. PARALLEL INTERFACE FOR IBM PC AND COMPATIBLE COMPUTERS

Stiquito II and Tensipede must be controlled by a computer or other electronic or mechanical device. These robots have ten or 12 actuators, too many to control manually. This interface allows you to use an IBM PC or compatible computer to control the actuators on Stiquito II or Tensipede and experiment with various gaits. The interface can also be modified to allow sensor inputs to be fed back to the computer, although this is **not** described in this technical report.

The interface is simple, uses inexpensive parts, is optimized to produce a tripod gait in Stiquito II, and can be fabricated on a single-sided, robust printed circuit board. The interface is attached to the parallel printer port on an IBM PC or compatible computer, one of the most readily available computers in the world. The control programs listed in this report are written in QBASIC, a dialect of BASIC provided free-of-charge by Microsoft with most IBM PC and compatible computers. The programs are also compatible with earlier versions of BASIC, such as GWBASIC.

The interface card and the BASIC programs described in this report reflect a reasoned and deliberate attempt to provide a 'lowest common denominator' for legged robot control. More sophisticated approaches, such as the analog VLSI Łukasiewicz logic arrays and Kirchhoff machines studied by the author, can be found in the literature. Remember that Stiquito II and Tensipede are platforms for research. To derive the most benefit from these simple robots you should use them as a foundation to develop more sophisticated robots and controllers.

7.1 MORE TOOLS AND RULES

Additional tools are needed to build the interface because you must solder the integrated circuits and the control wires to the card. You may want to provide sockets for the integrated circuits; sockets are **not** provided with the kit. Sockets, used primarily to allow an integrated circuit to be replaced easily, should not be needed if you take reasonable care building and operating the interface card.

7.1.1 MORE TOOLS

The following tools are **required** to build the interface card:

- needlenose pliers
- wire cutters
- small hobby knife (X-Acto™ type)
- soldering iron
- solder
- volt-ohmmeter
- 320 grit fine sandpaper

7.1.2 MORE GROUND RULES

Look for these *cues* (small pictures) as you follow the instructions to assemble the interface card. Fewer cues are needed because you are not fabricating parts to close tolerances. A new cue, the soldering iron, has been added to indicate that soldering is involved in the assembly step.

Cue	Meaning
✓	**Do** take the action indicated. No particular precision is required.
×	**Don't** do this! It is a mistake.
	Solder the part at the point or points indicated.
	Some variation is allowed. The dimensions are not critical. Stay within one or two millimeters of the specified measurement.
◉	**A loose or sloppy fit is OK.** Your interface will work fine if the fit is not tight.

PRECAUTIONS

✓ Soldering irons get **very hot.**

× Do **not** touch exposed metal on a hot soldering iron. Hold it by the insulated handle.

× Do **not** lay a hot soldering iron on the work surface or flammable material.

✓ Use a soldering iron holder or lay a piece of wood under-but-not-touching the tip to protect your work surface.

✓ Although the integrated circuits used in the interface are not particularly static sensitive...

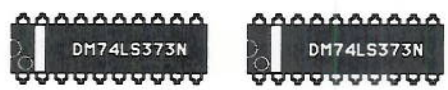
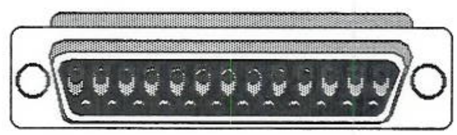
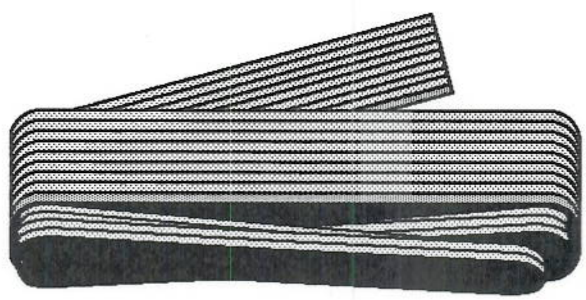
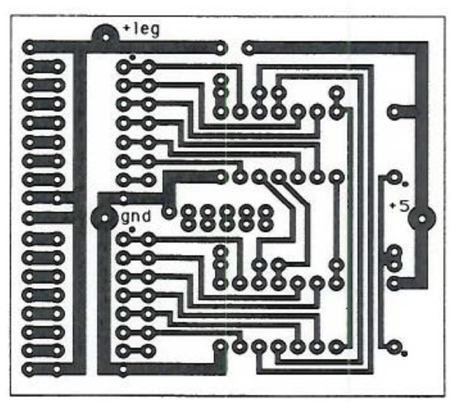
× ...do **not** handle them by the pins.

✓ In winter and dry weather, touch a large metal object (table, door frame) to discharge any static electricity before handling integrated circuits.

Now let's build the interface card and use it to control your robot.

7.2 IDENTIFY PARTS

Make sure you have all the parts. Match them against the illustration to be sure they are the correct parts. The printing on the integrated circuits may not exactly match the illustration, but the part number (or 1 KΩ for the resistor package) should appear somewhere on the integrated circuits.

qty	part number name	illustration
2 ea	DS2001 Darlington high-current driver	
2 ea	74LS373N Octal tri-state D flip-flop	
1 ea	G5102 5-element 1kΩ resistor network	
1 ea	225M-ND DB-25 male connector	
24 in	HC09G-100-ND 9-wire gray ribbon cable	
1 ea	n/a Printed circuit board (wiring side)	

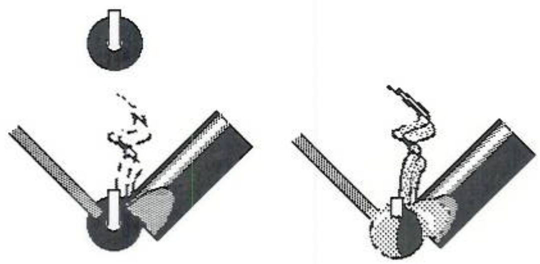
Hook-up wire and jumper wire and not provided with the kit. Wire is readily available at electronics and hobby shops, such as Radio Shack.

7.3 SOLDER THE INTEGRATED CIRCUITS TO THE INTERFACE CARD

7.3.1 SOLDERING

Soldering connects integrated circuits to the interface card mechanically and electrically. The basic technique for soldering is described below. You may want to practice on an old circuit board before you solder the parts to the interface card.

✓ Use the soldering iron's tip to heat the **pad**, not the integrated circuit pin. When the pad is hot, touch the solder to the heated pad, and the solder will flow onto the pad and the pin.



✓ Use just enough solder to wet the pin and cover the pad.

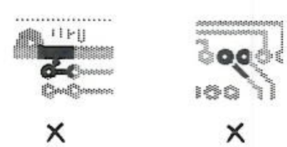
✓ Each solder joint should be bright, shiny, and have flowed evenly around the pin on the pad. The solder on adjacent pads must not touch.

✗ A solder joint should **not** be dull, cracked, or beaded up on the pad.

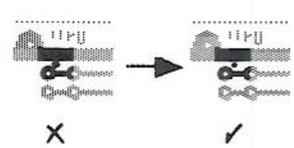
✗ A solder joint must **not** cross between two pads, or a pad and a trace. This will create a short circuit. Your interface card will almost certainly **not work correctly.**

7.3.2 CHECK THE BOARD FOR SHORT CIRCUITS AND BROKEN TRACES

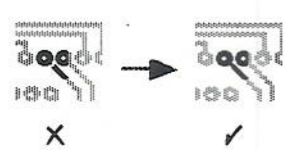
✓ Examine the wiring side of the interface board. Look at places where one trace or pad is near another; check that they do not touch. Look at long traces and near bends; check that the trace is not broken at that point.



✓ If traces or pads touch, but they should not, use the knife to cut the unwanted connection.



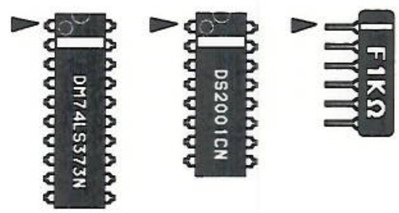
✎ If a trace is broken, lightly sand it on either side of the trace, then solder the broken ends together using a piece of fine wire to bridge the gap.



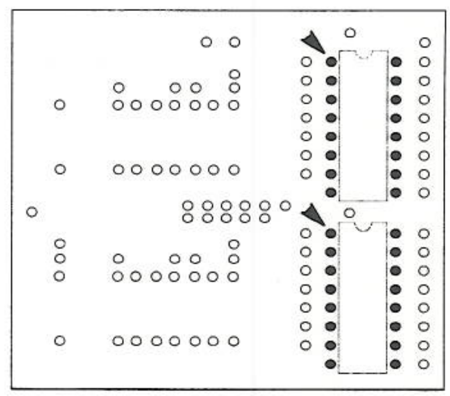
7.3.3 SOLDER INTEGRATED CIRCUITS TO THE BOARD

Avoid mistakes by fitting all integrated circuits to the board to make sure they are correctly placed **before** you solder them to the board.

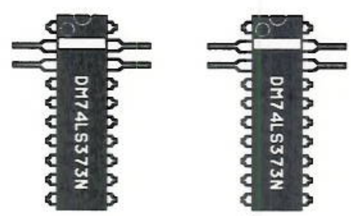
- ✓ Locate pin 1 on each part. It is the top left pin on each integrated circuit. The top of the integrated circuit is marked by a light-colored band, a U-shaped depression at one end of the integrated circuit, and/or a small circular depression next to pin 1 on the body of the integrated circuit.
- ✓ An arrow points to pin 1 in the illustration.



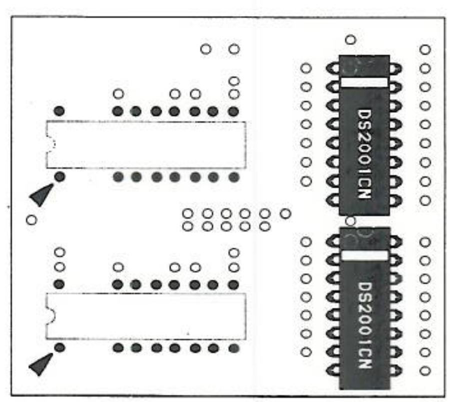
- ◉ Insert the DS2001 integrated circuits into the holes on the component side of the interface board.
- ✓ There is no wiring on the component side of the board.
- ✓ The holes into which the integrated circuit pins are inserted are black in the illustration.
- ✓ The outline of the DS2001 integrated circuits shows their orientation, and arrows in the figure point to the pin 1 locations.



