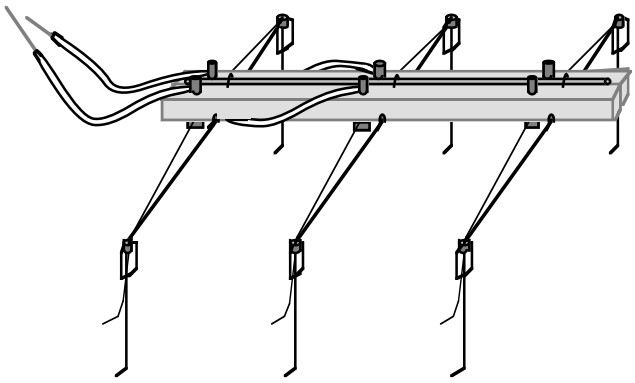
Stiquito: A Small, Simple, Inexpensive Hexapod Robot

Part 1. Locomotion and Hard-Wired Control



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80 figures illustrate the construction of a six-legged robot that walks up to 10 centimeters per minute and carries up to 50 grams. Nitinol actuator wires drive the robot's legs. Power and control are supplied through a tether or with on-board batteries and electronics. The robot provides an inexpensive platform to study computational sensors, subsumption architectures, neural gait control, behavior of social insects, and machine vision. A single robot costs between $10 and $30. The pro-rated cost of materials to construct robots in volume (200 or more) is less than $3. The design can be replicated to build complex arthropods, or colonies containing hundreds of insectoid robots.

1. INTRODUCTION

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

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A small, simple, and inexpensive six-legged robot that addresses these needs is described in this technical report. The robot is 60mm long × 70mm wide × 25mm high and weighs 10 grams. It is constructed of 32 parts of which 12 move: six legs bend in response to six nitinol actuator wires. (Nitinol wire, tradenamed *Flexinol™,* is an alloy of nickel and titanium that contracts when heated. It is also called shape-memory alloy. [1, 2]) Most parts of the robot perform more than one electrical or mechanical function, but the design can be easily modified. For example, pairs of legs and actuators can be replicated to produce a mechanical centipede with flexible joints between leg segments.

The robot is intended for use as a research and educational platform to study computational sensors [3, 4], subsumption architectures [5], neural gait control [6], behavior of social insects [7], and machine vision [8]. The robot may be powered and controlled through a tether, or autonomously with on-board power supply and electronics [9]. It is capable of carrying up to 50 grams while walking at a speed of 3 to 10 centimeters per minute over slightly textured surfaces such as pressboard, indoor-outdoor carpet, or poured concrete. The feet can be modified to walk on other surfaces. The robot walks when heat-activated nitinol actuator wires attached to the legs contract. The heat is generated by passing an electric current through the nitinol wire. The legs can be actuated individually or in groups to yield tripod, caterpillar, or other gaits.

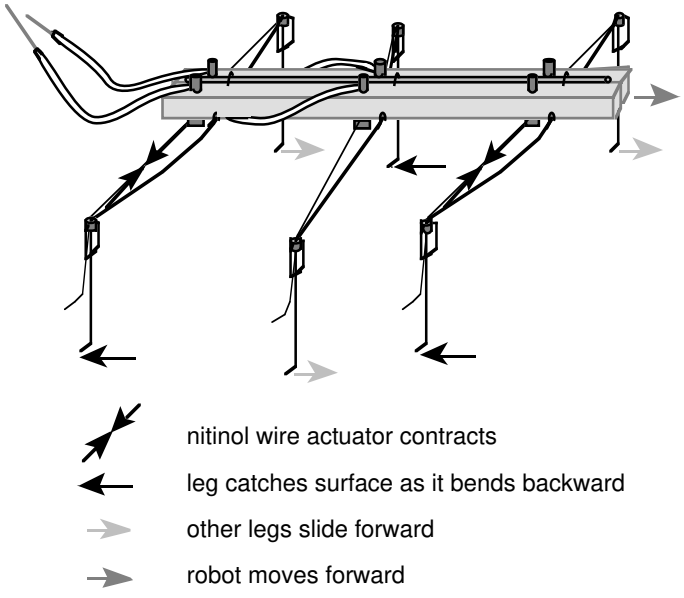


Figure 1. How the robot walks

The robot is named Stiquito after its larger and more complex predecessor, Sticky.

2. PREPARING TO BUILD STIQUITO

All materials and tools must be on hand before building the robot. This technical report may have been purchased with an attached kit that contains all the materials needed to construct Stiquito. If so, check the materials in your kit against the parts list. If anything is missing, or if you prefer to build the robot from scratch, obtain materials at a hobby shop or directly from the vendors. The tools needed to construct the robot are typically available in university shops or laboratories. If not, they may be purchased in electronics supply stores or hobby shops.

A clear workspace and a relaxed frame of mind will be helpful during construction, especially when installing the nitinol actuators. Correct installation of the actuators will result in a robot that walks well, while a sloppy job will almost certainly lead to one that barely twitches.

2.1 MATERIALS LIST

A single robot may be constructed for a cost of $10 to $30 depending on your ability to scrounge materials. Nitinol wire is available in a minimum length of one meter for a cost of $10, enough to build two Stiquitos. It is the most expensive part of the robot. The pro-rated cost of materials used to construct Stiquitos in volume (200 or more) is much less: $2.97 each in 1992.

Amount	Cost	Part Number	Item
180 mm	.24	Plastruct ST-4 570-704	$^1/_8$" square × 15" long plastic rod
200 mm	.16	K&S Engineering No. 100	$^1/_{16}$" o.d. aluminum tubing
370 mm	.08	K&S Engineering No. 499	.020" music wire
420 mm	2.31	Dynalloy .004" Dia. 70°C	.004" (100µm) nitinol wire (*Flexinol®*)
60 mm	.02	generic	20 AWG copper hook-up wire
200 mm	.01	generic	28 AWG wire-wrap wire
1500 mm	.05	generic	34 AWG copper magnet wire
1 ea	.10	generic	9-volt terminal assembly

A kit including all materials and this report is available from the Computer Science Department, ATTN: TR 363a Stiquito, 215 Lindley Hall, Indiana University, Bloomington, Indiana, 47405 for **$15 US pre-paid**. The charge covers materials, a kitting fee, this technical report, and mailing. You are authorized to build as many Stiquitos as you want for research or education. Indiana University reserves all rights to commercial sale or use. The kit is provided as a non-profit service by Indiana University. The author receives no fee or reimbursement from the sale of the kit.

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 on qualifying orders. The

aluminum tubing and music wire are available from K&S Engineering (tel. 312-586-8503), 6917 W. 59th Street, Chicago, IL. Hobby shops carry these products, also. The hook-up wire, wire-wrap wire, and magnet wire are available at electronic supply stores. 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 (510-351-5930), 2476 Verna Court, San Leandro, CA, 94577 (who also sell a great tutorial book about working with nitinol [2]).

2.2 TOOLS LIST

The following tools needed to build this robot:

- needlenose pliers
- wire cutters
- butane lighter (or matches)
- small knife (X-Acto type)
- pin vise with 1/16" drill bit and 1/64" drill bit
- small saw (X-acto or Zona type)
- miter box (or other holder/stop)
- ruler graded in millimeters
- volt-ohm meter *or* two AA batteries and holder
- fine sandpaper (320 grit)
- ultra fine sandpaper or emery paper (600 grit)
- model cement (methyl ethyl ketone)

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 if many robots will be built.
- Avoid inhaling the fumes of model cement: work in a well-ventilated area.
- Use a piece of pressboard, dense cardboard, a cutting board, etc. to protect your work surface, if necessary.

2.3 REQUIRED SKILLS

This section has been included for the benefit of those readers who have not assembled kits before. Practice the skills needed to build Stiquito before assembling the robot, using scrap plastic and thin wire. The kit has extra material in case of mistakes, but there is not enough to practice with.

2.3.1 MEASURING

Following the adage *measure twice, cut once* will prevent most mistakes. Use any metric ruler graded in millimeters. Most figures in this report are life-size, so any dimensions included may be used to measure parts. If many robots will be made, mark part measurements on the miter box.

2.3.2 SAWING

Clamp plastic rod and aluminum tubing in the miter box with a small scrap of wood (one-half of a spring-closed clothespin works nicely). Either mark the rod or tube before cutting it, or mark the miter box, with the length of the part. Saw with light, even pressure using full strokes. Hold the saw vertically to keep it from binding in the part. To prevent tubing from rolling as it is being sawed, place the miter box on a surface that is not slippery. This transfers most of the energy of the stroke into the cut.

2.3.3 CUTTING

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. Make small cuts to avoid removing too much material or making too large or deep a cut.

2.3.4 DRILLING

Mark the location of holes with a pencil before you drill. 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 bends, ease up on the pressure. Be careful not to drill through the material used to brace the part. After making the hole, twist the bit in it, as well as sliding the bit into and out of the hole. This will ensure that the hole is the correct diameter and smooth inside.

2.3.5 DEBURRING

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

2.3.6 SANDING

The ends of plastic rod and aluminum tubing should be sanded with fine (320 grit) sandpaper to debur them. Lightly sand nitinol and music wire with ultra fine (600 grit) sandpaper or emery

paper to remove oxide. Sand the wire after it is bent or knotted to avoid breaking it. Sanding wire too much may weaken it enough to break during assembly or when the robot is operating.

2.3.7 GLUING

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 let the assembly dry at least two hours before cutting or drilling it.

2.3.8 KNOTTING AND CRIMPING NITINOL WIRE

Nitinol is similar to stainless steel. The .004" nitinol used in this robot can be knotted without breaking the wire as long as the knot is not tightened excessively. Knotting and crimping nitinol wire is the most reliable way tested to attach the actuators. Nitinol actuators must be taut, and attached so they cannot pull loose, if this robot is to walk well. The knot-and-crimp attachments have proven reliable for over 300,000 cycles (approximately 100 hours of continuous walking).

Of the other ways to anchor nitinol actuators, a U-shaped bend in the nitinol wire can pull far enough out of a crimp to reduce leg motion; soldering is difficult to control because the wire contracts and may lose its "memory"; soldering and epoxying nitinol wire may not hold under repeated actuation; and pinning or screwing the nitinol wire to the small parts used in the robot is more complex than knotting and crimping.

To tie a knot, make a loop in the wire, run one end of the wire through the loop to make an overhand knot, then pull by hand to decrease the diameter of the knot's loop to about 3mm. Slide the knot nearly to the end of the wire using a length of stiff wire, then grasp the end of the wire nearest the knot with the needlenose pliers, and holding the other end of the wire (or the crimp if one is attached to the other end) with your hand, pull sharply several times with the needlenose pliers to tighten the knot. The knot is tight enough when a small loop, approximately 0.1mm in diameter, remains. Continuing to tighten the knot may break the wire.

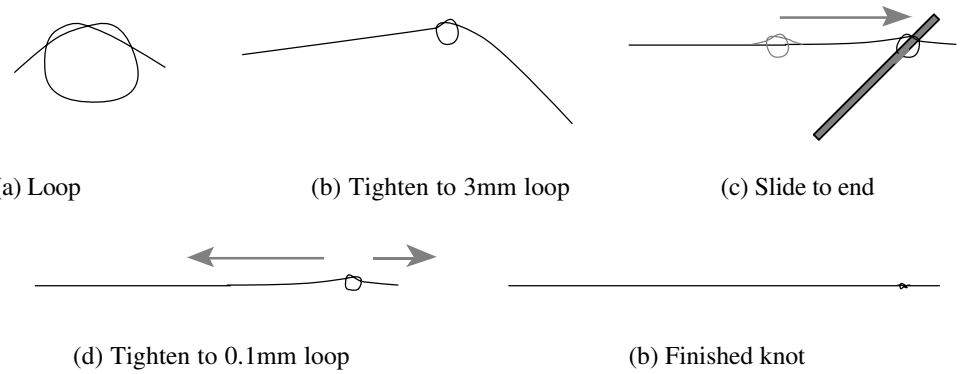
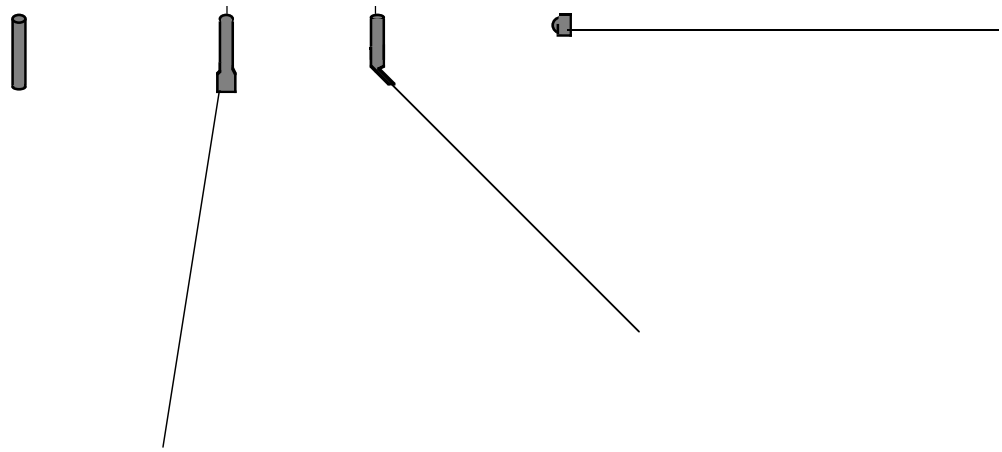


Figure 2. Knotting nitinol

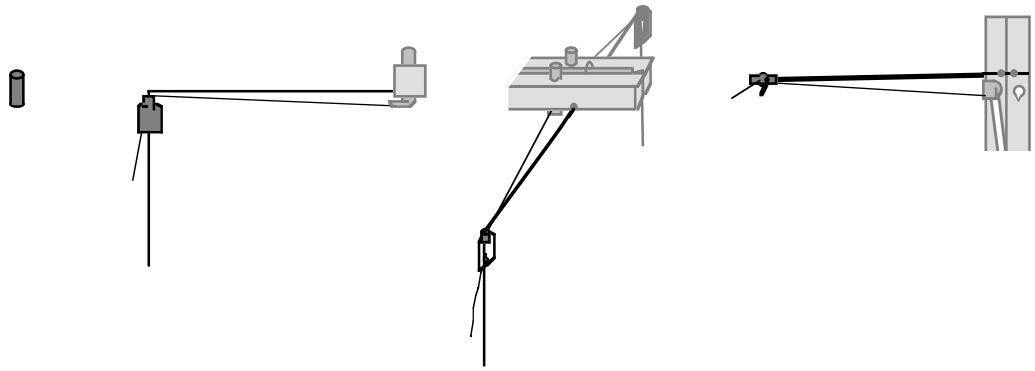
Crimps are hollow connectors that are squeezed shut to hold, attach, or connect one or more objects. This robot uses short lengths of aluminum tubing as crimps to anchor the knotted nitinol actuator wires securely. Two types of crimps are needed. Body crimps hold the actuator wire alone. They are press-fitted into holes in the robot's body to attach the actuator wires indirectly to the control wires. There is no electrical connection between the actuator wire and the plastic body.



(a) Crimp (b) Side view (c) Side view rotated 90° (d) Bottom end view

Figure 3. Body crimp (views with respect to body crimp)

Leg crimps hold both the actuator wire and the music-wire leg. Leg crimps directly attach and electrically connect the actuator wire to the music-wire leg.



(a) Crimp (b) Side view (c) Side view rotated 90° (d) Bottom end view

Figure 4. Leg crimp (views with repect to leg crimp)

2.3.9 FIXING MISTAKES

No matter how carefully you work, mistakes do happen. Most are easy to fix, because almost all steps in the construction of Stiquito allow some tolerance, **except for tensioning the nitinol actuator wires, where no slack is allowable.** Here are some common problems, and how to work around them.