- ✓ Pins 2, 3, 18, and 19 on each 74LS373 are not used. Bend them upward and outward so that the chip can be inserted into the interface board.



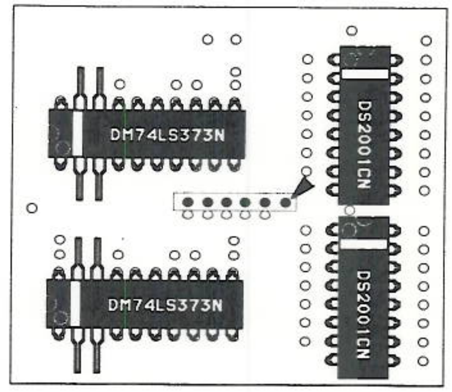
- ◉ Insert the 74LS373 integrated circuits into the holes on the component side of the interface board.
- ✓ The holes into which the integrated circuit pins are inserted are black in the illustration.
- ✓ The outline of the 74LS373 integrated circuits shows their orientation, and arrows in the figure point to the pin 1 locations.



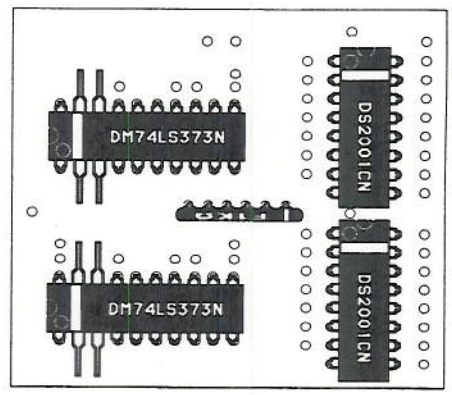
◉ Insert the 1 KΩ resistor package into the holes on the component side of the interface board.

✓ The holes into which the resistor package pins are inserted are black in the illustration.

✓ The arrow in the figure points to the location of pin 1 and shows the orientation of the resistor package.

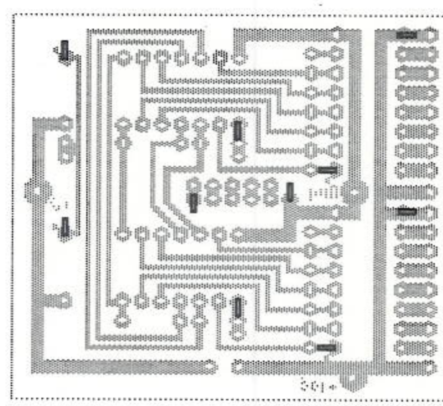


✓ The component side of the interface card should look like this after the integrated circuits and the resistor package are inserted.

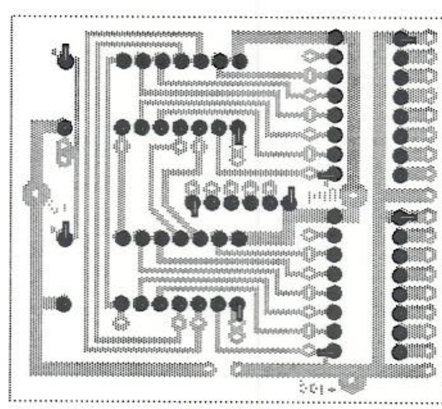


✓ Next, **carefully** turn the interface card over, keeping the integrated circuits pressed firmly to the surface of the card, so that the wiring side is uppermost.

✓ To hold the integrated circuits in place bend pins 1 and 11 on each 74LS373, pins 1 and 9 on each DS2001, and pins 1 and 6 on the resistor package toward the surface of the card.



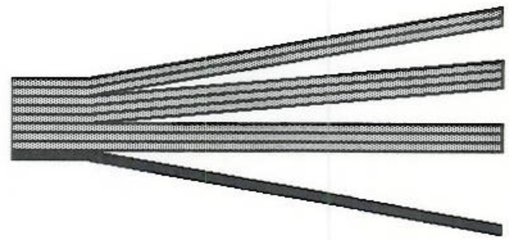
✍ Solder all the pins on each integrated circuit and the resistor package to the pads on the wiring side of the interface card.



7.4 ATTACH THE INTERFACE CARD TO THE DB-25 CONNECTOR

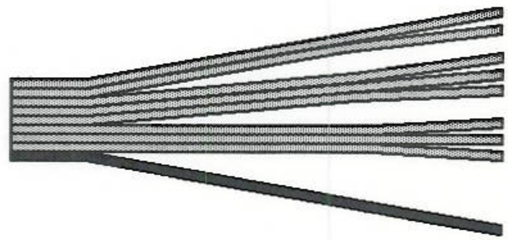
7.4.1 PREPARE EACH END OF THE RIBBON CABLE

- Separate each end of the ribbon cable into four groups of wires by splitting the cable with the knife and pulling the groups of wires apart for about 50 mm.

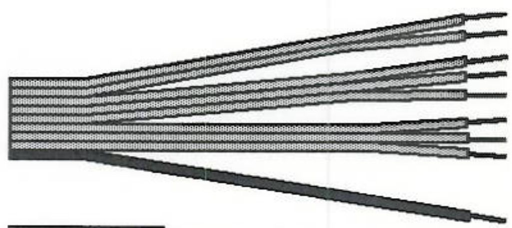


  - ✓ The red wire enables both latches' outputs.
  - ✓ The two-wire group enables either or both latches to capture data from the parallel port.
  - ✓ The remaining two groups of three wires carry data (bits 0 through 5) from the parallel port.

- Separate the wires in each group by splitting the cable with the knife and pulling the wires apart for about 20 mm.



- Strip approximately 5mm of insulation from the end of each wire at each end of the cable.



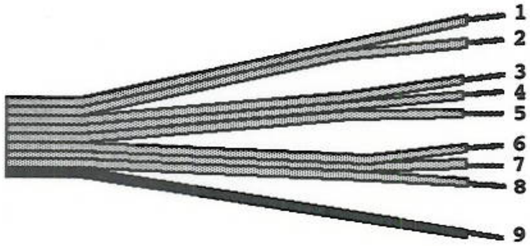
  - ✓ Nick the plastic insulation with the knife, then pull off the insulation with your fingers.

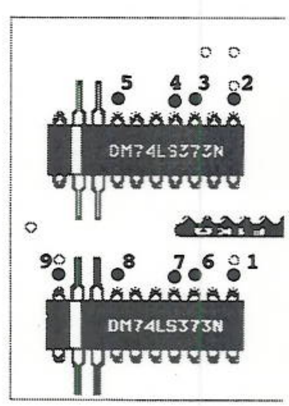
- Heat each of the bare wires and 'tin' it by saturating the wire's strands with solder.

- Tin all wires at both ends of the ribbon cable.

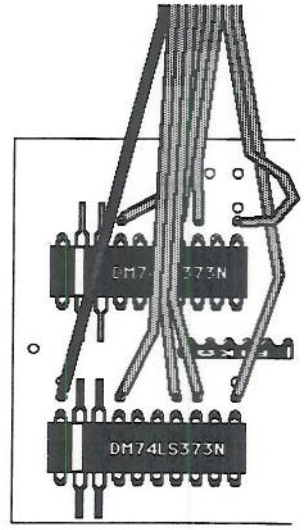
7.4.2 SOLDER THE CABLE TO THE INTERFACE CARD

- Insert the wires into the component side of the board, matching numbered wires and holes.





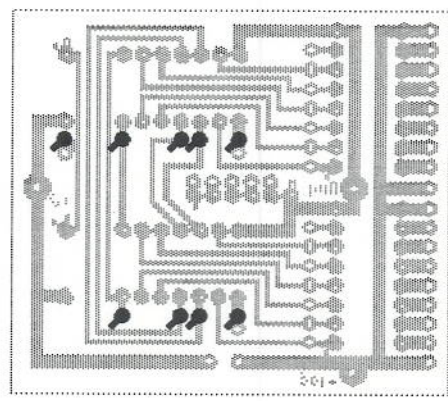
✓ The cable and board should look like this when you have finished inserting the wires into the interface card.



✓ Next, **carefully** turn the interface card over, keeping the wires in place on the interface card.

✓ The wiring side will be uppermost.

✍ Solder the cable wires to the pads on the wiring side of the interface card.

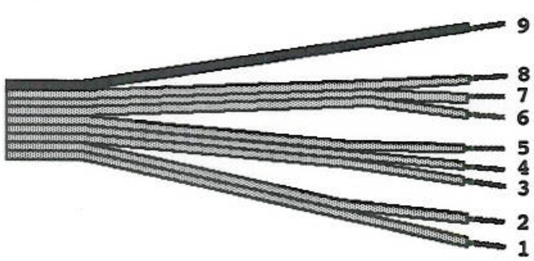


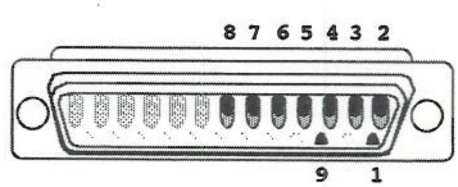
7.4.3 SOLDER THE CABLE TO THE DB-25 CONNECTOR

◉ Start by inserting one wire into the DB-25 connector, matching the numbered wire to the numbered solder socket as shown in the illustration.

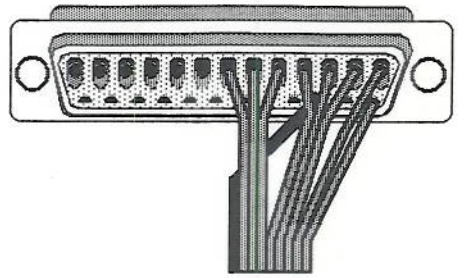
✗ Do **not** match the cable wires to the tiny numbers on the DB-25 connector. Use the numbers in the illustration.

✍ Continue to insert and solder one wire at a time in order from 1 to 9 until finished.





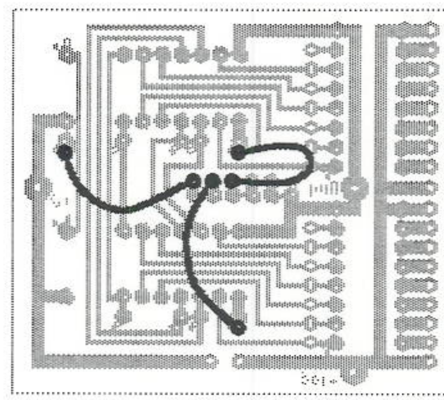
✓ The cable and DB-25 connector should look like this when you have finished inserting the wires into the interface card.



7.5 SOLDER JUMPERS AND POWER WIRES TO THE BOARD

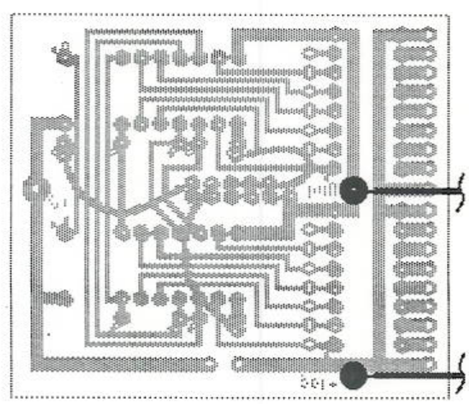
- Cut three jumper wires, each about 30 mm long.
- Strip about 5 mm of insulation from each end of all the jumper wires.

- Insert the jumper wires into the holes indicated in the illustration. The jumper wires are attached to the wiring side of the interface card.
- Solder the jumper wires to the pads on the interface card.



- Cut two power leads, each about 70 mm long.
- Strip about 5 mm of insulation from each end of each power lead.

- Insert the power leads into the holes indicated in the illustration. The power leads are attached to the wiring side of the interface card.
- Solder the power leads to the pads on the interface card.

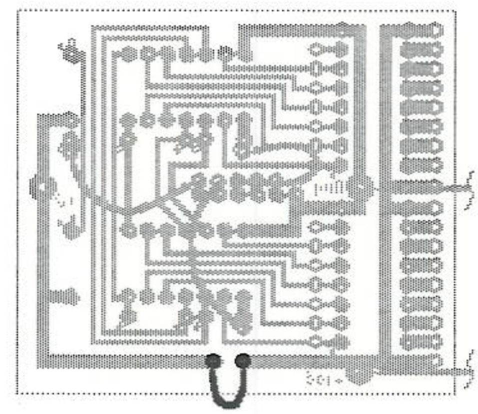


You can use the same power supply to drive the nitinol and power the latches (approximately 4.5 volts and 1.5 amps) or you may use a separate power supply for the latches and the nitinol. **Choose now,** then follow the appropriate instructions to either **jumper the interface card** or **add a third power lead.**

Of course, you can always change your mind — and the wiring — later!

To use the same power supply for the nitinol drivers and the latches:

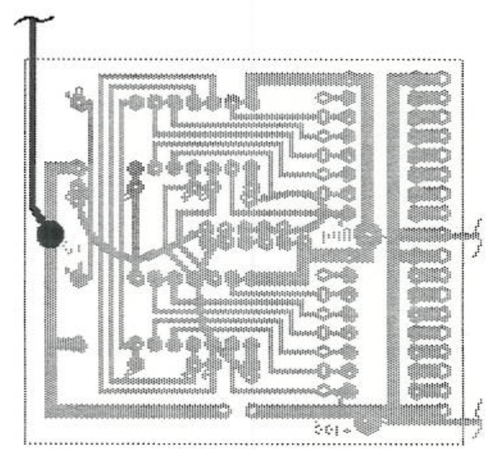
- Cut one jumper wire about 20 mm long.
- Strip about 5 mm of insulation from each end of the jumper wire.



- Insert the jumper wire into the holes indicated in the illustration. The jumper wire is attached to the wiring side of the interface card.
- Solder the jumper wire to the pads on the interface card.

To use different power supplies for the nitinol drivers and the latches:

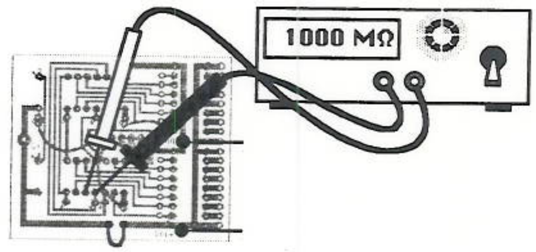
- Cut one power lead about 70 mm long.
- Strip about 5 mm of insulation from each end of the power lead.

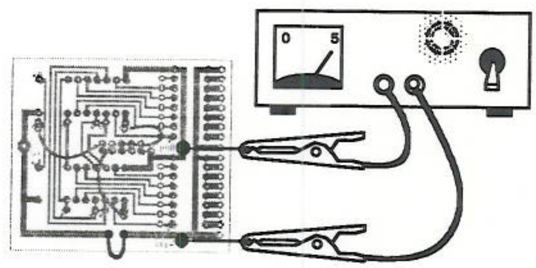


- Insert the power lead into the hole indicated in the illustration. The power lead is attached to the wiring side of the interface card.
- Solder the power lead to the pad on the interface card.

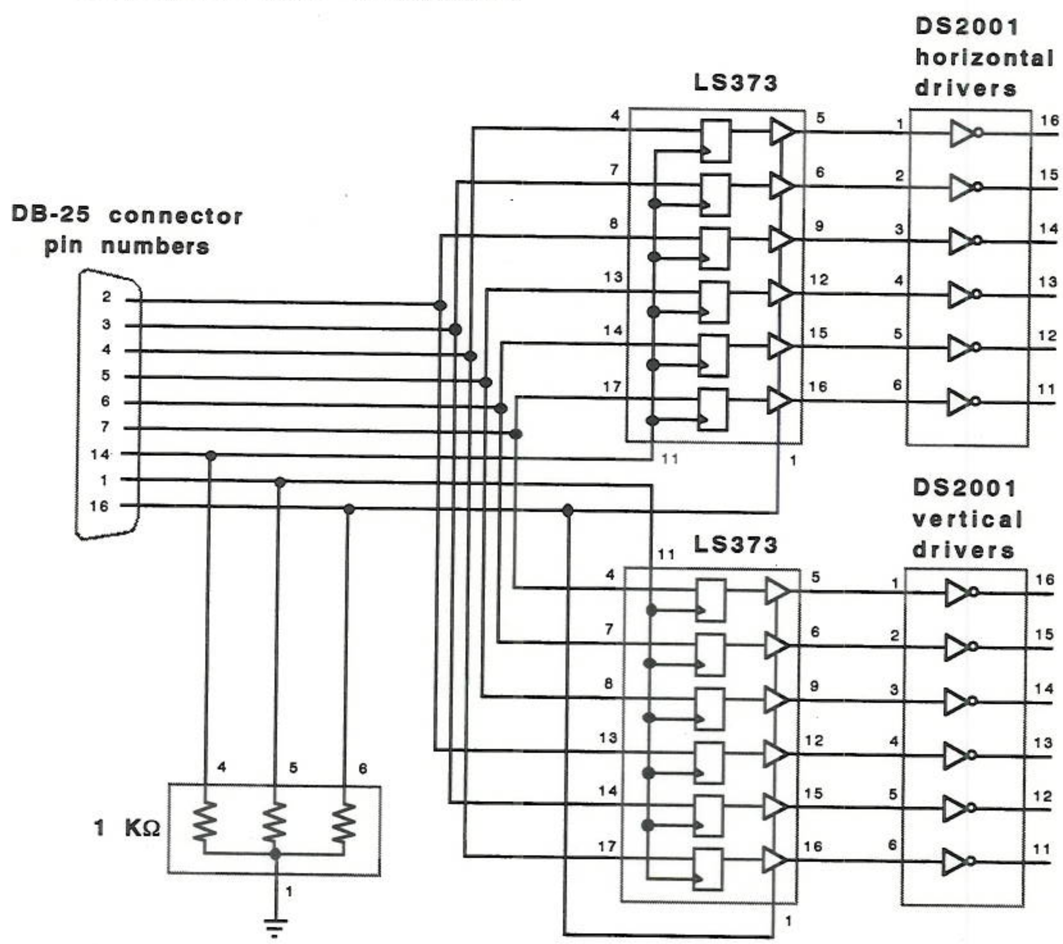
7.6 CHECK THE BOARD

- ✓ Test adjacent pads with a volt-ohmmeter to make sure they are not shorted.
- ✓ Check continuity between inputs and outputs with a volt-ohmmeter to be sure that solder joints are present and well-made.
- ✓ Visually inspect the board to make sure that the integrated circuits and the jumper wires have been installed correctly.
- ✓ Connect leg+ to a +5 volt power source. Connect ground on the interface card (gnd) to ground on the power supply. Turn the power supply on.
- ✗ The board should **not** emit smoke, flame, or sparks. Just kidding! Well, almost.
- ✓ Check that the DS2001 outputs are either at 4.5 volts or ground. If so, it's time to program the board.





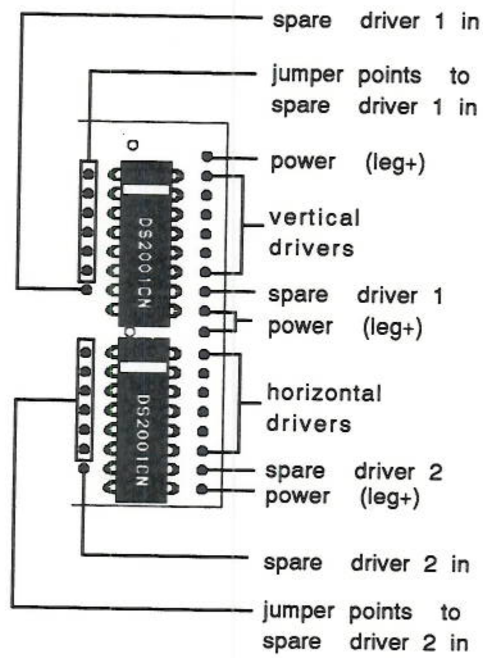
7.7 INTERFACE CARD SCHEMATIC



8. CONTROLLING STIQUITO II AND TENSIPEDE

You will learn how to program Stiquito II and Tensipede, and make them walk using various gaits in this section. The example programs use the parallel interface as an open loop system. In an open loop system the robot does not have any sensors to provide feedback to the controller. Without any feedback the controller cannot vary its commands if an actuator fails or the robot gets stuck. For simple experiments, this is an adequate approach. More complex behaviors require sensors and feedback, and are outside the scope of this technical report.