Part cut too short or too long. If the error is 5mm or less, reduce or increase the length of other parts, or the distance between parts (such as the legs). Smaller (or larger) Stiquitos will still work.

Parts misaligned. The top and bottom sides of the body halves should be even. If the halves do not align along the seam use a small knife to cut them apart, then re-glue them. The ends of the legs can be 5mm or more out of position after installation. Adjust the legs by bending them into position, and they will work.

Groove or hole out of position. If it is really bad (more than 2mm out of position), there is room to re-cut the groove or re-drill the hole at the right place. Otherwise use the groove or hole as is.

Leg clip groove too deep. Fix a leg clip groove that is too deep by gluing a piece of scrap plastic into the groove to restore structural strength, then making a new leg clip groove 2mm away from the bad one.

Body breaks at leg clip groove. If the body breaks, or if you saw through the body while making a leg clip groove, saw two new **vertical** faces at the break and glue the body back together. The body may be 2 or 3mm too short, but it will still work.

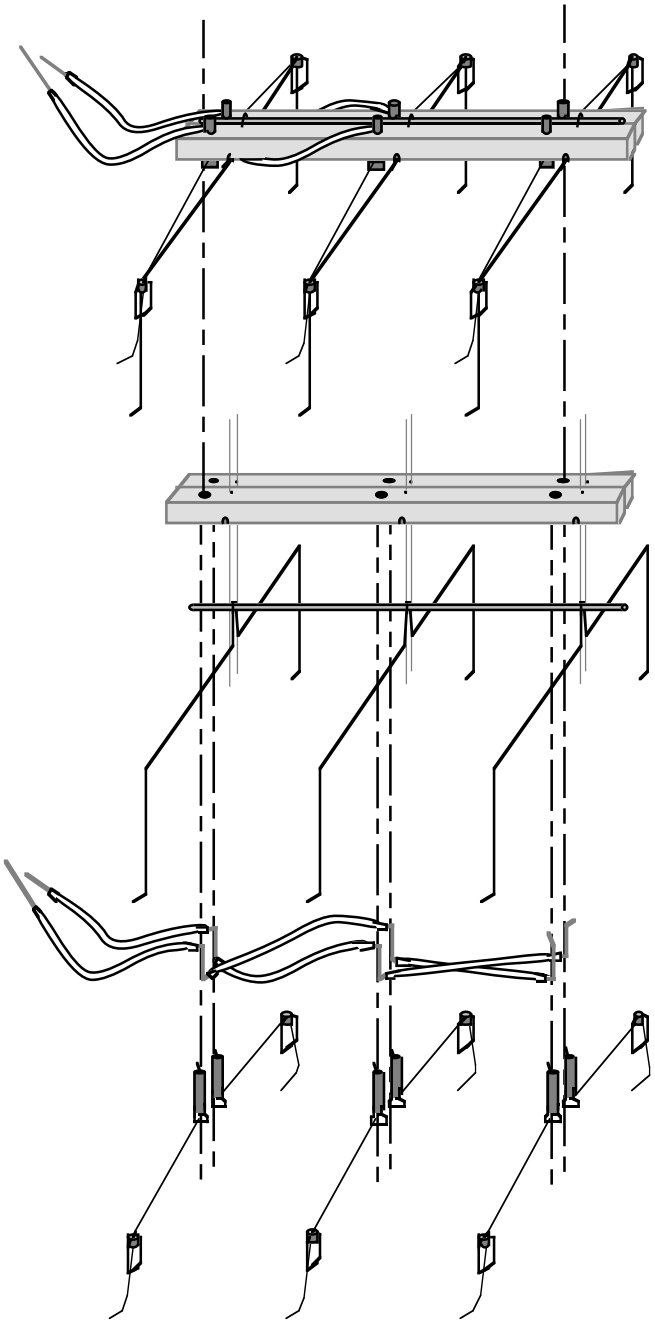
Music wire bent incorrectly. 90° bends or greater can be re-bent gently once or twice before breaking the wire. Bends less than 90°, such as the 15° V-clamp in the legs, usually break if re-bent. Stiquito will work with four legs if you can not find more music wire. Stiquito will work with .015" diameter music wire, but can not carry much weight.

Knot in wrong place. Tie a new knot and keep going. You may want to cut the nitinol to 70mm lengths instead of 60mm lengths for this reason. Untying tight knots in nitinol usually breaks it.

Crimp must be removed or replaced. Crimps can be gently squeezed across the wide dimension to undo them, but should then be discarded. Extra tubing is provided to make new crimps. You will probably re-do the leg crimps once or twice until you get the hang of tensioning the actuator wires.

3. CONSTRUCTING STIQUITO

Stiquito has four major assemblies: the body, the legs and power bus, the control wires, and the actuators. The actuators are made of nitinol wire.



1. Body
2. Legs and power bus
3. Control wires
4. Actuators

Figure 5. Stiquito assemblies

3.1 THE BODY

The body provides structural strength and locates the attachment points for the legs and the nitinol actuator wires.

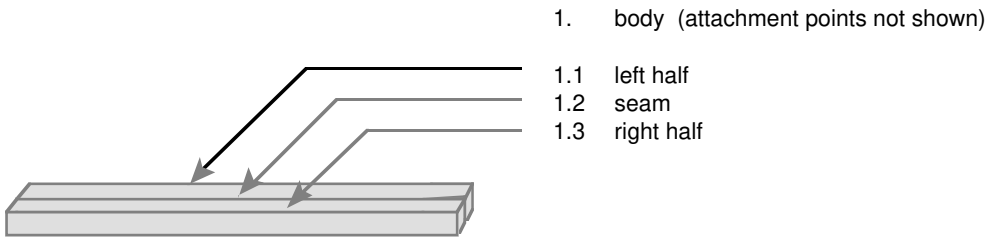


Figure 6. The body

To construct the body, cut two 60mm lengths of 1/8" styrene rod (or remove the two pre-cut lengths from the kit). Apply model cement to one entire side of each of the two lengths of rod. Let the cement dry for one or two seconds (or enough to become tacky; it will appear dull), and apply five additional, evenly-spaced drops of cement to each side.

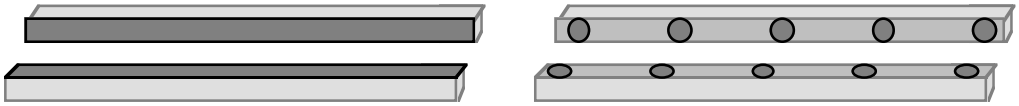


Figure 7. Applying cement

Let dry for one or two seconds more, then press the two sides together and hold for 15 seconds.

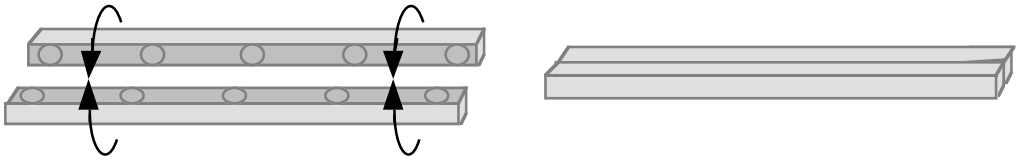
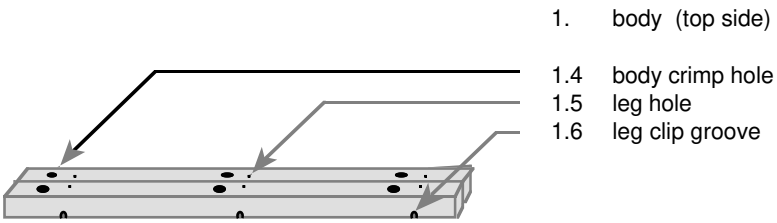


Figure 8. Joining the sides

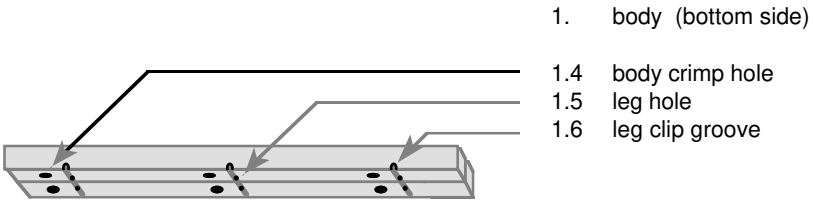
Let dry for several minutes, then brush the top and bottom seam lightly with cement. Set aside for at least 15 minutes, or preferably for two hours, to develop full strength.

Figure 9. Strengthening the seams (top side shown)

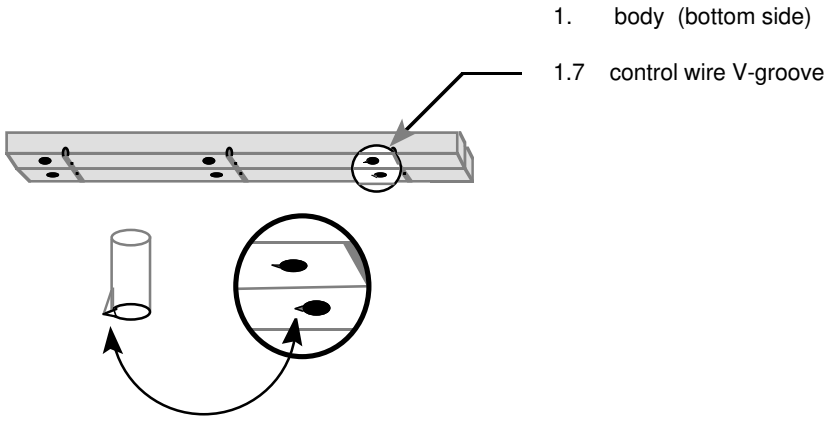
The attachment points for the legs and actuators are a series of holes and grooves that are drilled, sawed, and cut into the body.



(a) Top side of body



(b) Bottom side of body



(c) Detail of control wire V-groove (enlargement ×2)

Figure 10. Attachment points

Begin constructing the attachment points by marking three horizontal lines on one wide side of the body. This will be the bottom side. The lines locate the leg holes and the leg clip grooves. Mark two lines 7mm from each end. Mark a third line in the middle 30mm from each end. This spaces the three lines 23mm apart.

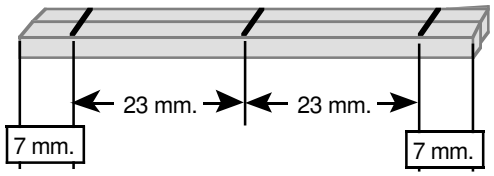
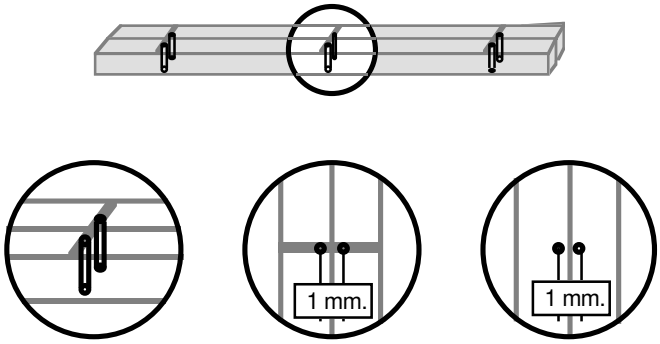


Figure 11. Mark three horizontal lines

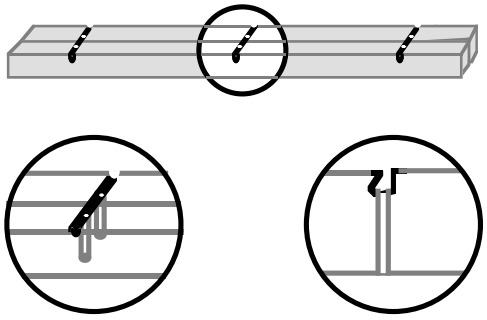
Drill two .025" diameter leg holes 1mm apart on each line. Center the seam between the leg holes so that each leg hole is 0.5mm from the seam. Drill completely through the body, keeping the leg holes vertical. If drilled perfectly, the leg holes will emerge on the top side 1mm apart, with the seam centered between them. The leg holes locate and align the leg pairs and locate the bend in the music wire that will clamp the power bus securely to the top side of the body.



(a) Detail (b) Bottom view (c) Top view

Figure 12. Leg holes (all enlargements ×2)

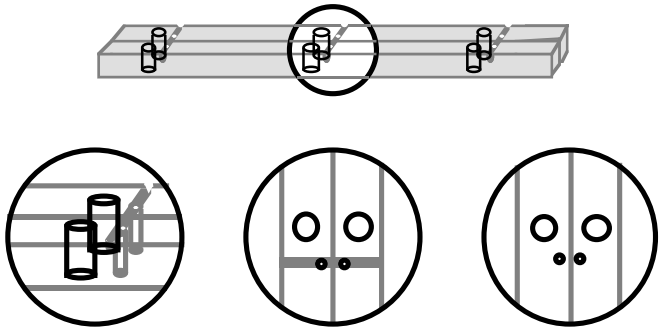
Construct the leg clip grooves next. Saw a cut 1mm deep along each horizontal line on the bottom side of the body. The cut should cross the center of each leg hole. Next rotate the saw forward about 45° and make a cut, then, while slowly rotating the saw back to vertical, saw continuously to make a rounded or triangular channel that is wider at the bottom than the top. This is the leg clip groove that holds each leg horizontally and isolates it mechanically from the other leg in the pair. The leg clip groove can also be made by pressing a length of heated music wire into the body, removing it, and drilling through the melted plastic to re-open the leg holes.



(a) Detail ×2 (b) Side view ×4

Figure 13. Leg clip grooves (enlargements vary)

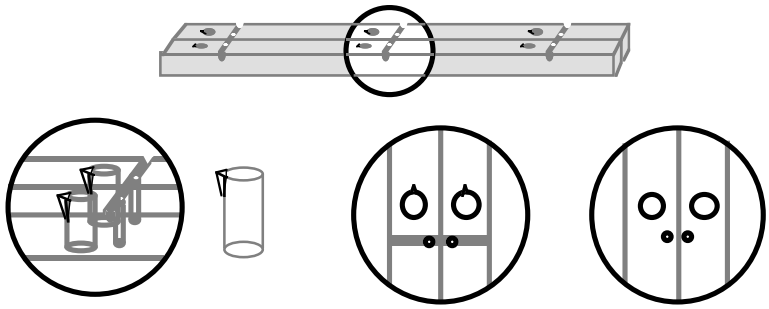
Drill two 1/16" diameter body crimp holes 1mm behind each clip-groove, centered in each half of the body. Drill completely through the body, keeping the body crimp holes vertical.