8.1 ATTACH STIQUITO II OR TENSIPEDE TO THE INTERFACE



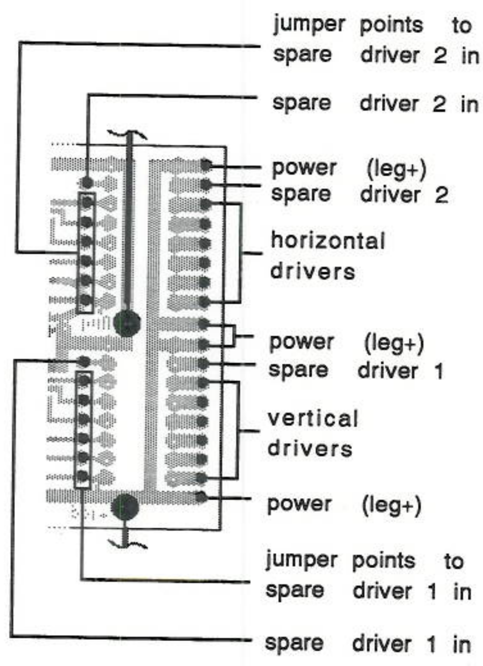
✓ The driver outputs to control your Stiquito II or Tensipede are located to the right of the DS2001 driver integrated circuits (viewed after orienting the board component side upwards, with pin 1 of the DS2001 driver oriented to the top left.

✓ Hook-up wires (magnet wire or wire-wrap wire) can be used to carry power and driver signals to Stiquito II or Tensipede.

✓ Six (6) vertical driver signals and six (6) horizontal driver signals are available.

✓ Two (2) spare driver signals are available, one on each DS2001 integrated circuit. A row of jumper points allows any of the six vertical or horizontal inputs to generate the spare driver signal.

✓ When you turn the interface card over to solder hook-up wires to the driver outputs the signals are located as shown in the illustration.

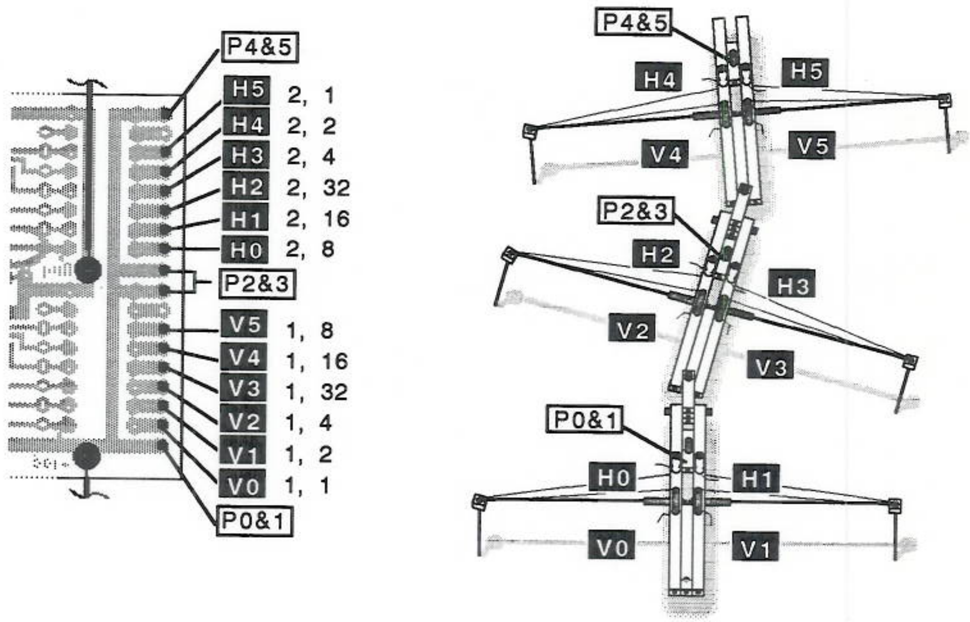


✎ Solder hook-up wires directly to the board, or use a header strip (row of sockets) to connect the hook-up wires so that they may be easily inserted and removed.

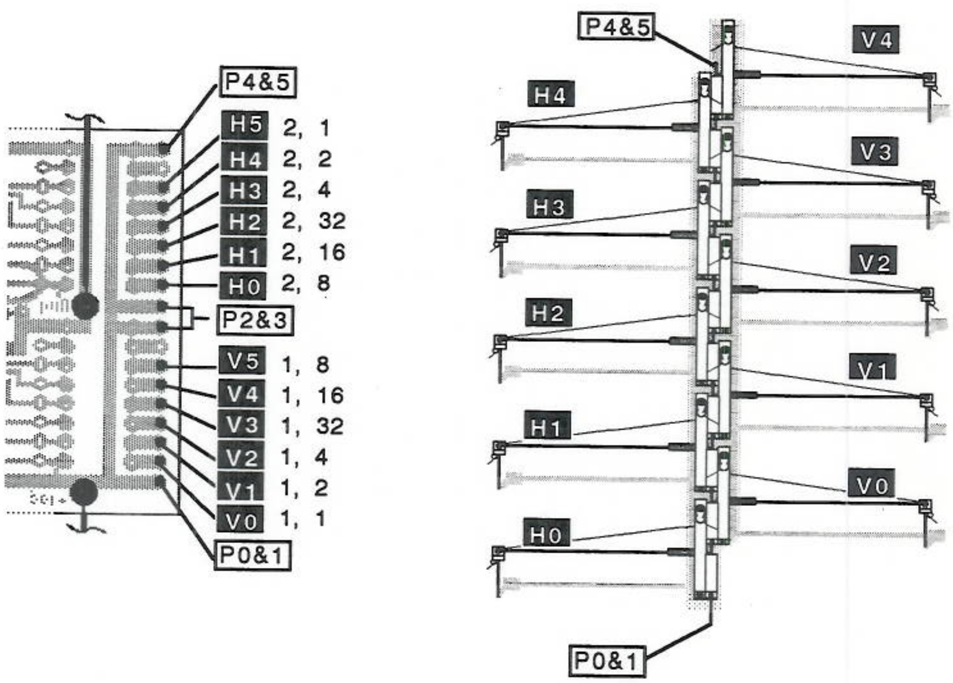
✓ It is easiest to provide a power connection to each body segment of Stiquito II. There are four power pads on the interface card to provide enough connection points for power wires. All power is supplied by a single supply.

✓ Note that the individual actuators are powered when a positive input to the DS2001 causes the actuator to be **connected to ground.** The power bus is **positive** and provides the current to heat the nitinol.

To use the programs in this report **without change** to control your Stiquito II, connect the wires between the interface card and Stiquito II **exactly** as shown in the following illustration. **White-on-black text** indicates an **active low** signal. The pairs of numbers are the latch function and actuator identification for testing the robot.



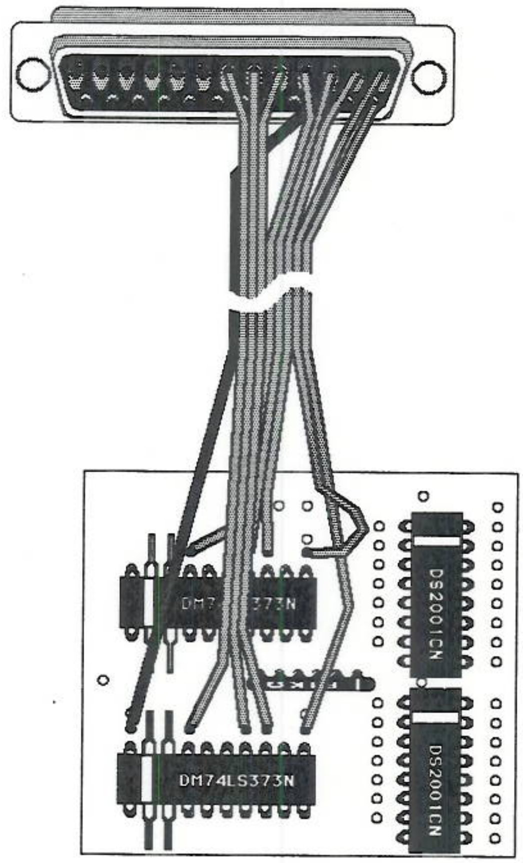
To use the programs in this report **without change** to control your Tensipede, connect the wires between the interface card and Tensipede **exactly** as shown in the following illustration. **White-on-black text** indicates an **active low** signal.The pairs of numbers are the latch function and actuator identification for testing the robot.



8.2 PROGRAMMER'S GUIDE TO THE INTERFACE

8.2.1 OVERVIEW

In IBM PC and compatible computers there is a parallel printer interface that has a **control port** and a **data port.** Data from the most recent write to the data port is held **inside the PC**, but to hold two bytes simultaneously latches on the interface card must be used.



When the interface card is attached to the parallel printer port, the **control port** is used to choose whether the horizontal driver latch, the vertical driver latch, both latches, or neither latch will **track** or **capture and hold** data sent to the **data port.**

The DB-25 connector is used to connect the interface card to the parallel printer port. Data and control signals are sent from the program to the control and data ports, then via the DB-25 connector through the ribbon cable to the interface card. The data is latched on the interface card, then, if the latches' output is enabled, passed to the drivers which activate the corresponding nitinol actuators.

Only three of the six bits available in the control port are used by the interface card.

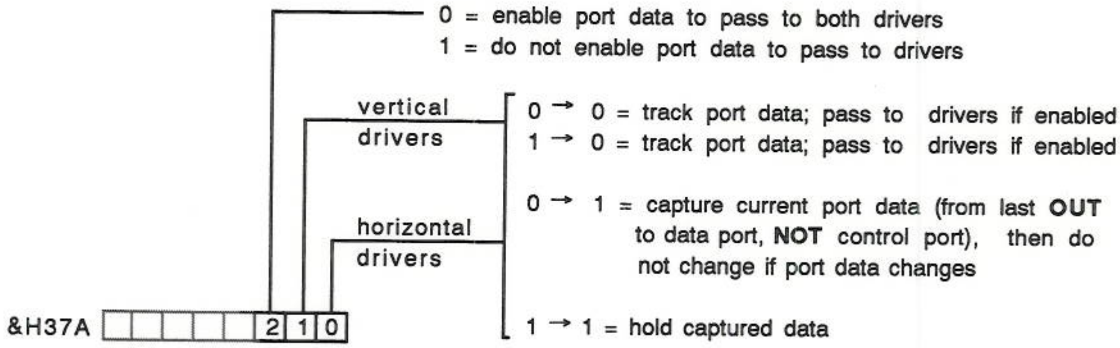
Only six of the eight bits available in the data port are used.