(a) Detail (b) Bottom view (c) Top view

Figure 14. Body crimp holes (all enlargements ×2)

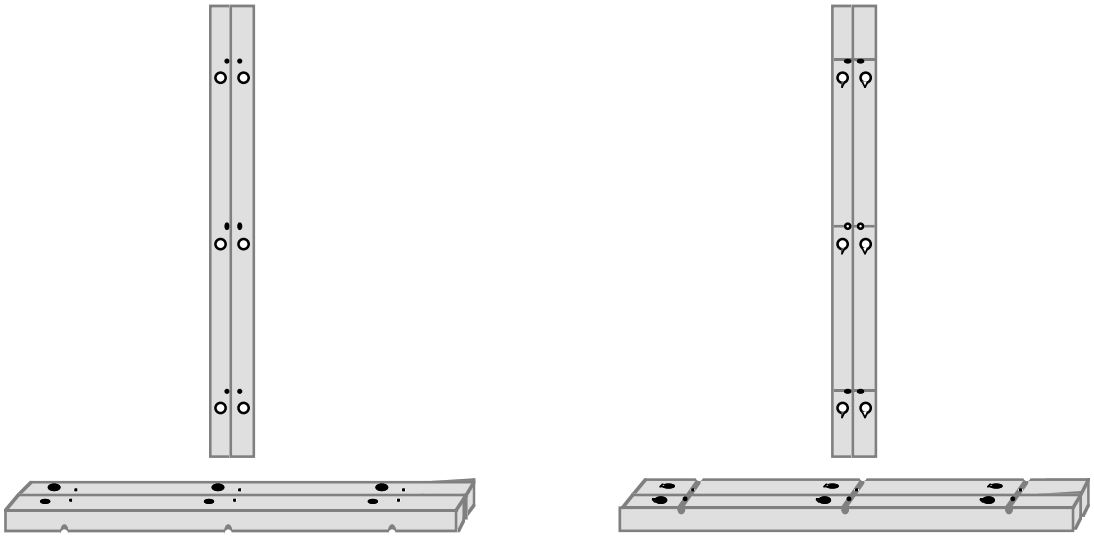
Use the knife to cut a small V-shaped groove on the bottom rear side of each hole. The groove should be deepest on the bottom side of the body, and tapered to a finish about 1mm into the body crimp hole. The V-groove should not extend to the top side of the body, or the control wires may not make a good electrical connection to the body crimp. The V-shaped grooves locate the control wires, allowing the body crimps to be press-fitted into the body crimp holes without breaking the body crimps or the control wires. Pressure holds the control wires in place and and electrically connects them to the outside of the body crimps.



(a) Detail (b) Bottom view (c) Top view

Figure 15. Control wire V-grooves (all enlargements ×2)

This completes the body.



(a) Top side (b) Bottom side

Figure 16. Finished body

3.2 THE LEGS AND POWER BUS

The legs are assembled in pairs from three 100mm lengths of .020" music wire. The music wire legs perform three functions:

- Support. The legs support the weight of Stiquito, and its battery and control electronics. Because the wire is bent to fit into a leg clip groove sawed in the body, each leg in the pair is mechanically isolated.

- Power distribution. All legs share a common electrical power connection to the power bus, and route current to the nitinol actuator wires. The V-bend in the music wire clamps the power bus to the top of the body and electrically connects it to the legs.

- Recovery force. The music wire acts a leaf spring to provide recovery force for the nitinol wire actuator. Without this spring, or if the actuator is attached loosely, the nitinol wire will contract, but fail to return to its original extended length.

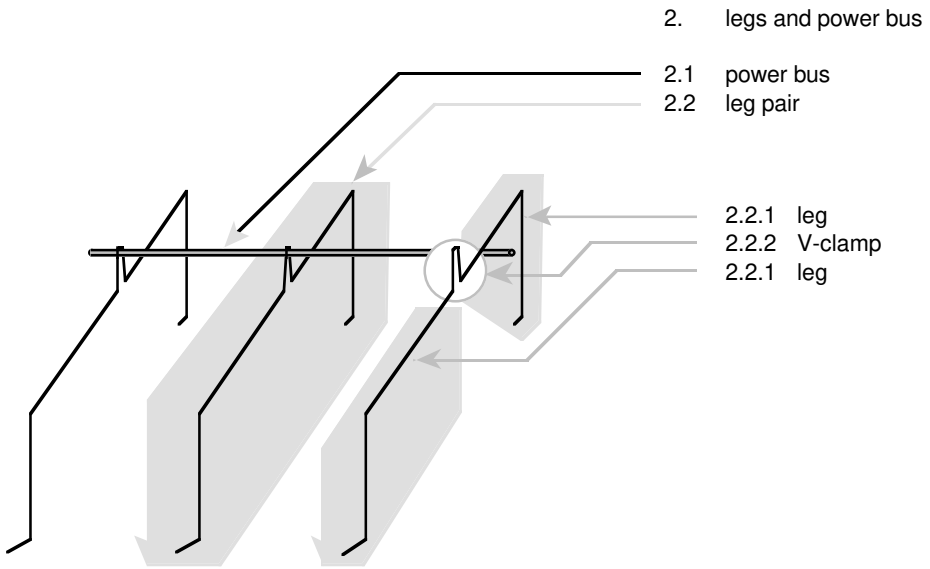


Figure 17. Legs and power bus

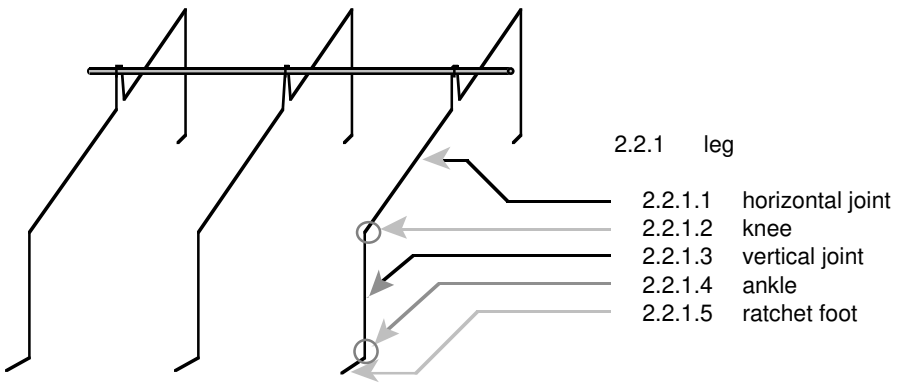


Figure 18. Leg detail

Begin assembling the legs by cutting three 100mm lengths of .020" music wire (or remove the three lengths from the kit). Bend each music wire in the middle to a 15° angle. Do not bend the wires too far, or they may crack or break. The apex that forms the V-clamp should be rounded, not sharp. Lightly sand the inside of each V-clamp with the 600 grit sandpaper to remove oxide.

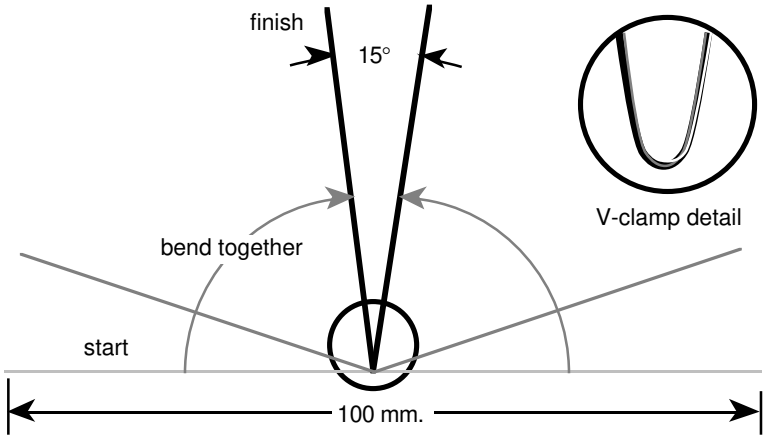


Figure 19. Bending the legs (enlargement ×6)

Cut a 60mm length of 20 AWG copper wire (or remove the length of copper wire from the kit). This is the power bus.

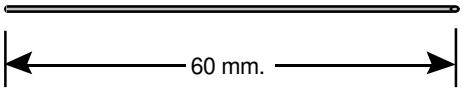
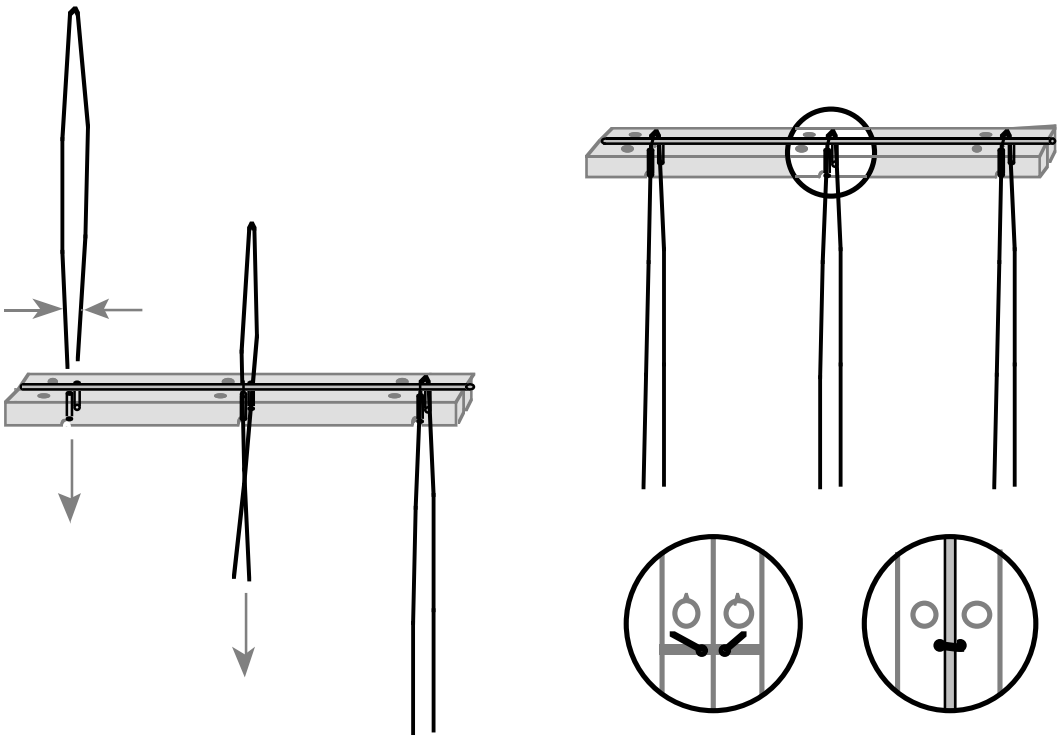


Figure 20. Power bus

Lay the the power bus along the top body seam between the leg holes. Temporarily clamp the power bus by bending the legs together, inserting them through the leg holes, then pulling the legs through from the other side until the power bus is held tightly by the V-clamp.



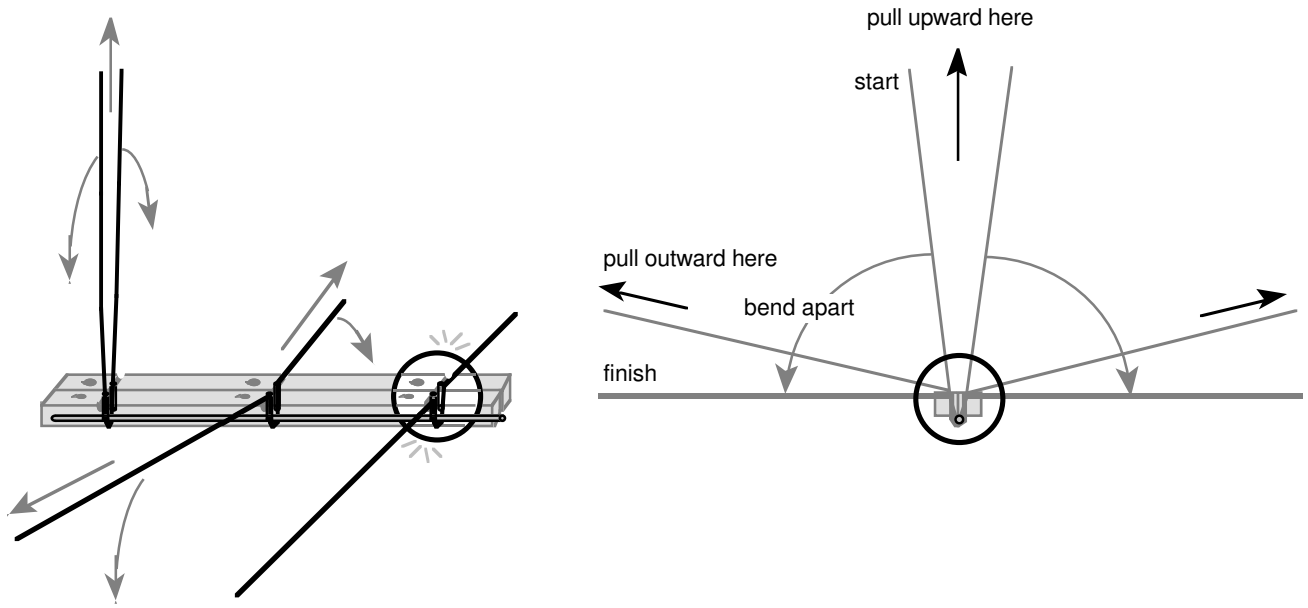
(a) Inserting the legs (b) Bottom view (c) Top view

Figure 21. Temporarily clamping power bus with the legs (all enlargements ×2)

Turn the body over and permanently clamp the power bus, simultaneously attaching the legs, by spreading each leg in the pair outward by hand, at the same time pulling upward on the legs. When the legs are almost horizontal, grasp each leg in turn with the needlenose pliers and firmly bend it downward, while continuing to pull outward, until the leg snaps into the clip groove.

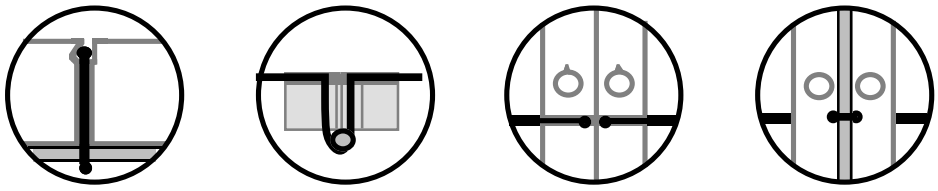
At this point the power bus should be securely clamped into place. Check to ensure that it will not touch any of the body crimps (insert the length of aluminum tubing and check with the volt-ohm meter). Also check that the electrical connection between the power bus and the legs is good. It should be less than 2 ohms.

Adjust the legs so that they are in a plane horizontal with the bottom of the body, and parallel to each other.



(a) Side view, bottom of body (b) End view

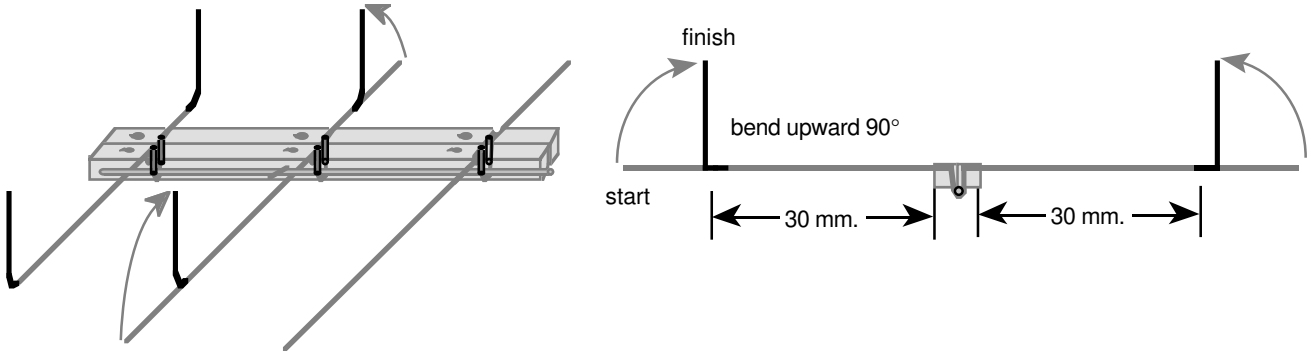
Figure 22. Permanently attaching the legs and clamping the power bus



(a) Side view ×4 (b) End view ×2 (c) Bottom view ×2 (d) Top view ×2

Figure 23. Detail of attached legs and clamped power bus (enlargements vary)

Working with the bottom of the body facing upward, form the knee, which separates the horizontal joint from the vertical joint of each leg, by bending the music wire 90° up about 30mm from the edge of the body. Adjust the vertical joints so they are parallel.



(a) Side view, bottom of body (b) End view

Figure 24. Forming the knee, and the horizontal and vertical joints

Trim the vertical joints using the wire cutters so that all legs touch the ground. This completes assembly of the legs and power bus.