The six data bits are **doubled to 12 bits** by being captured in separate latches. Because each latch can be controlled individually, the data each latch holds can differ. This allows ten actuators on a Tensipede or 12 actuators on a Stiquito II to be controlled.

8.2.2 THE CONTROL PORT

The three bits of the control port determine the operation of each latch on the interface card. Use the control port to choose whether you want to pass data to the DS2001 drivers (bit 2), and whether you want each latch to track the data you send in subsequent writes to the data port, or capture and hold the data you sent in the previous write to the data port (bits 1 and 0). Note that when a latch does not pass or track data, it has captured and is holding constant the data from the **last time it tracked a data port write**, not the data port write that follows the control port write, and definitely not from the control port write. **A value written to the control port is not seen at all by the data port.**

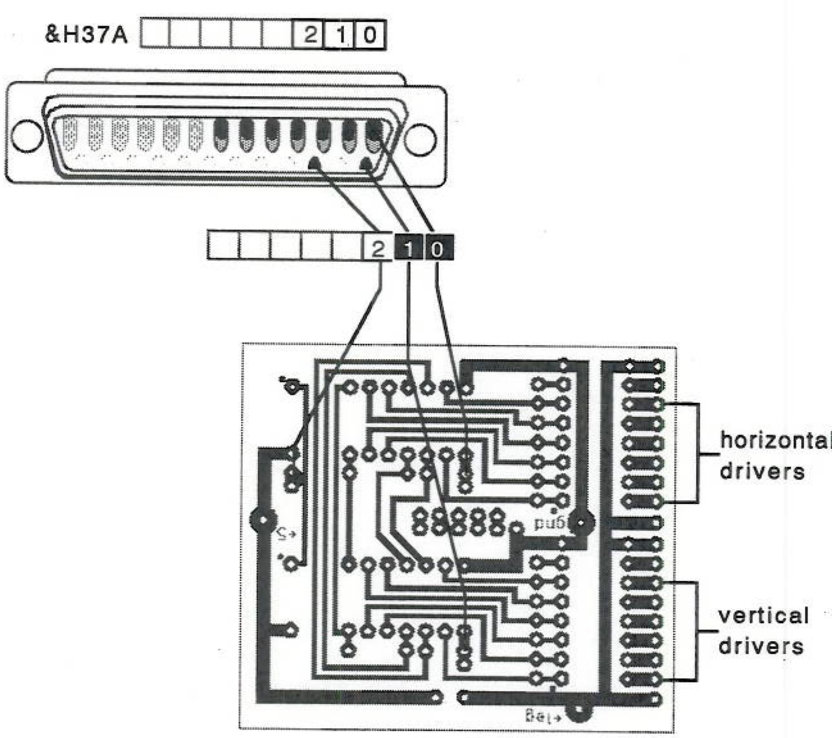
This illustration summarizes the operation of the control port bits.



Typically the IBM PC and compatible computer control port is located at the **hexadecimal address 37A**, written in BASIC as **&H37A.** BASIC output statements for some useful functions of the interface card are listed below.

```
OUT &H37A,1 'subsequent data port writes tracked & sent to vertical driver
OUT &H37A,2 'subsequent data port writes tracked & sent to horizontal driver

            'the following commands do not pass data to the driver chips

OUT &H37A,4 'subsequent data port writes tracked by both latches
OUT &H37A,5 'previous data port write captured by horizontal latch
OUT &H37A,6 'previous data port write captured by vertical latch
```

The relatonship between the control port and the interface card is shown in the following figure. **White-on-black text** indicates an **active low** signal.

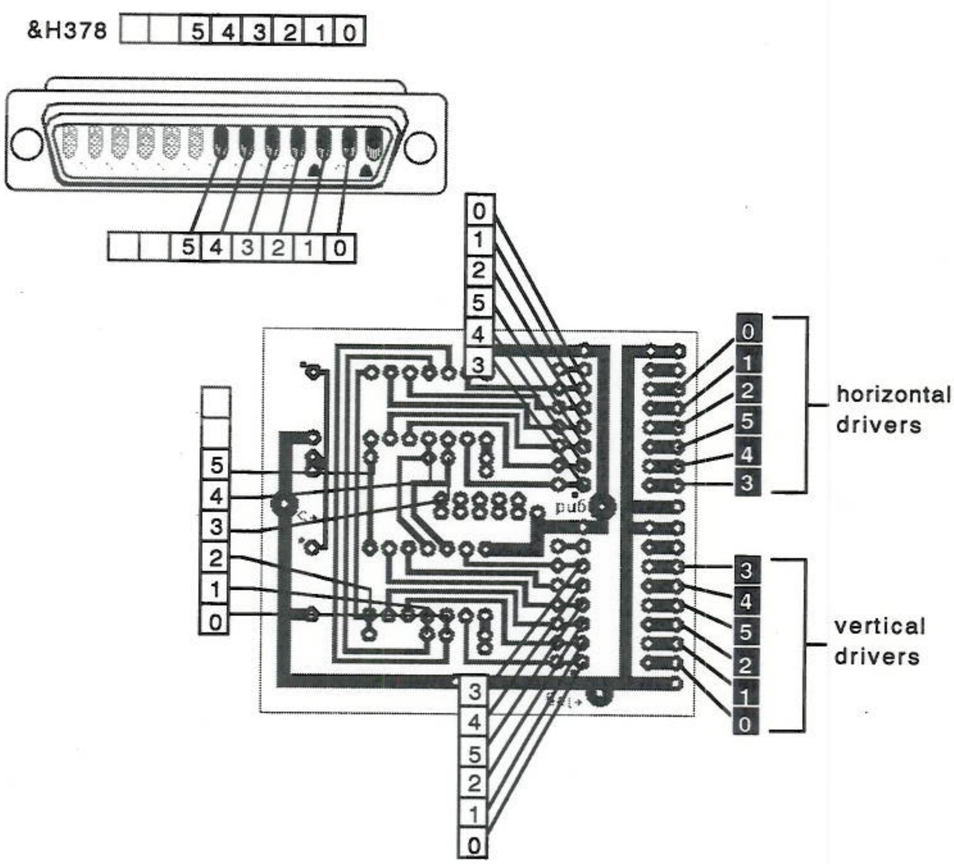


8.2.3 THE DATA PORT

The data port for the IBM PC and compatible computer printer interface is located at the **hexadecimal address 378**, written in BASIC as **&H378**. A data port write is **usually** combined with a control port write to direct the data to the desired latch and its associated driver. Occasionally it is meaningful to write the same data to each latch, **usually** when both latches are initialized to zero. In this case only one control port write is necessary. The following BASIC program fragment illustrates the no-glitch approach to activating the horizontal and vertical drivers.

```
OUT &H378,V 'send vertical data to card
OUT &H37A,1 'turn vertical actuators on/off
OUT &H37A,3 'capture and hold vertical data

OUT &H378,H 'send horizontal data to card
OUT &H37A,2 'turn horizontal actuators on/off
OUT &H37A,3 'capture and hold horizontal data
```

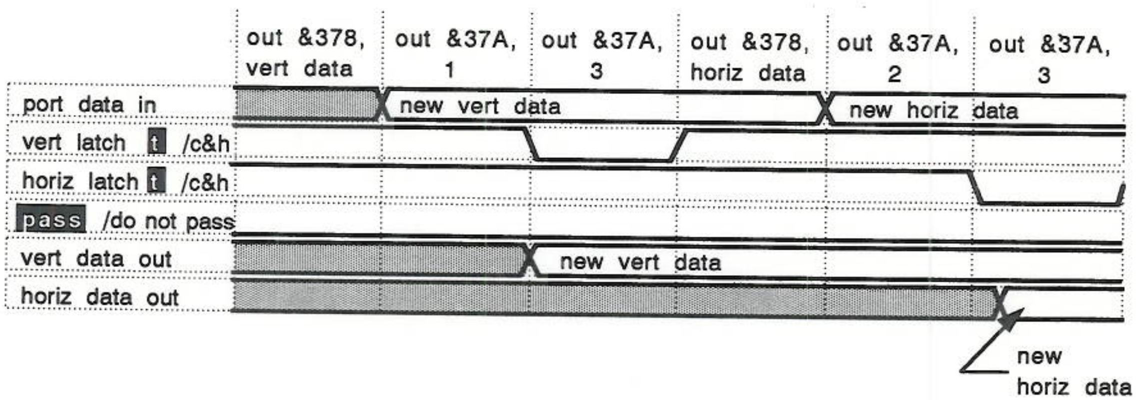
The relatonship between each bit in a byte sent to the data port, and the signals at the output of the drivers on the interface card (identified by the bit address), is summarized in the figure. **White-on-black text** indicates an **active low** signal.



8.2.4 DRIVING NITINOL ACTUATORS WITH A CONSTANT CURRENT

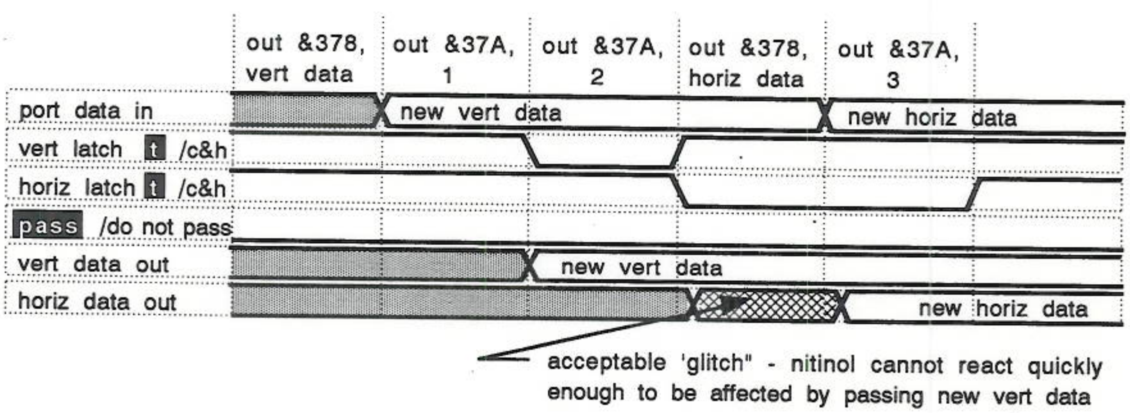
The program to drive the nitinol actuators shown in the previous section can be shortened because the nitinol actuators are not affected by very short changes in drive current. Here is the glitch-free driver program, and the timing diagram that corresponds to it. Notice that the actuators always have the desired data driving them, whether from the previous write to the horizontal or vertical drive latch or the current write. **White-on-black text** indicates an **active low** signal.

```
OUT &H378,V 'send vertical data to card
OUT &H37A,1 'turn vertical actuators on/off
OUT &H37A,3 'capture and hold vertical data

OUT &H378,H 'send horizontal data to card
OUT &H37A,2 'turn horizontal actuators on/off
OUT &H37A,3 'capture and hold horizontal data
```



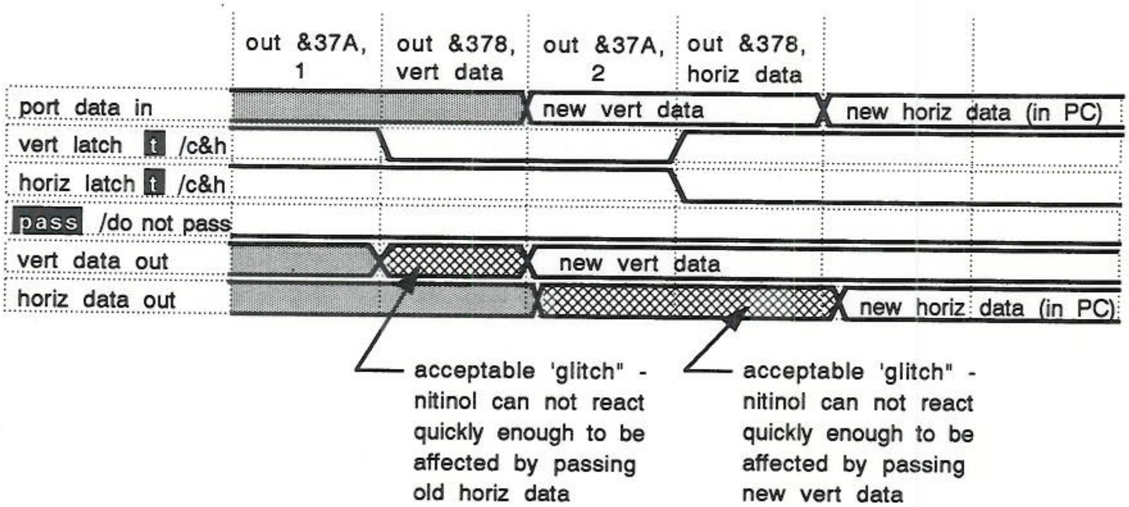
This program can be shortened if we are willing to accept a 'glitch,' or unwanted data present for a short time, as the actuators are driven.

```
OUT &H378,V 'send vertical data to card
OUT &H37A,1 'turn vertical actuators on/off
OUT &H378,2 'capture and hold vertical data; turn horiz actuators on/off

OUT &H378,H 'send horizontal data to card
OUT &H37A,3 'capture and hold horizontal data
```



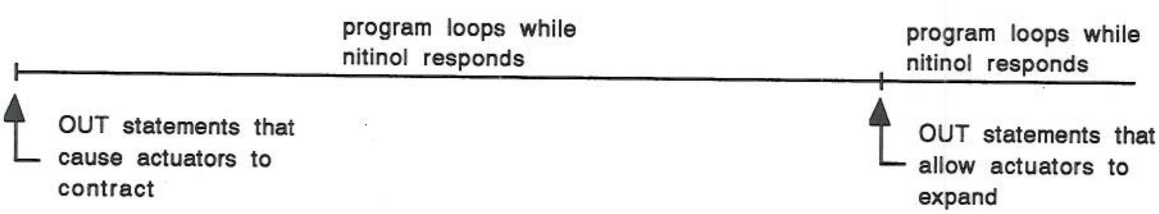
The program can be shortened even further if we accept two 'glitches' and can guarantee that the data written to the IBM PC parallel printer port will not change while the horizontal nitinol actuators are being driven. The second condition allows the printer port to drive the DS2001 chip directly : the 74LS373 latch passes the data until new data is written to the printer port, and never captures and holds data for the DS2001 horizontal driver chip.

```
OUT &H37A,1 'turn vertical actuators on/off
OUT &H378,V 'send vertical data to card
OUT &H378,2 'capture and hold vertical data; turn horiz actuators on/off

OUT &H378,H 'send horizontal data to card
```



Because the nitinol reacts so slowly the 'glitches' are acceptable, as can be seen by this program fragment that runs on a 33 MHz 486 laptop. The program must wait while a loop executes 9000 times to ensure that the nitinol is fully contracted, and 3000 times to allow the nitinol to expand.

```
OUT &H37A, 1    'contract vertical and horizontal actuators
OUT &H378, 49   'to move all legs for one step
OUT &H37A, 2
OUT &H378, 49
FOR x = 1 TO 9000
NEXT x

OUT &H37A, 0    'let the actuators expand for the next step
OUT &H378, 0
FOR x = 1 TO 3000
NEXT x
```

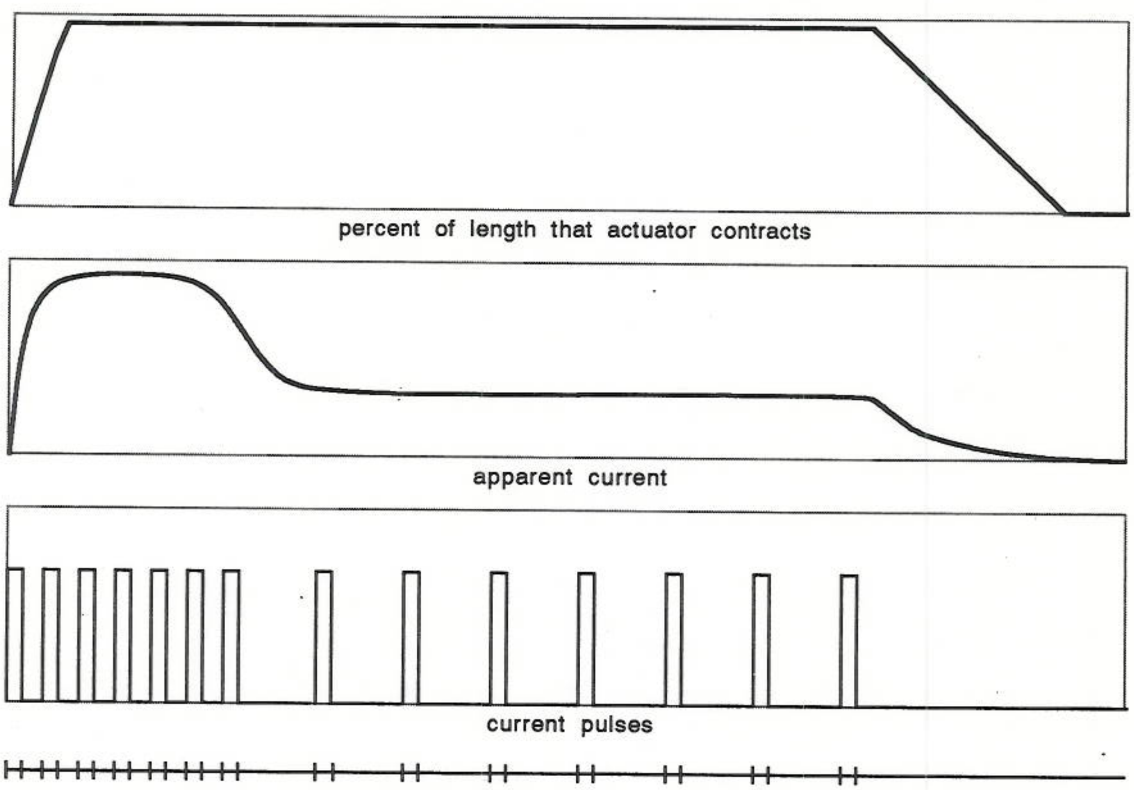


The loop constant **must** be changed for different computers because they run BASIC at different speeds. Begin with a small loop constant and increase it until the nitinol moves. **Starting with the loop constant too high may damage the nitinol.**

8.2.4 DRIVING NITINOL ACTUATORS WITH A PULSE FREQUENCY MODULATED CURRENT

Driving the nitinol actuator with the same amount of current is unnecessary after the nitinol has contracted. Only enough current to keep the nitinol contracted is needed, which is just enough to replace the energy that escapes as heat. The current and the voltage supplied to the nitinol cannot be changed dynamically, but the **power** can be varied using a technique called **pulse frequency modulation (PFM).**

Pulse frequency modulation means that the number of pulses (their frequency) is varied over time. The PC parallel printer port and the interface card can generate a PFM signal because the nitinol reacts slowly compared to the speed with which a BASIC program can turn the DS2001 driver chips on and off. By varying the length of time that the driver chips are left off, the frequency of the pulses can be increased or decreased. This allows the power used to drive the robot to be varied dynamically. The nitinol actuator behaves as a **leaky integrator** of the current pulses sent to it: the nitinol actuator responds to the heat generated by the current pulses, and lost to convection from the wire. The figures show how a PFM driver program works.