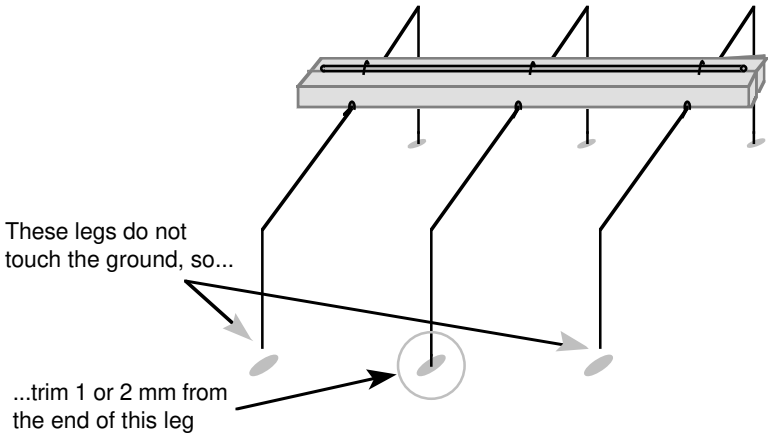


Figure 25. Triming the vertical joints

Do not bend the music wire to make the ratchet feet now. Wait until the actuators have been completed and tested.

3.3 THE CONTROL WIRES

Cut two 120mm lengths of wire-wrap wire for control wires (or remove the two lengths from the kit). Prepare the control wires for a hardwired tripod gait by stripping 12mm of insulation from each end.

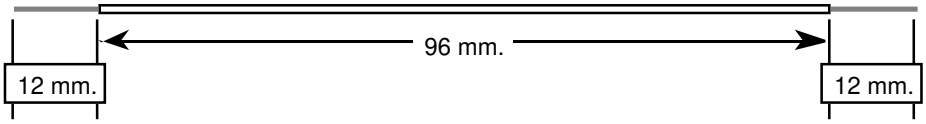


Figure 26. Control wire

Next, separate two lengths of insulation, leaving them on the wire. Use a knife to make a cut in the insulation 34mm from one end of the wire. Make a second cut in the insulation 61mm from the same end. Cut all the way through the insulation, all around the wire. Do not cut the wire.

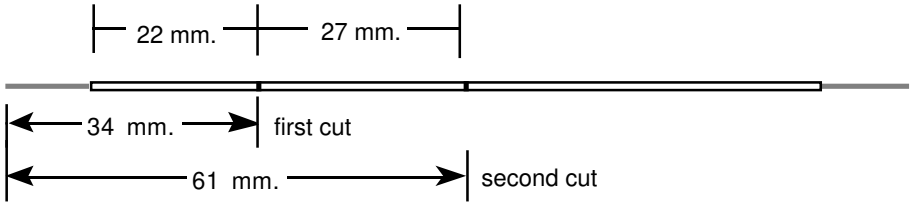


Figure 27. Separating two lengths of insulation

Gently slide the sections of insulation toward the nearest end, leaving 4mm of bare wire at the end and at two places in the middle of the wire. This is a control wire. Make two of them.

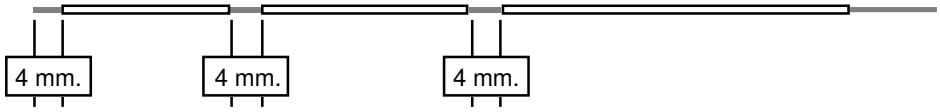


Figure 28. Finished control wire

> Do not install the control wires now. The control wires will be installed when the actuators are attached.

3.4 THE ACTUATORS

Stiquito is small and simple because it uses nitinol actuator wires.

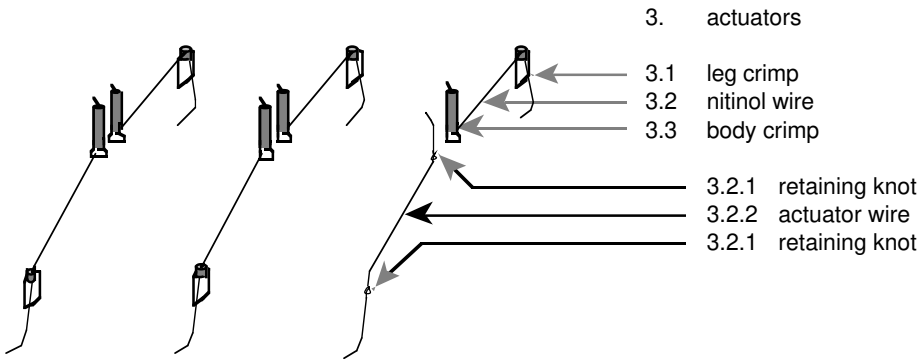


Figure 29. Actuators

The nitinol wire translates the heat induced by an electric current into mechanical motion, replacing stepping motors, screws, and other components otherwise needed to make a leg move. The mechanical motion results from changes in the crystalline structure of nitinol. The crystalline structure is in a deformable state (the martensite) below the martensite transformation temperature, M_t. In this state the wire may change its length by as much as 10%. The nitinol wire is purchased as an expanded martensite (that is, a *trained* wire).

When the wire is heated above the austenite transformation temperature A_t (1), the crystalline structure changes to a strong and undeformable state (the austenite). As long as the temperature of the wire is kept slightly above A_t, the wire will remain contracted. During normal use of the nitinol wire, a recovery force, or tension, is applied while it is an austenite.

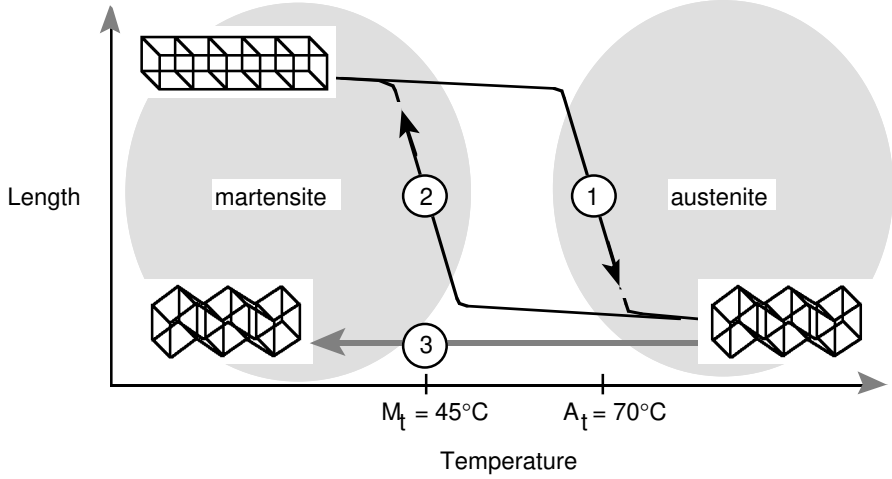


Figure 30. Changes in crystalline structure of nitinol

When the temperature falls below M_t the austenite transforms back into the deformable martensite (2), and the recovery force pulls the wire back into its original, expanded form. If no recovery force is applied as the temperature falls below M_t, then the wire will remain short as it returns to the martensite (3), although it can recover its original length by cycling again while applying a recovery force. If the wire is heated too far above A_t, then a new, shorter length results upon transformation to the martensite; the "memory" of the original, longer length cannot be restored.

Nitinol wire will operate for millions of cycles if it is not overheated and if a suitable recovery force is applied during each transformation. Stiquito's manual controller prevents overheating if used as directed. Autonomous controllers must limit the current supplied to the nitinol actuator wires to avoid overheating them. The music wire legs provide the correct recovery force.

The actuators, legs, and power bus combine to route power, provide the recovery force, and support the robot.

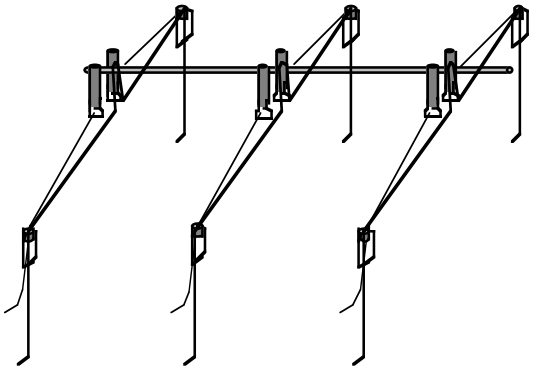


Figure 31. Actuators, legs, and power bus

Six steps are needed to build the actuators, attach them to the legs and body, and form the ratchet feet.

3.4.1 CUT NITINOL WIRES TO SIZE

Begin making the actuators by cutting six 60mm lengths of nitinol wire (there will be an extra 60mm length of nitinol wire left over if you purchased the kit). You may prefer to use all the nitinol in the kit, and cut six 70mm lengths to make it easier to tie the retaining knots during installation of the leg crimps.

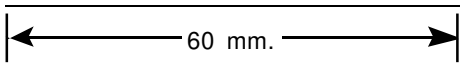


Figure 32. Nitinol wire

3.4.2 MAKE BODY AND LEG CRIMPS

Next select a length of aluminum tubing at least 100mm long (or remove the 100mm length of aluminum tubing from the kit). It will be used to make the leg and body crimps. Using the saw and miter box, cut six 9mm body crimps and six 4mm leg crimps from the aluminum tubing. Sand the ends of the crimps, then run the .025" bit through them to deburr the ends.

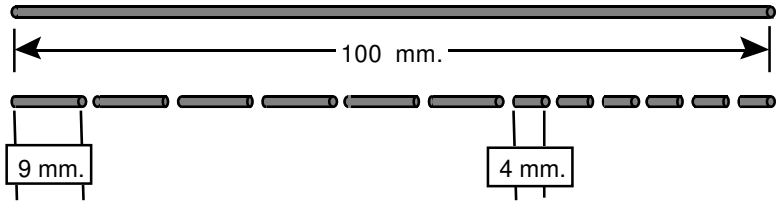
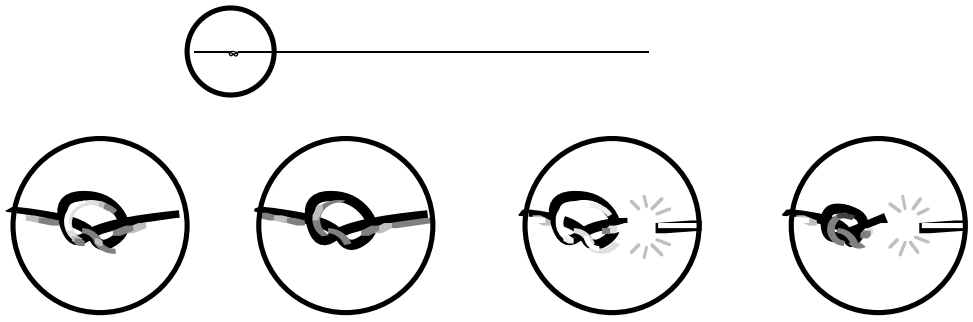


Figure 33. Body and leg crimps

3.4.3 ATTACH BODY CRIMPS TO NITINOL WIRES

Attach a body crimp to each length of nitinol wire. Tie a retaining knot in one end of the wire. Using the 600 grit sandpaper, lightly sand the nitinol wire at the knot to remove oxide and improve the electrical connection to the body crimp.



(a) Correct (b) Sanded too lightly (c) Sanded too much (d) Tied too tightly

Figure 34. Tying and sanding retaining knot (all enlargements ×10)

Select a 9mm body crimp, insert the .025" bit, and twist it back-and-forth while sliding it in and out. This removes aluminum oxide for a better electrical connection. Insert the knotted end of the wire into a body crimp and pull it through the crimp; the knot must extend out the other end.

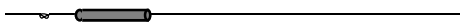
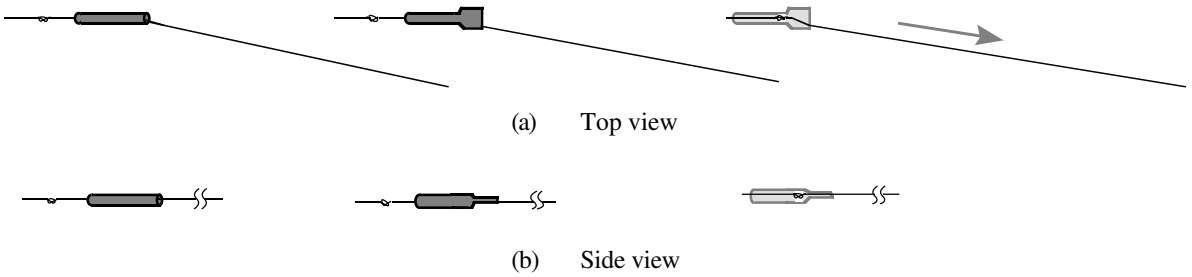


Figure 35. Knotted end of nitinol wire inserted into body crimp

Turn the crimp until the nitinol wire is at either the right or left side of the crimp, then, using the needlenose pliers, squeeze shut about 2mm of the body crimp at the end opposite the knot. The unknotted wire should protrude from either the right or left side of the flattened part of the crimp, not the middle. Pull the knotted end back into the crimp until the retaining knot catches in the crimped end.



(a) Top view

(b) Side view

Figure 36. Attaching body crimp to nitinol wire

Orient three body crimps so the nitinol wire exits from the left side of the flat, crimped end, and three so the nitinol wire exits from the right side of the flat, crimped end. This ensures that the nitinol wire will protrude as far to the rear as possible from the music-wire leg when the actuator is attached to the body.

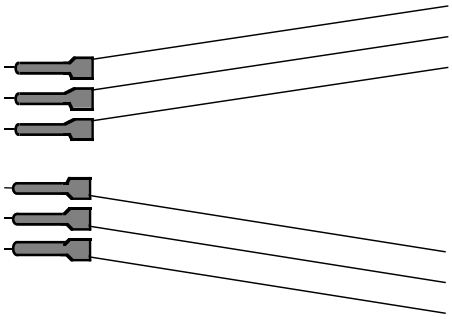


Figure 37. Left- and right-oriented body crimps

Next, retaining the left- and right-handed orientation of each body crimp, grasp the flat end of each body crimp with the needlenose pliers and bend it upward to a 45° angle.

Figure 38. Bending the body crimp

You should now have three left and three right body crimps with nitinol wire attached.

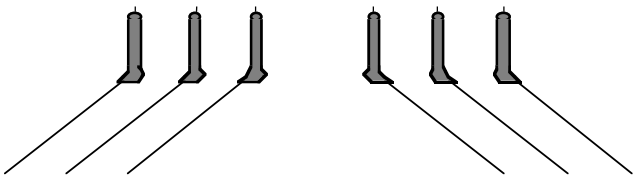


Figure 39. Finished left- and right-handed body crimps

3.4.4 INSERT CONTROL WIRES AND BODY CRIMPS INTO BODY CRIMP HOLES

Viewing the body with the bottom side facing upwards, and the front of the body at the top, use left-handed body crimps on the left side of the body, and right-handed body crimps on the right side of the body. This will locate the attachment point for each actuator wire as far to the rear of the leg as possible.