OUT statements that generate current pulses (note variable delay)

The following BASIC program subroutines illustrate how a PFM driver is constructed.

```
                'contract vertical and horizontal actuators
                'to move all legs for one step

OUT &H37A, 0    'pass all data port writes to both drivers (this
                'works only if a tripod gait is being used)


FOR x = 1 to 20
GOSUB 100       'high frequency pulses initially contract actuators
NEXT x

FOR x = 1 to 40
GOSUB 200       'low frequency pulses maintain actuator contraction
NEXT X

OUT &H378, 0    'let the actuators expand for the next step
FOR x = 1 TO 2000
NEXT x
END


                '---------------------
100             'high frequency pulses
OUT &H378, 49   'drivers on
FOR x = 1 TO 50
NEXT x

OUT &H378, 0    'drivers off
FOR x = 1 TO 50
NEXT x

RETURN


                '---------------------
200             'low frequency pulses
OUT &H378, 49   'drivers on
FOR x = 1 TO 50
NEXT x

OUT &H378, 0    'drivers off
FOR x = 1 TO 100
NEXT x

RETURN
```

8.3 INTRODUCTION TO GAITS WITH EXAMPLE PROGRAMS

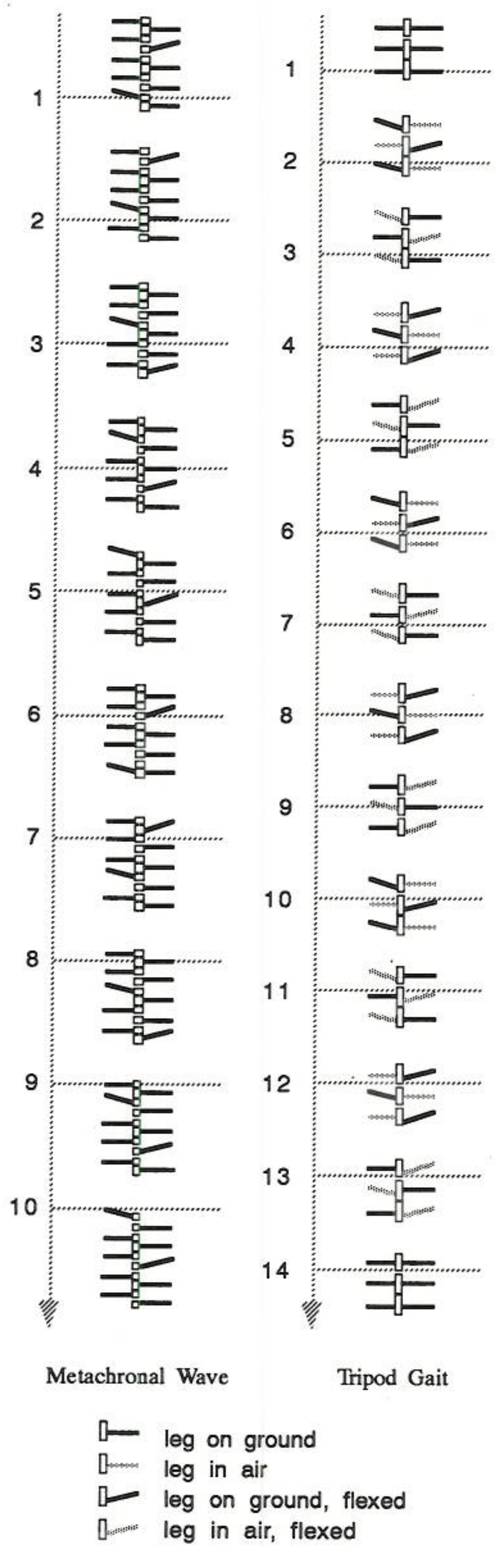
8.3.1 GAITS

The mechanisms of arthropod locomotion are complex, and have been extensively studied. The structure of an insect leg is also quite complicated. But, even though Stiquito II and Tensipede are simple, the fundamental features of arthropod locomotion can be demonstrated by small programs. Later, if you choose, you can develop more realistic models of gait controllers based on neural networks or central pattern generators, and feedback from strain gauges or other sensors that mimic the sensorimotor loop in a real insect.

The gaits of insects are believed to be due to central pattern generators that vary the animal's gait from a **metachronal wave** to a **tripod gait**, and all the variations in between. Each gait conserves energy as it preserves the balance of the insect. As the animation sequences indicate, the insect is always in a stable position with at least three legs, and often more, on the ground at all times.

The metachronal wave is the slowest and most stable gait. It is seen when a "wave" of leg movement ripples down each side of the insect or arthropod. The animation sequence shows two "waves" flowing done each side of the Tensipede. The tripod gait is the fastest stable gait, with two legs on one side of the insect and one on the other side alternately on the ground or in the air, as shown in an animation of Stiquito II.

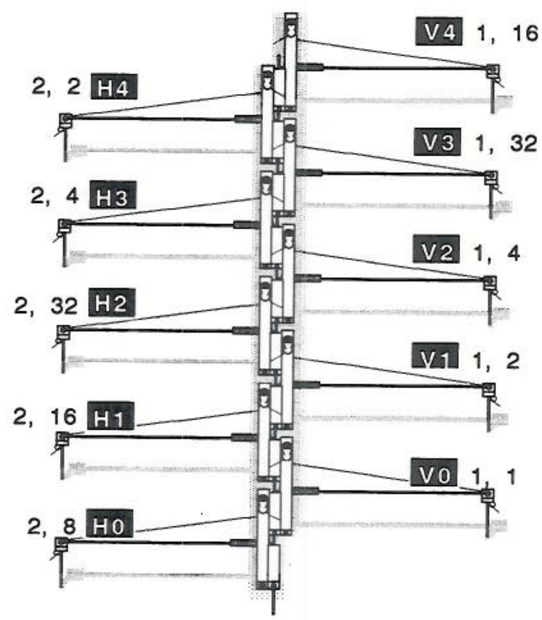
These two extremes in locomotion can be programmed into Stiquito II and Tensipede. Central pattern generator controllers are left as an exercise for the reader; they are covered in detail in books by Donner and Beer.



8.3.2 PROGRAMMING THE METACHRONAL WAVE FOR TENSIPEDE

Before you enter and run the Tensipede metachronal wave program, use this program to verify that the actuator wires are correctly hooked up. The illustration shows a pair of numbers next to each actuator. These numbers are read as **latch function, actuator control number** for each leg, and repeatedly entered into the BASIC program when requested until you are satisfied that all actuators work correctly. You can activate multiple actuators simultaneously by entering the **sum** of their actuator control numbers. To make the Tensipede legs designated by H4 and H1 move together, enter 2 + 16, or 18, as the actuator control number.

```
10 OUT &H378, 0   'init both latches
   OUT &H37A, 4

   INPUT "latch function"; L
   INPUT "actuator control number"; A

   OUT &H37A, L
   OUT &H378, A

   FOR x = 1 TO 9000: NEXT x
   GOTO 10
```



This program causes Tensipede to walk forward. Because the robot is not articulated, it does not turn or negotiate obstacles well. If the robot just twitches and does not move forward, bend the tip of each leg backward to make a **ratchet foot**. This will allow the driven leg to catch the surface, pushing the rest of the legs forward along the backward-slanted foot.

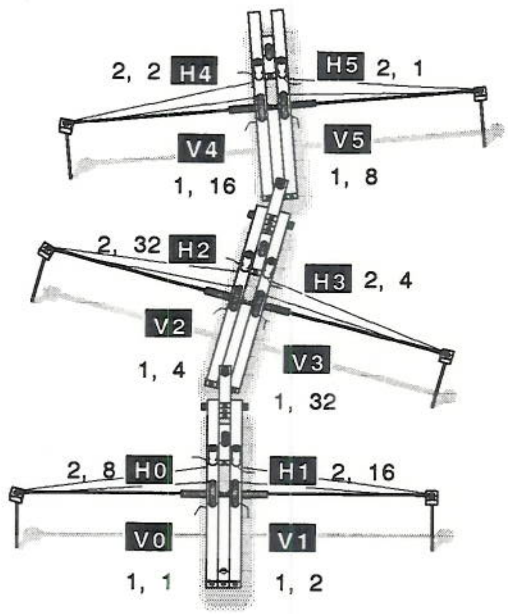
```
      OUT &H37A, 0   'initialize both latches and all legs
      OUT &H378, 0

3     PRINT : PRINT : PRINT "turn on power supply now, then..."
      PRINT "press any key to start tensipede walking"
5     start$ = INKEY$
      IF start$ <> "" THEN GOTO 7 ELSE GOTO 5

7     PRINT "press any key to stop tensipede"
      PRINT "(you may have to wait a second or two)"
```

```
10  OUT &H37A, 1
    OUT &H378, 32
    OUT &H37A, 2
    OUT &H378, 8
    FOR x = 1 TO 9000: NEXT x

    OUT &H37A, 0
    OUT &H378, 0
    FOR x = 1 TO 3000: NEXT x

    OUT &H37A, 1
    OUT &H378, 16
    OUT &H37A, 2
    OUT &H378, 16
    FOR x = 1 TO 9000: NEXT x

    OUT &H37A, 0
    OUT &H378, 0
    FOR x = 1 TO 3000: NEXT x

    OUT &H37A, 1
    OUT &H378, 1
    OUT &H37A, 2
    OUT &H378, 32
    FOR x = 1 TO 9000: NEXT x

    OUT &H37A, 0
    OUT &H378, 0
    FOR x = 1 TO 3000: NEXT x

    OUT &H37A, 1
    OUT &H378, 2
    OUT &H37A, 2
    OUT &H378, 4
    FOR x = 1 TO 9000: NEXT x

    OUT &H37A, 0
    OUT &H378, 0
    FOR x = 1 TO 3000: NEXT x

    OUT &H37A, 1
    OUT &H378, 4
    OUT &H37A, 2
    OUT &H378, 2
    FOR x = 1 TO 9000: NEXT x

    OUT &H37A, 0
    OUT &H378, 0
    FOR x = 1 TO 3000: NEXT x


    a$ = INKEY$

    IF a$ <> "" THEN OUT &H37A, 5: OUT &H378, 0: GOTO 3

    GOTO 10
```

8.3.3 PROGRAMMING THE TRIPOD GAIT FOR STIQUITO II

Before you enter and run the Stiquito II tripod gait program, use this program to verify that the actuator wires are correctly hooked up. The illustration shows a pair of numbers next to each actuator. These numbers are read as **latch function**, **actuator control number** for each leg, and repeatedly entered into the BASIC program when requested until you are satisfied that all actuators work correctly. You can activate multiple actuators simultaneously by entering the **sum** of their actuator control numbers. To make the Stiquito legs designated by V4 and V1 lift at the same time, enter 2 + 16, or 18, as the actuator control number.

```
10 OUT &H378, 0   'init both latches
   OUT &H37A, 4

   INPUT "latch function"; L
   INPUT "actuator control number"; A

   OUT &H37A, L
   OUT &H378, A

   FOR x = 1 TO 9000: NEXT x
   GOTO 10
```