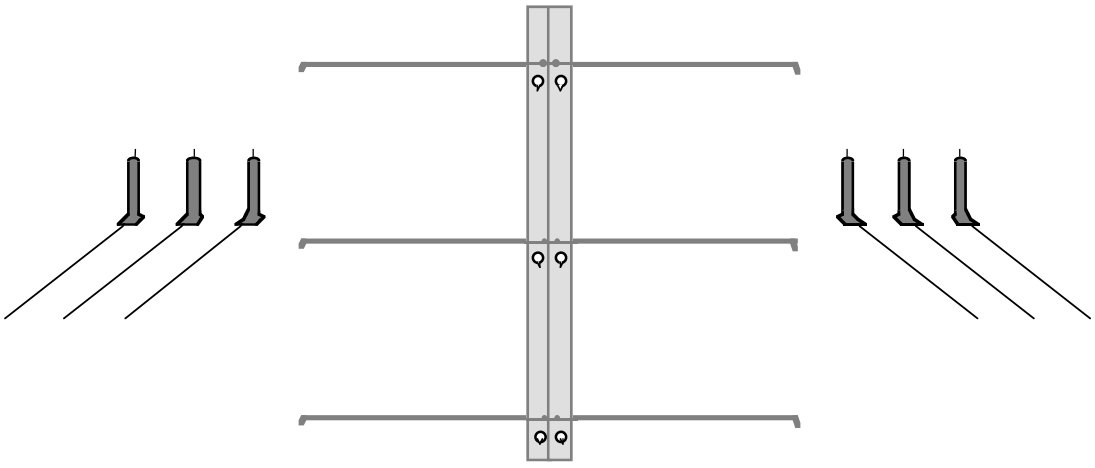


Figure 40. Orienting body crimps to the bottom side of the body, front of body at top

Beginning at the front of the body, insert the end of one control wire so that the bare wire enters the front left body crimp hole at the V-groove.

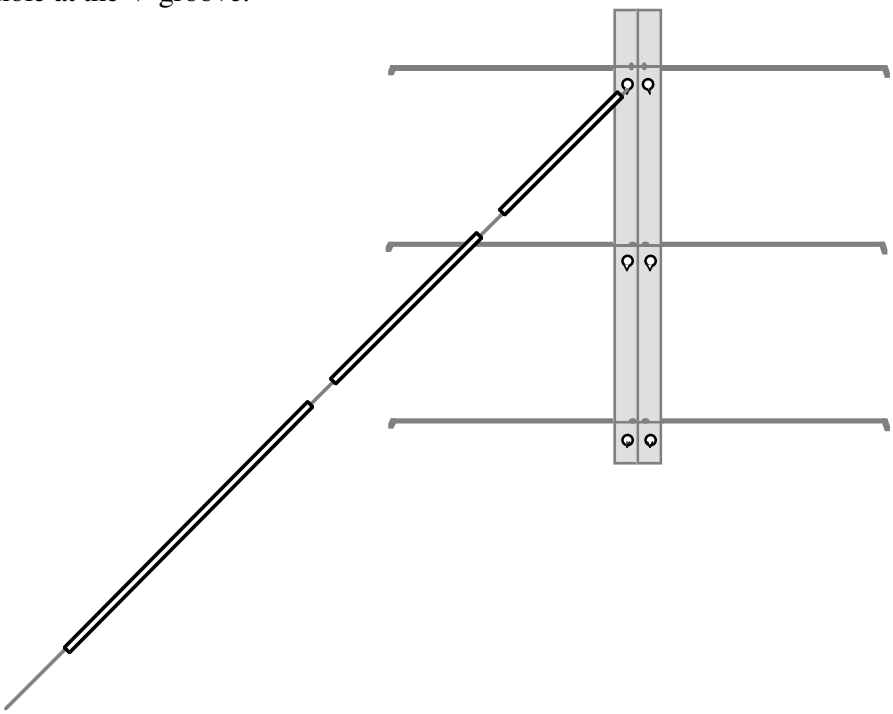


Figure 41. Inserting control wire

Orient and insert a left-handed body crimp into the body crimp hole, securing the control wire.

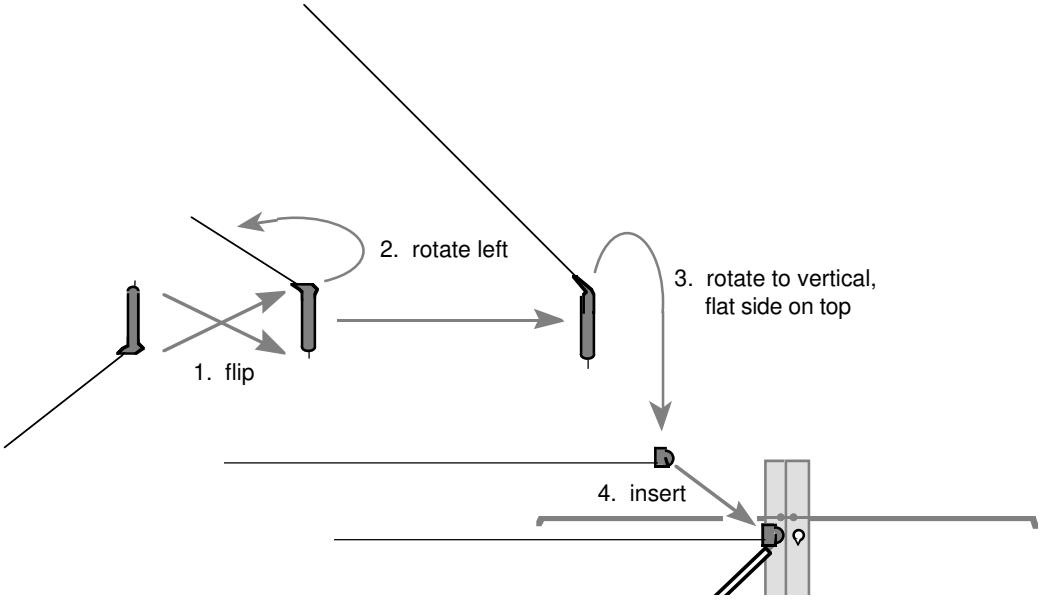


Figure 42. Attaching body crimp

Continue to string the control wire and secure it with body crimps, hardwiring a tripod gait. The control wire should be run through the front left, middle right, and rear left body crimp holes.

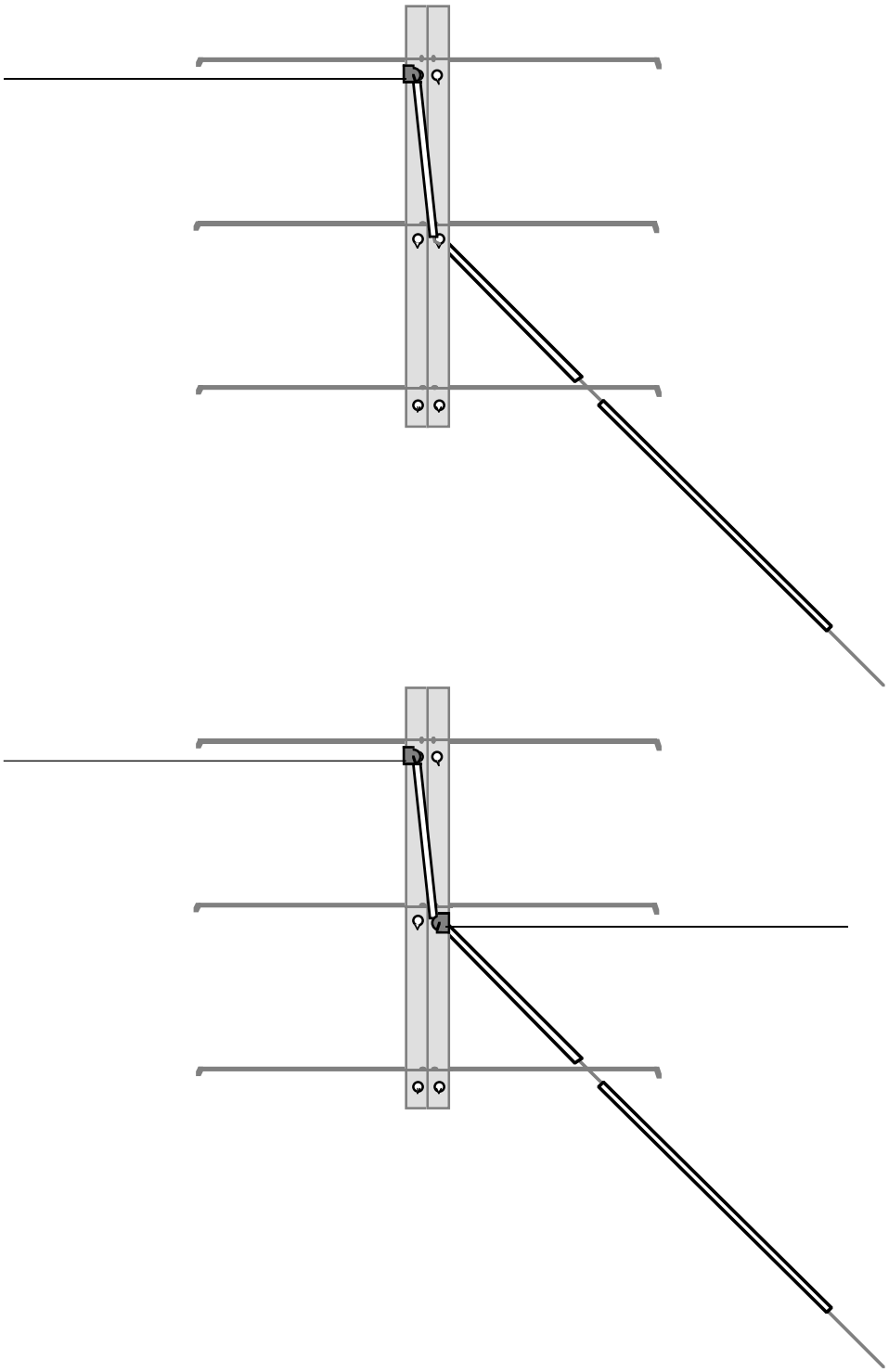


Figure 43. Securing control wire with right-handed body crimp in middle right body crimp hole

When installing the rear crimp, wrap the control wire around the body so that it enters the body crimp hole from the bottom side of the body.

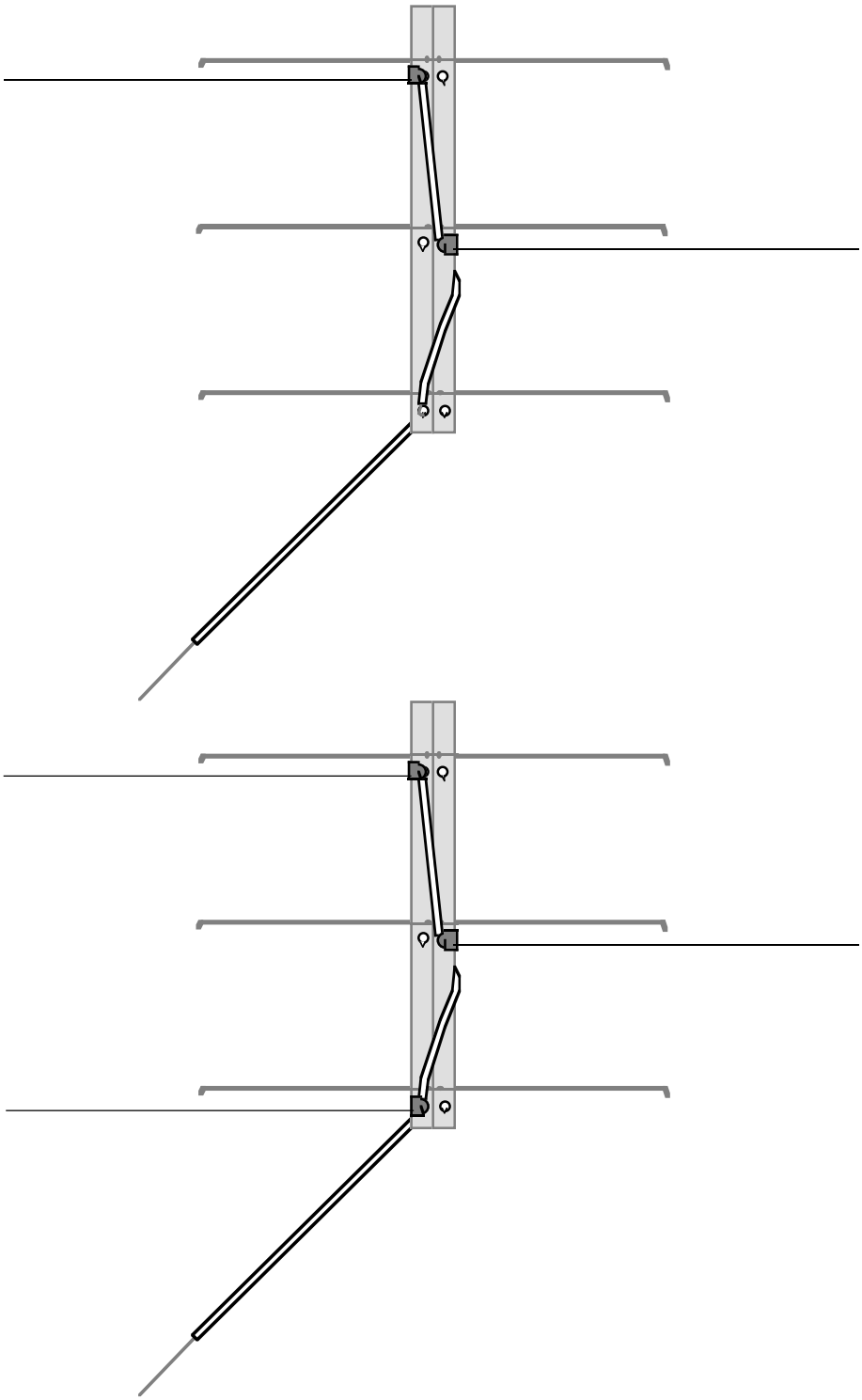


Figure 44. Securing control wire with left-handed body crimp in rear left body crimp hole

Following a similar sequence, install the second control wire in the opposite holes.

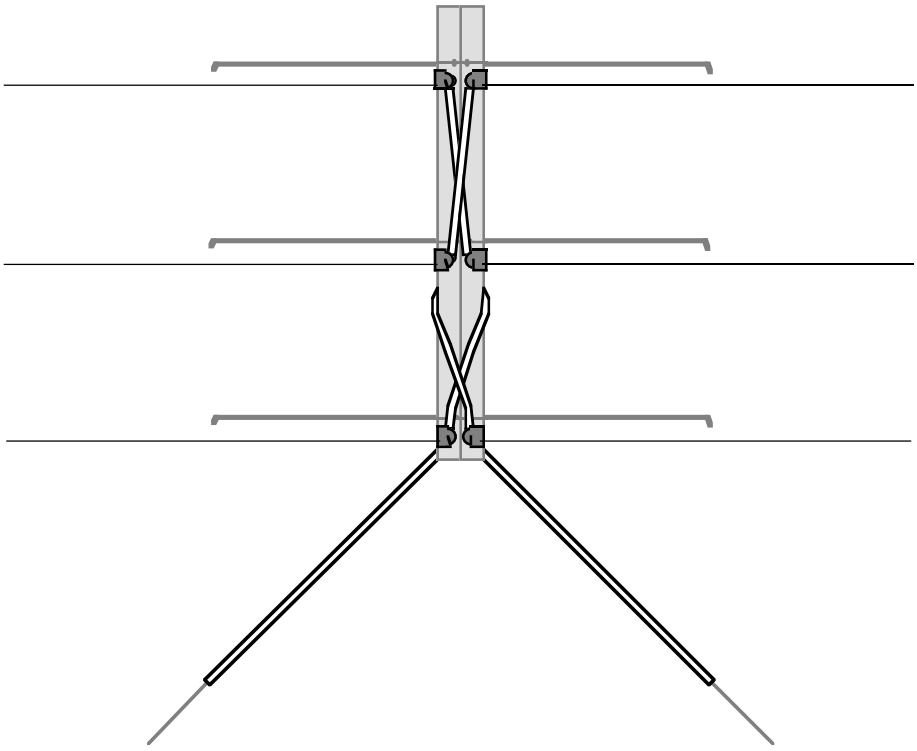
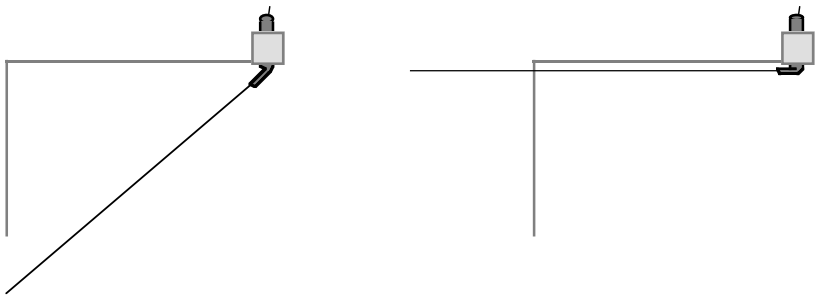


Figure 45. Body with attached body crimps securing control wires

Finish the control wire and body crimp assembly by bending the 45° tabs on the body crimps flat against the body using the needlenose pliers. This causes the finished nitinol actuator wires to pull the leg backward and slightly downward during operation.



(a) 45° tab (b) Bent flat against body

Figure 46. Finishing the body crimps (end view)

3.4.5 ATTACH LEG CRIMPS

For each nitinol wire actuator, position a knot at the knee near the vertical joint by tying an overhand knot around the vertical joint.

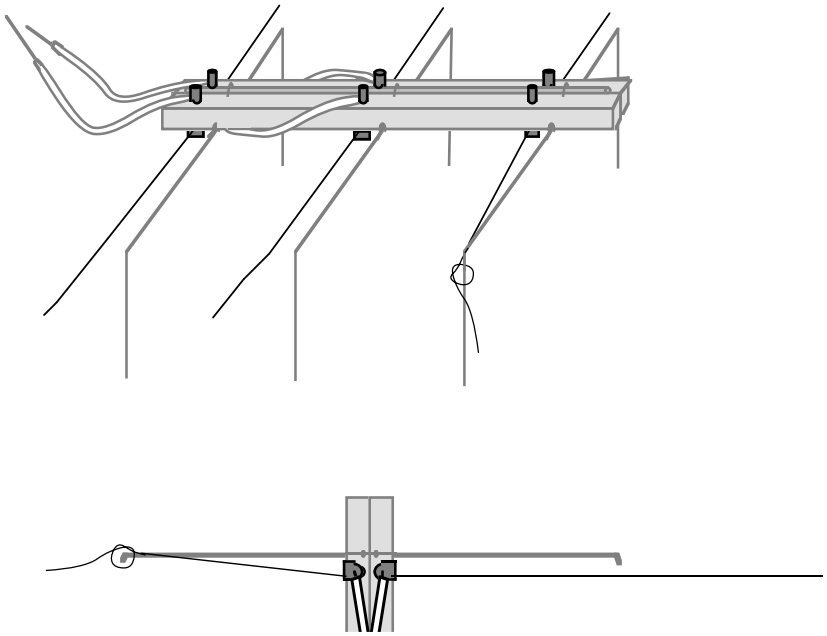


Figure 47. Locating leg crimp knot

Pull the knot into a 1mm loop. Free the knot by sliding the knot carefully off the vertical joint, bending the leg to avoid loosening the knot.

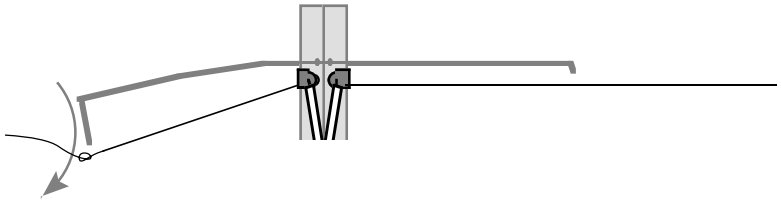


Figure 48. Freeing leg crimp retaining knot

Tighten the knot to a 0.1mm loop with the pliers.

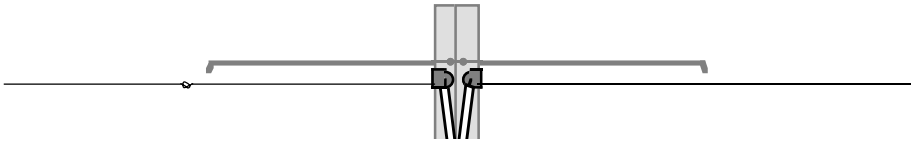


Figure 49. Finished knot

Sand the knot and the vertical joint near the knee with 600 grit sandpaper. Select a 4mm leg crimp, insert the .025" bit, and twist it back-and-forth while sliding it in and out. This removes aluminum oxide from the inside of the crimp, improving the electrical connection.

Slip the leg crimp onto the vertical joint and slide it up to the knee.

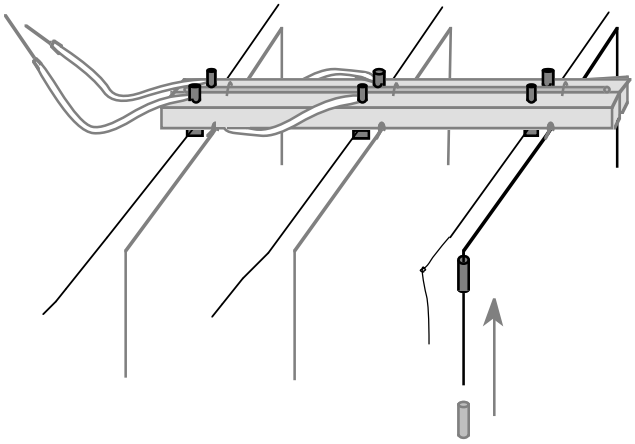


Figure 50. Slip crimp onto leg

Thread the nitinol wire through the crimp.

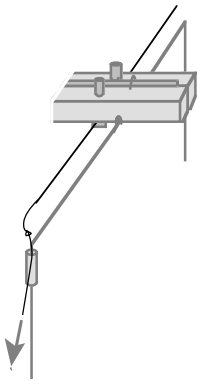


Figure 51. Threading wire through crimp

Pull the wire taut, so that there is a slight backwards bend in the horizontal joint. The slight bend ensures there is no slack in the nitinol actuator wire. There is not enough tension if there is no bend in the leg. There is too much tension if the leg is bent more than 2mm backwards at the knee.

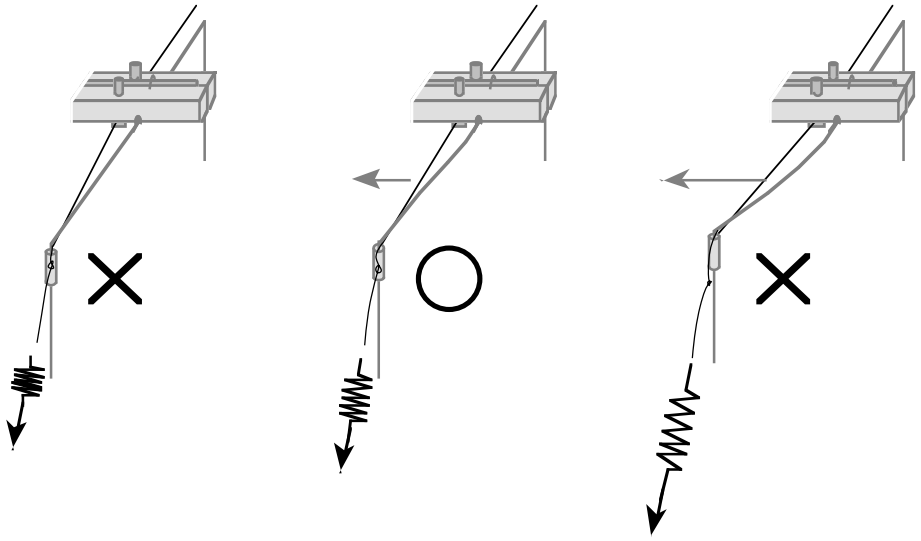


Figure 52. Correct tension (O) and incorrect tension (X)

The nitinol actuator wire should enter the crimp at the point nearest the body. The knot should be inside the crimp. When these conditions are met, use the needlenose pliers to make a loose crimp by squeezing the bottom 3.5mm of the crimp just enough to catch the knot.

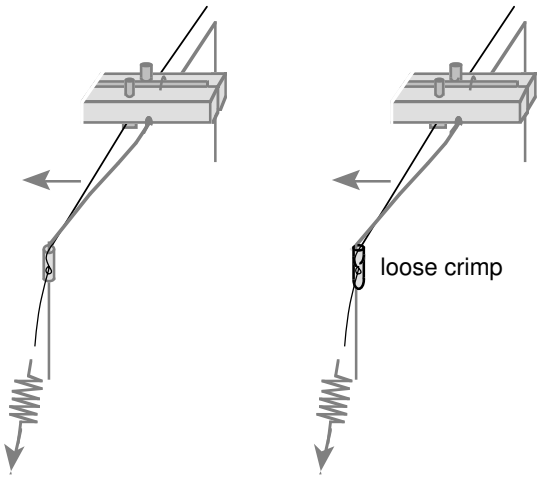


Figure 53. Making the loose crimp

Crimping changes the tension in the actuator wire, and may allow it to become slack. Adjust the tension while the crimp is loose by pulling on the wire (the horizontal joint should be bent slightly backward). When the actuator wire is taut, hold it in place and squeeze the crimp shut tightly.

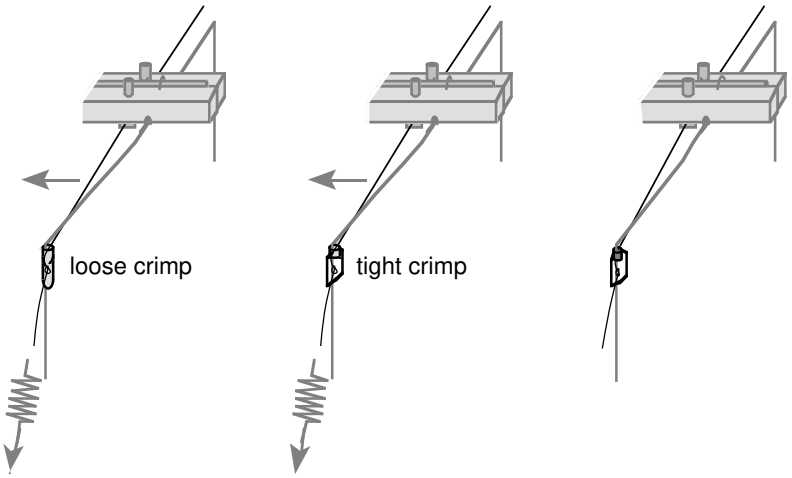


Figure 54. Making the tight crimp

Measure the resistance from the leg near the clip groove to the body crimp where it protrudes above the top of the body. The initial resistance should be between 5 and 7 ohms. The resistance will increase to between 15 and 25 ohms as the connections age. Test the operation of the actuators by applying current from two 1.5 volt AA cells at the leg near the body and the body crimp for no more than half a second to prevent the actuator wire from overheating. The leg should immediately bend backwards 3mm to 7mm measured at the vertical joint, then return to its original position.

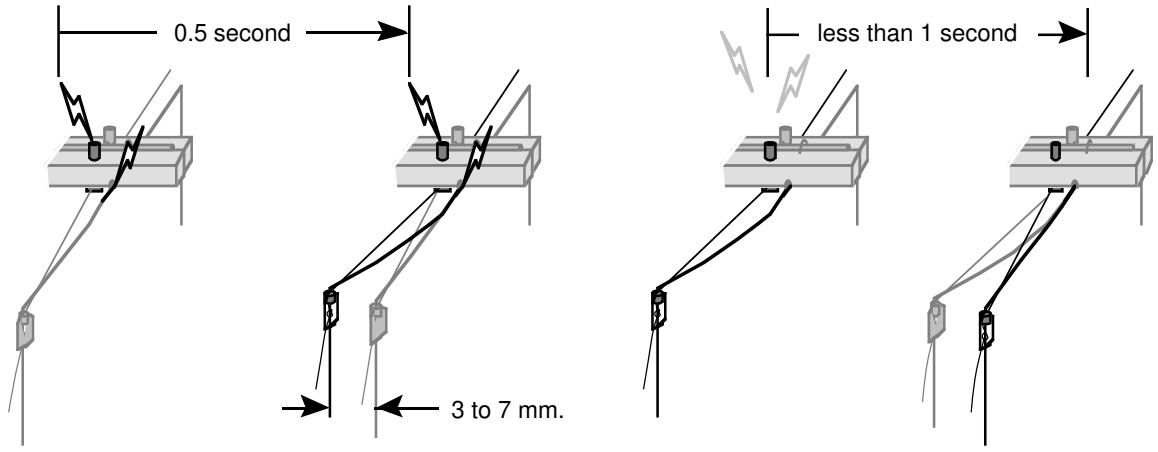
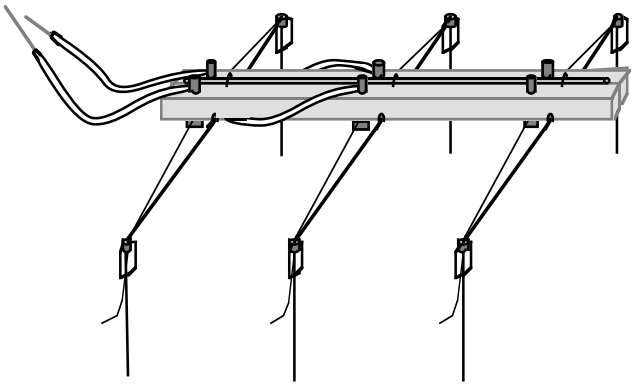


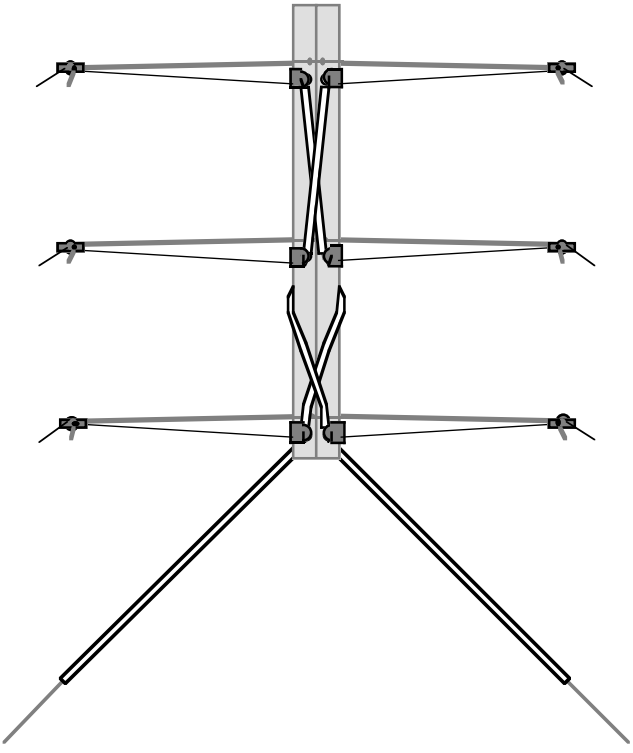
Figure 55. Testing the actuator

Test the leg and actuator assembly after installing each leg crimp.

If the test is successful, continue to attach and test the remaining leg crimps.