This is a program to make Stiquito II walk forward using a tripod gait. Because the robot is articulated, you can place small obstacles in its path, and it will negotiate its way around or over them. Stiquito II will climb up and down a staircase with three or four broad shallow steps (about 3 inches deep × 8 inches wide × $^1/_8$ inch high).

```
      OUT &H37A, 0   'initialize both latches and all legs
      OUT &H378, 0

3     PRINT : PRINT : PRINT "turn on power supply now, then..."
      PRINT "press any key to start stiquito walking"
5     start$ = INKEY$
      IF start$ <> "" THEN GOTO 7 ELSE GOTO 5

7     PRINT "press any key to stop stiquito"
      PRINT "(you may have to wait a second or two)"
```

```
10   OUT &H37A, 1
     OUT &H378, 49
     OUT &H37A, 2
     OUT &H378, 49
     FOR x = 1 TO 9000
     NEXT x

     OUT &H37A, 1
     OUT &H378, 49
     OUT &H37A, 2
     OUT &H378, 0
     FOR x = 1 TO 9000
     NEXT x

     OUT &H37A, 0
     OUT &H378, 0
     FOR x = 1 TO 3000
     NEXT x

     OUT &H37A, 1
     OUT &H378, 14
     OUT &H37A, 2
     OUT &H378, 14
     FOR x = 1 TO 9000
     NEXT x

     OUT &H37A, 1
     OUT &H378, 14
     OUT &H37A, 2
     OUT &H378, 0
     FOR x = 1 TO 9000
     NEXT x

     OUT &H37A, 0
     OUT &H378, 0
     FOR x = 1 TO 3000
     NEXT x

     a$ = INKEY$

     IF a$ <> "" THEN OUT &H37A, 5: OUT &H378, 0: GOTO 3

     GOTO 10
```

8.4 IN CONCLUSION, SOME PROJECTS AND EXPERIMENTS

Here are some experiments and projects to try. Some are very difficult, others are very easy.

- Attach different feet to walk on different surfaces; use the results to design a dynamically reconfigurable foot actuated by nitinol.
- Use micro strain gauges to provide feedback to the controller about leg position.
- Compute the Froude number[1] of Stiquito II, Tensipede, and any insects you can obtain; compare the numbers to determine how insect-like nitinol-propelled robots are.
- Investigate different gaits and different ways to implement the tripod gait with Stiquito II; try to discover the optimal gait for Stiquito II and prove that it is or is not the tripod gait, and that it is or is not the same as an ant's actual gait (you may want to videotape both an ant and Stiquito II as they walk for later analysis).
- Design and build a self-contained Stiquito II or Tensipede that uses sensors, a microprocessor controller, and batteries to operate autonomously.
- Design and build a Stiquito II colony to investigate if and how cooperative and competitive behavior can emerge from primitive goals programmed into each robot.
- Design a genetic algorithm to evolve the tripod gait in Stiquito II.
- Build a solar-powered Stiquito II or Tensipede.
- Design a "space Stiquito" that uses shadow panels to alternately place nitinol actuators in light and shade; this is a mechanical oscillator with the side-effect of causing the robot to walk.
- Develop a gait controller that can be varied continuously from a metachronal wave gait to a tripod gait by changing only one variable.
- Use analog VLSI retina chips to control locomotion.
- Design and build new effectors using nitinol.
- Design and build sensors for heat, light, sound, motion, toxic chemicals, or radioactivity.
- Build a snake using the basic leg as a rib. Program the snake for serpentine locomotion.
- Build a biped using the basic leg as a segment in a larger biped leg.
- Store nitinol's energy to to build a robot flea. Find an analog to the substance *resilin* used by fleas to incrementally accumulate energy for their leaps.

Stiquito II and Tensipede are platforms for research and education. There are many more things to do with them than I have listed here. Build one of these robots yourself, and I hope **you** will get an idea for a Stiquito II or Tensipede project that interests **you**. If you do, then you will understand why I have taken the time, and tried my best, to teach you how to build these robots.

---

1 $$\text{Froude number} = \frac{(\text{speed of locomotion})^2}{\text{gravitational acceleration} \times \text{leg length}}$$

ACKNOWLEDGEMENTS

I want to thank all the persons who have written to suggest improvements and tell me of their work with Stiquito. There are hundreds of you who found different and interesting ways to use this tiny robot. If you had not showed such interest in Stiquito, I would not have written this report, or at least not invested as much effort in it.

Jon Blow, a graduate student in programming language design at the Experimental Computing Facility at the University of California, Berkeley, established and maintains the Stiquito mailing list that provides a forum for Stiquito users. Send requests to be added to or removed from the list to:

stiquito-request@xcf.berkeley.edu

Special thanks to the Stiquito II beta testers:

John Bay, Virginia Polytechnical Institute (Blacksburg)
Jim Conrad, University of Arkansas
John Estell, The University of Toledo
Russ Fish, University of Utah
Deryl Shields, Boeing Aerospace

Rod Douglas, Christof Koch and Terry Sejnowski, organizers of the NSF Neuromorphic Engineering Workshop, let me try Stiquito II out on a group of VLSI designers. I observed many mistakes that occur building Stiquito II; a number of participants built working robots...well, almost-working robots. Wait until next year's workshop!

All mistakes and errors in this report are mine. However, if you do not *read* this report before you try to build the robot, the mistakes and errors you make will belong to you alone. Nag mode off.

REFERENCES

References are legion because robotics spans so many disciplines. These references have been selected because they provide some "jumping off points" for research using Stiquito II, not a survey of all relevant books and articles. This technical report is long enough as it is.

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Mills, J. 1992. Stiquito: A Small, Simple, Inexpensive Hexapod Robot, Part 1: Locomotion and Hard-Wired Control. Technical Report #363a, Computer Science Department, Indiana University, September 1992.

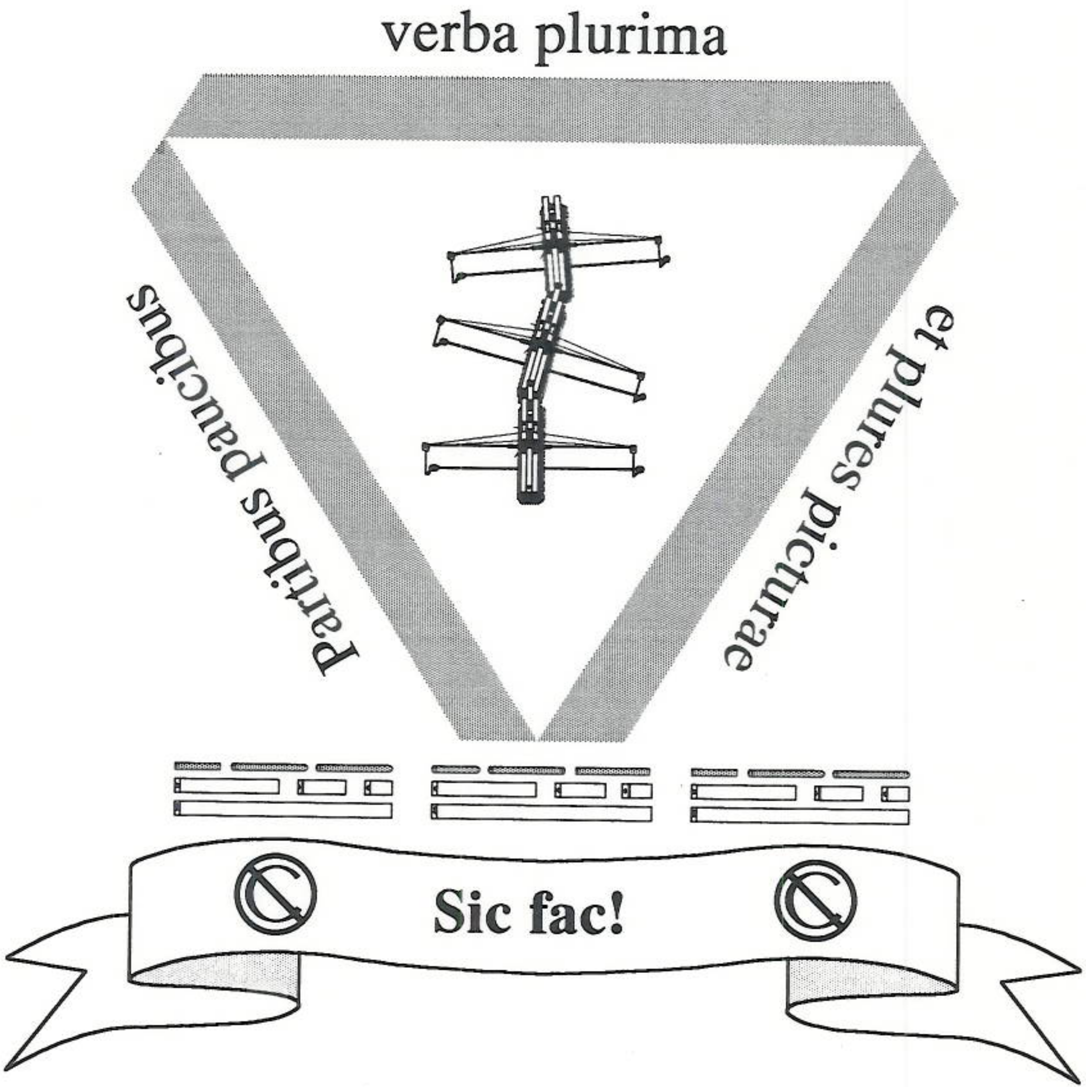
Mills, J. 1993. Lukasiewicz' Insect: The Role of Continuous-Valued Logic in a Mobile Robot's Sensors, Control and Locomotion. 23rd International Symposium on Multiple-valued Logic. Sacramento, California. May 24-27, 1993. p. 258-265.

A PARTING GIFT

Here is Stiquito's family crest.[2]

Copy the *enseigne orange pour l'appareil de la vitesse lente* at about half-size...

✓ ...and attach it to the last body segment before you send Stiquito II to visit its ants in Boston.



2 As explained by the Chevalier Pursuivant Mechaniqué: A Stiquito II *gris rampant sur une enseigne orange pour l'appareil de la vitesse lente,* enclosed by the motto *Paucibus partibus verba plurima et plures picturae,* surmounting *quatres baguettes grises et trois rayons de cuivres crouchants* over a *drapeau volant* emblazoned with *deux cachets noirs de droits d'auteur gratuits* and the command *Sic fac!* (From few parts, many words and more pictures; Just build it!)