(a) Side view

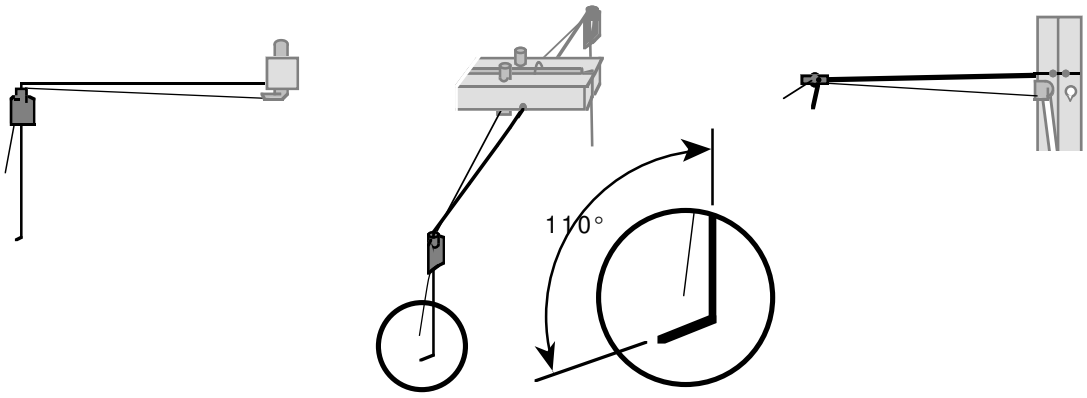


(b) Bottom view

Figure 56. Finished actuators

3.4.6 THE RATCHET FEET

Be sure to test the actuators before making the ratchet feet in case the leg crimps must be replaced. Form an ankle and ratchet foot by bending the tip of each vertical joint backwards and slightly outwards. The ratchet foot should be about 2mm long, and make a 110° degree angle downward from the vertical joint. The ankle faces toward the front of the robot.



(a) End view (b) Side view (c) Detail ×4 (d) Bottom view

Figure 57. Ratchet foot

This completes the robot. The next section describes how to manually control Stiquito.

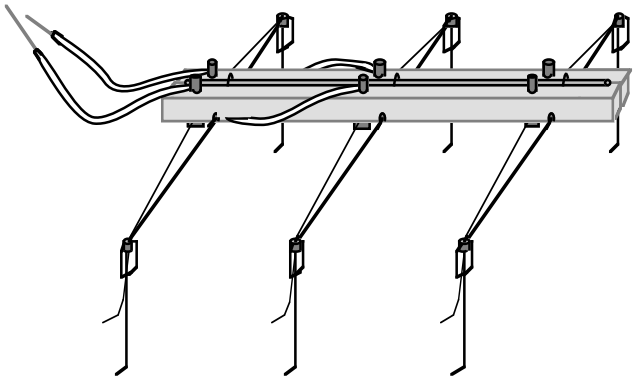


Figure 58. Side view of finished robot

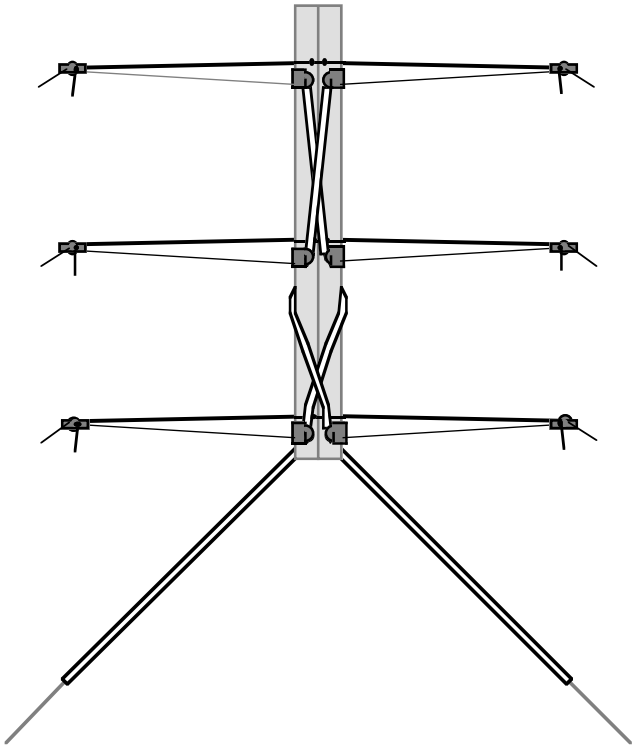


Figure 59. Bottom view of finished robot

4. TAKING STIQUITO FOR A WALK

Stiquito is hard-wired to walk in a tripod gait. Other gaits can be hard-wired by removing the body crimps and re-wiring the control wires. Each leg may be wired separately for more complex gaits, especially when using a VLSI controller on an autonomous robot [9].

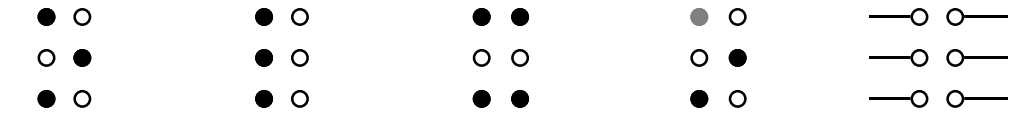


Figure 60. Gaits

To test Stiquito's walk, a simple manual controller is described in the next section. Following that is a troubleshooting section. It contains the symptoms and causes of some common problems you may encounter, based on experience with this robot.

4.1 MANUALLY OPERATED CONTROLLER

A manual controller is a good way to test hard-wired gaits. It is simple and almost foolproof. If used as directed it will prevent overheating that could damage the nitinol actuator wires. The manual controller is a pair of normally-open switches with a terminal to attach a 9-volt cell. Pressing the switches alternately will power the legs, causing Stiquito to walk. If Stiquito walks with the manual controller, then the control circuits described in Part 2 should work equally well.

Make the manual controller by cutting one 60mm length of 1/8" styrene rod (or remove the pre-cut length from the kit). Mark three horizontal lines 15mm apart on one side of the rod. This defines the top of the controller. Mark one line in the middle of the rod 30mm from either end. Mark two lines 15mm from each end.

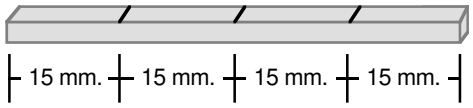


Figure 61. Mark three lines

Drill two .025" switch holes 1mm apart, centered on the middle mark. Drill one 1/16" contact crimp hole through each mark 15mm from each end, centered on the mark.

Figure 62. Contact crimp holes and switch holes

Extend the middle mark down the side of the rod that faces you. The mark should be in the center of the rod 30mm from either end.

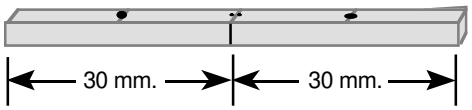


Figure 63. Extend middle mark

Drill one 1/16" power crimp hole centered on the mark. The power crimp hole should pass between the switch holes. This completes the controller handpiece.

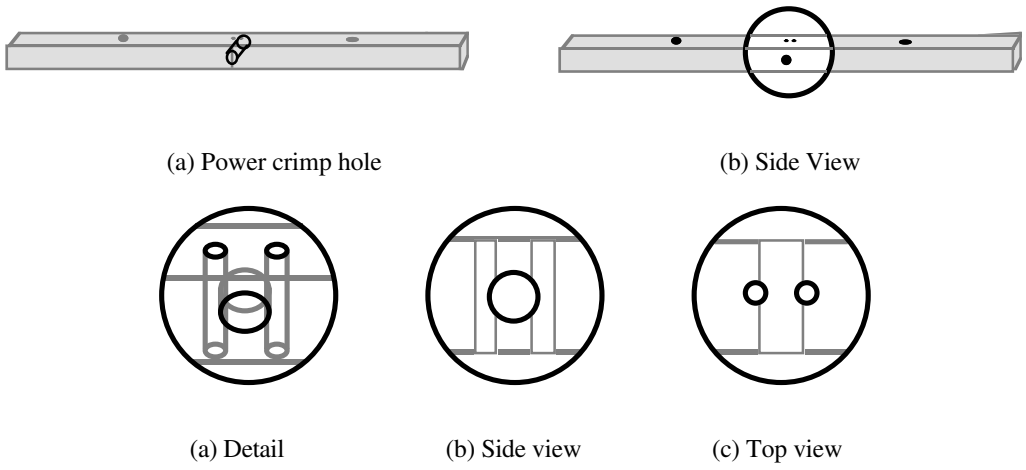


Figure 64. Finished controller handpiece (all enlargements ×4)

Next cut two 120mm lengths of 28 AWG wire-wrap wire (or remove the wires from the kit). Remove 12mm of insulation from each end.

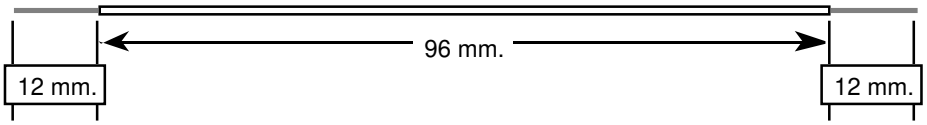


Figure 65. Control wire

Bend one end of each wire in half, leaving a sharp V-bend of bare wire 6mm long.

Figure 66. V-bend

Select a piece of aluminum tubing at least 60mm long (use the second 100mm piece of tubing if the kit was purchased). Cut three 9mm crimps. Two are contact crimps, and one is a power crimp. Cut six 4mm connecting crimps. Approximately 40mm of kit tubing remains for spare crimps.

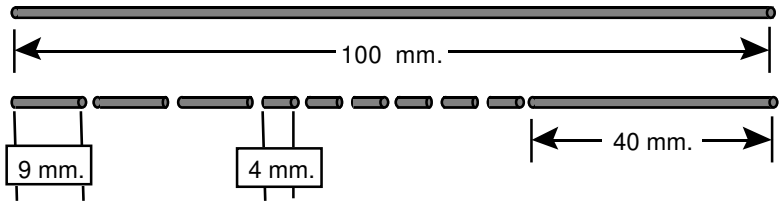


Figure 67. Contact, power, and connecting crimps (spare tubing shown)

Make two contact crimp assemblies. Into each of two 9mm crimps insert a V-bend until the tip protrudes slightly beyond the crimp. Using the needlenose pliers, crimp 2mm of the end with the slightly protruding V-bend.

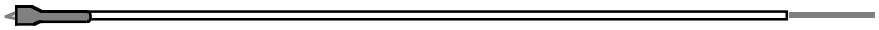


Figure 68. Contact crimp assemblies

Bend the flat part of the crimp to a 45° angle.

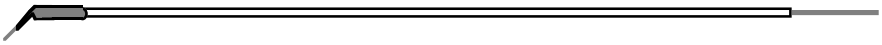
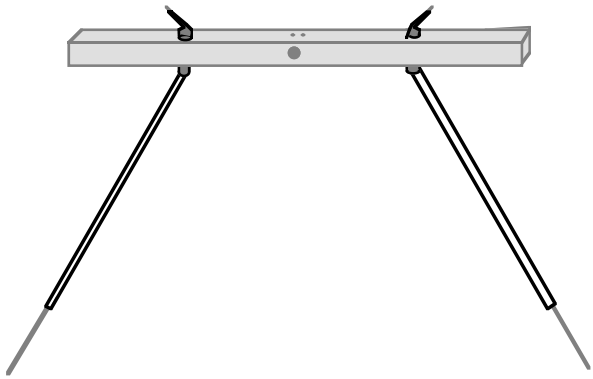


Figure 69. 45° bend in contact crimp

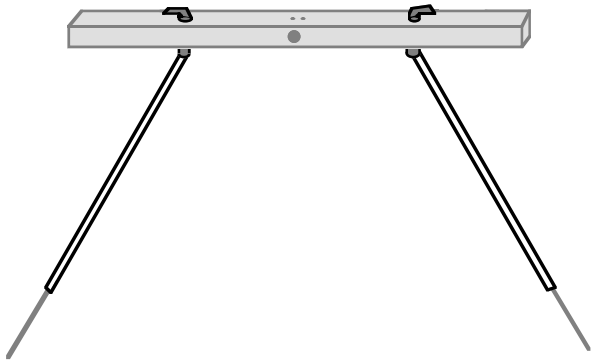
Next make one power crimp assembly. Select the 9-volt terminal. If necessary, remove 5mm of insulation from the end of each wire attached to the terminal. Insert one of the wires into the remaining 9mm crimp all the way to the insulation and crimp 2mm at the end nearest the insulation.

Figure 70. Power crimp assembly

Now insert the contact crimp assemblies into the outer holes on the top of the handpiece. Bend the flat ends of the crimps parallel to the top of the handpiece.



(a) Contact crimps inserted



(b) Bent flat

Figure 71. Insert and bend contact crimp assemblies

Insert the power crimp into the center hole on the side of the handpiece. Leave the remaining wire from the 9-volt terminal free, for the moment.

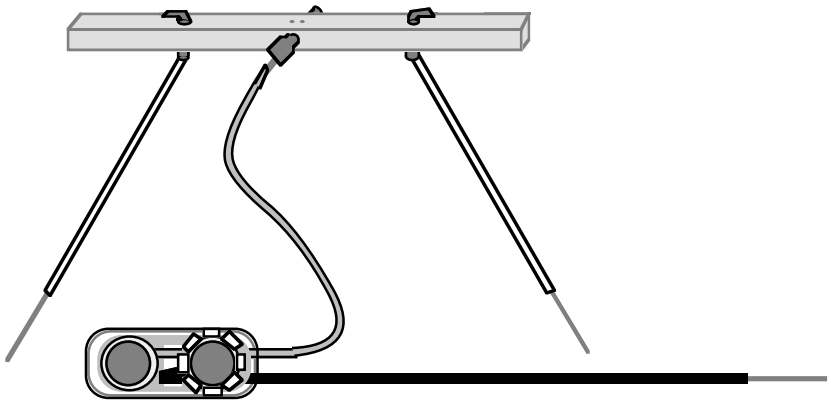


Figure 72. Insert power crimp

Next cut one 70mm length of .020" music wire (or remove the wire from the kit). Bend the wire in the center to a 15° angle to make a V-clamp.

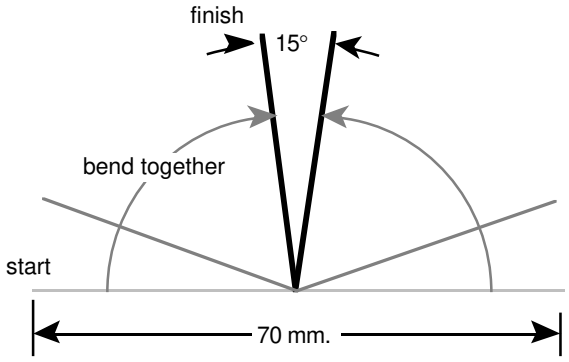


Figure 73. V-clamp

Insert the music wire halfway into the switch holes in the handpiece. If the music wire cannot be inserted past the power crimp, then re-drill the switch holes through the power crimp using the .025" bit, and re-insert the music wire halfway into the handpiece.

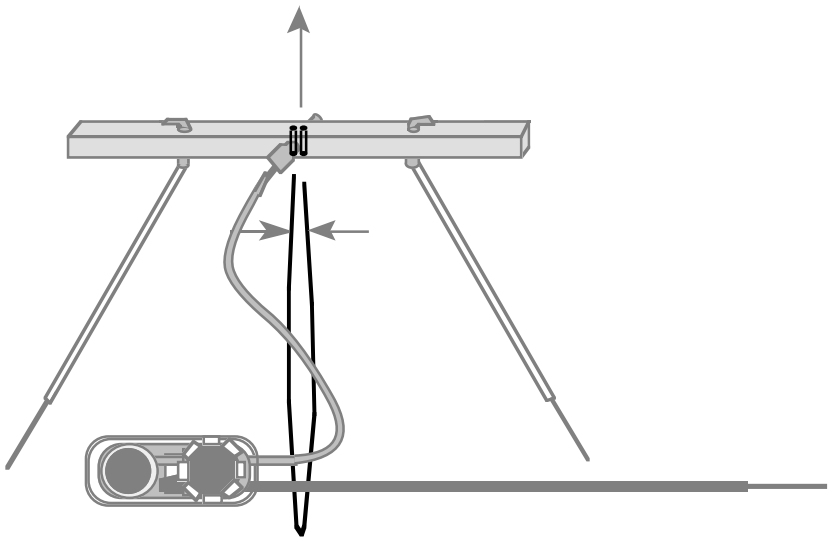


Figure 74. Insert music wire

Insert an insulated portion of the free wire attached to the 9-volt terminal into the V-clamp.

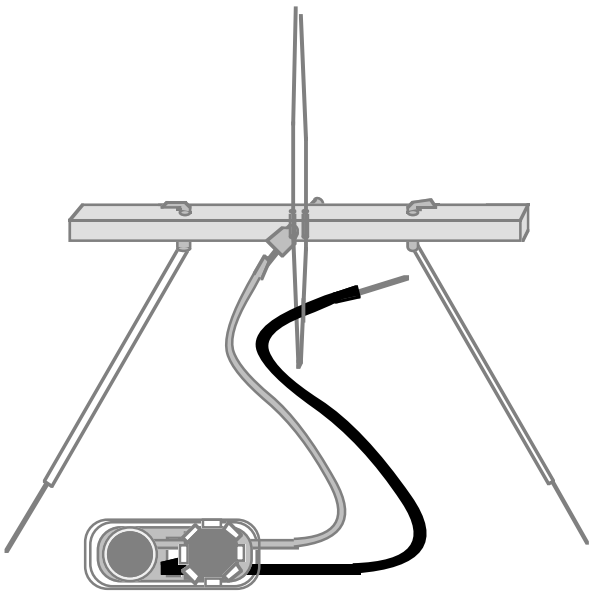


Figure 75. Insert free wire into V-clamp

Holding the insulated portion of the free wire in place, pull the V-clamp through the handpiece, and bend it outwards. Bend each end of the V-clamp back on itself to prevent poking yourself in the finger when you use the controller.

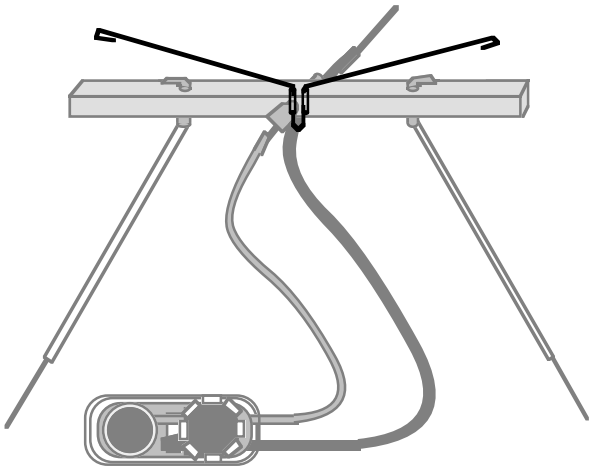


Figure 76. Bend V-clamp outwards

The V-clamp attaches the insulated portion of the free wire to the handpiece. The external arms of the V-clamp form the two manual actuators of the double switch. The arms of the V-clamp inside the handpiece connect the power crimp to the double switch.

This completes the manual controller.

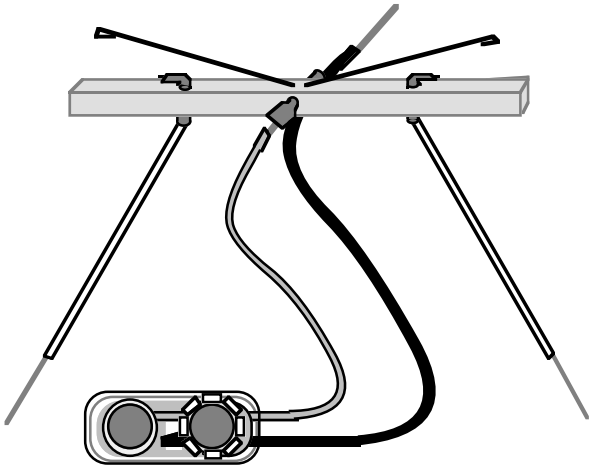


Figure 77. Completed manual controller

To use the manual controller to make Stiquito walk, cut three 500mm (50cm) lengths of 34 AWG magnet wire (or remove the three lengths of wire from the kit). Use a match or butane lighter to burn the insulation from 14mm of each end of the magnet wire. Pass the wire back-and-forth through the flame quickly: if you leave the wire in the flame too long, it will melt. Sand the burned end with 600 grit sandpaper to remove the burned insulation.

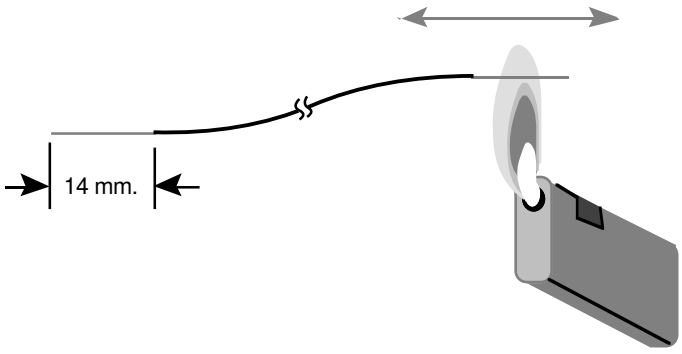


Figure 78. Remove insulation from magnet wire

Use the six connecting crimps to attach the bare magnet wire to the ends of Stiquito's power bus and control wires, and to the ends of the manual controller's wires. Attach a 9-volt cell to the terminal, then **briefly** and alternately press each arm of the double switch. Stiquito should walk with a tripod gait. If it does not, then continue to the next section for troubleshooting suggestions.

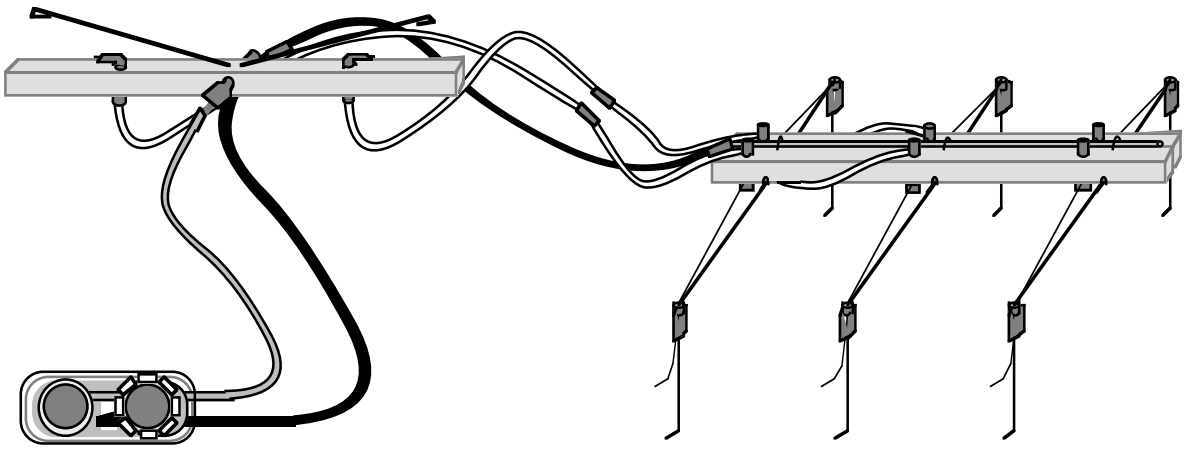
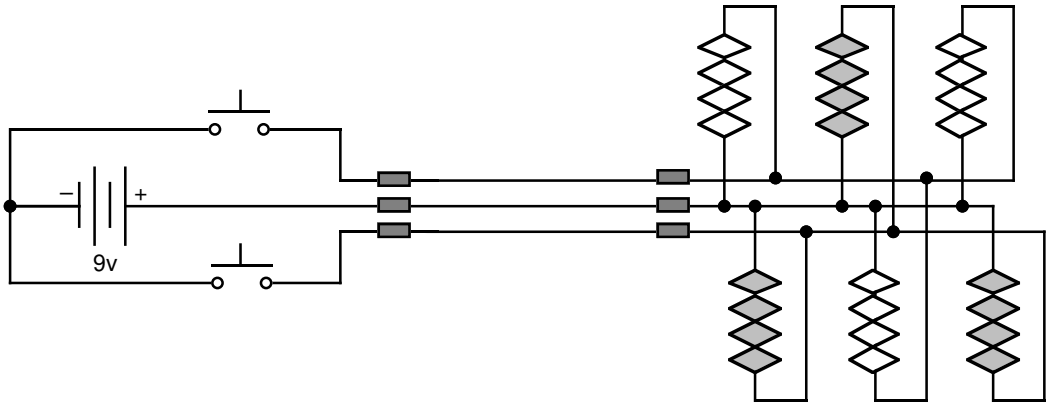


Figure 79. Controller connected to Stiquito (magnet wire not shown)



(a) controller and 9-volt cell (b) magnet wire (c) Stiquito

Figure 80. Controller, magnet wire, and Stiquito circuit schematic

4.2 TROUBLESHOOTING

Troubleshooting is applied logical deduction. To avoid the frustration encountered when a project fails to work as expected, *expect it not to work!* Take this attitude from the start, and think about factors that could affect the operation of the robot, and the behavior (or lack of it) that would result. Then, when the inevitable happens, you will have a set of hypotheses about why the robot failed to work. The hypotheses may be wrong, but that is OK: wrong assumptions lead to right deductions if you are willing to discard assumptions that are not supported by experiment.

4.2.1 STIQUITO WALKS IN A STRAIGHT LINE

This is perfect. You do not have any trouble. Congratulations on a good job!

4.2.2 STIQUITO WALKS TO THE LEFT OR RIGHT, BUT NOT STRAIGHT

This is OK, and is very common. The reason is that one or more of the legs is crooked, or does not operate at full extension. Check for loose actuator wires, loose crimps, poor electrical connections (look for open or high-resistance paths from the power supply to the legs and back), a weak power supply (nitinol draws about 180mA per leg, which will drain a 9-volt cell after several weeks of occasional use), legs that are not parallel, or ratchet feet bent at different angles.

4.2.3 STIQUITO DOES NOT WALK AT ALL

If there is nothing obviously broken or loose (actuator wires, crimps, control wiring, magnet wire), then check the power source. The 9-volt cell may be dead. Check the power bus and the body crimps for shorts. Check for shorts between connecting crimps (you may need to hold them apart with a piece of tape). If you did not bend the ratchet feet, or if you operate Stiquito on a smooth surface, the legs may move but will not catch the surface — and Stiquito will thrash around but not walk. Stiquito walks best on slightly textured surfaces such as indoor-outdoor carpet, a cloth-covered book, pressboard, or poured concrete. Stiquito walks poorly on glass, smooth plastic, or tiled floors.

4.2.4 LEG MOVES TO FULL EXTENSION (4-5MM)

This is perfect. You obviously built Stiquito carefully.

4.2.5 LEG DOES NOT MOVE AT ALL

The probable causes include a very loose actuator wire or a dead 9-volt cell. Check the cell with a volt-ohm meter. If the power is OK, then check the electrical connection between the control wire and the body crimp. Use the volt-ohm meter or apply power to various points in the circuit until the leg moves. Do **not** use a 9-volt cell to test a single leg. It will snap the actuator wire. Test single actuator wires using 3 volts supplied by two 1.5-volt AA cells in series. If the leg cannot be activated from points farther away in the control circuit, then there is an open circuit between that point and the actuator wire. If the electrical connections are good, then examine the actuator wire. If it is loose, or the body or leg crimps are not tight, then the actuator is too slack to operate. Tighten the actuator wire (you may have to remove the old leg crimp and attach a new one), then test the leg. It should work.

4.2.6 LEG MOVES SLIGHTLY (1-3MM)

The actuator is probably loose, but is taut enough to take up the slack, then move the leg. Re-tension the actuator, replacing the leg crimp. Another cause is increased resistance as the crimps age. Aluminum oxide builds up inside the crimps. Its effects can be alleviated by operating the leg. This causes the retaining knots to expand and improve contact with the aluminum inside the crimp. Squeezing the crimp also helps to improve the electrical connection.

4.2.7 LEG MOVES IN ONE OR MORE JERKS

There is probably an intermittent open or shorted connection. **If the leg jerks backward continuously** in small increments, **remove power immediately** or the actuator wire may be damaged. Check the manual controller for an intermittent connection between the double switch and the contacts.

4.2.8 LEG HEATS UP, SMOKES, AND/OR MELTS PLASTIC NEAR BODY CRIMP

A little smoke is typical when the actuator wires are first used, probably as oils or oxide on the nitinol wire burn away. But **if you see a lot of smoke** (equivalent to a cigarette left on the edge of an ashtray), or **if you smell something "hot" like burning or melting plastic** then **remove power immediately** or the actuator wire may be damaged. There may be a short in the wiring. You may be powering a slack actuator for longer than one second: a slack actuator will not work. Continuing to apply power to the leg will only cause the nitinol actuator wire to overheat, damaging the wire and heating the body crimp enough to melt the plastic body.

4.2.9 LEG WORKS OK FOR AWHILE, THEN MOVEMENT STOPS ALTOGETHER

The actuator wire has developed slack, a connection has broken, or the battery is dead. If the actuator wire is slack, it may need to be re-tensioned and re-crimped. Check for broken connections, especially where the magnet wire is crimped. Try a fresh 9-volt cell.

4.2.10 LEG WORKS OK FOR AWHILE, THEN MOVEMENT DIMINISHES BY 2MM OR MORE

The actuator is probably somewhat loose, but is taut enough to take up the slack, then move the leg. Another cause is increased resistance as the crimps age. Apply power to the leg and/or squeeze the body and leg crimps to improve the electrical connection.

4.2.11 MAGNET WIRES OR CONTROL WIRES BREAK

Magnet wire breaks easily. If it does break, remove the connecting crimp, burn away some insulation, and crimp it back into place. If the control wires break, it will probably occur as the hard-wired gaits are being changed. Avoid breakage by using the V-grooves to hold the control wire while the body crimp is press-fitted. Do not bend any wires back-and-forth repeatedly: the wire will become fatigued, and break.

4.2.12 ACTUATOR WIRE BREAKS

If the actuator wire breaks during assembly then it was sanded too much, or nicked (probably while removing the knot from a music wire leg). Actuator wires may also break from these causes during operation. Do not power a single actuator wire with a 9-volt cell: the wire will contract so rapidly that it cannot overcome the inertia of the leg, causing the actuator wire to snap.

4.3 FUTURE RESEARCH USING STIQUITO

Part 2 of the technical report, *Sensors and Controllers,* will describe tethered control interfaces and software drivers for personal computers and workstations, discrete-component rate-variable and stroke-length-variable controller circuits, VLSI digital and analog controllers for robots with legs having one and two degrees of freedom, legged Braitenburg vehicles based on Stiquito, interfaces to various sensors, and inter-robot optical communications links. Part 3 of the technical report, *Experiments with Arthrobots*, will describe a variety of arthropod robots and report on experiments in emergent cooperative behavior using a colony of Stiquitos.

ACKNOWLEDGEMENTS

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Christopher Stone encouraged me to prototype inexpensive robots (he prefers stiff paper for his), and also shared his expertise in crayfish neurology.

John Warren interested me in nitinol wire before he returned to his first love, biology. Thanks, John: without nitinol Stiquito wouldn't exist.

Bill D'Amico, Steven Johnson, Gregory Rawlins, and Peter Shirley were extremely enthusiastic, commented on the draft, and built Stiquitos. I apologize for giving you guys the alpha version of the kit and then making the dimensions of the pre-cut parts larger.

Ellen Mills and Gregory Rawlins provided the encouragement to make the figures and text accessible to the mechanically dyslexic. They refused to understand anything until it was written and diagrammed. Thank them if you figured out how to build Stiquito. Naturally, blame me if you still couldn't get it right. Send e-mail to jwmills@cs.indiana.edu and I'll try to help you out.

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