

WAM™ Arm

Cable-Maintenance Guide



Barrett Technology[®] Inc.

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This manual is most useful when printed in **color** or viewed on screen.

This guide is intended to aid in the recabling of damaged or worn cables in the 4-DOF WAM arm. See <http://web.barrett.com/videosupport> for a helpful video version of these procedures.

1 The Three Rules of Handling Drive Cables

The cables in the WAM arm are designed to be – and are – robust once they are installed on the pulleys and pinions of the WAM arm’s drives and tensioned appropriately. The WAM is shipped in this condition. A healthy cable is pictured in Figure 1. The helical patterns are uniform and there are no line-of-sight gaps between the fibers and the bundle of fibers¹. The cable may be bent into smooth arcs or coiled (if done properly according to Rule 2 below). The replacement cables are shipped in a coiled condition, and must be uncoiled according to Rule 2. Note that these cables are expensive so it pays to refresh your familiarity of the Three Rules of Cable Handling (henceforth “Three Rules”) before attempting your first cable replacement.



Figure 1 -- Healthy drive cable before installation

Before installation, the WAM cables are susceptible to avoidable damage, even though the handling seems gentle. While the cause may be subtle, the result is (fortunately) not, as shown in Figure 2; it is easy for an alert installer to see damage when it happens. Although it may be possible to coax the cable fibers back into the condition of Figure 1, in general, the harm is irreversible. Fortunately, the instructions in this section will prevent this expensive damage.



Figure 2 -- Typical appearance of a cable damaged during handling

¹ Each fiber is only about 1/10th the thickness of a human hair. The production process of taking a rod of stainless steel several centimeters in diameter and drawing it through progressively smaller dies increases the axial yield strength (a function of area reduction ratio) to extraordinary levels. In Figure 1 there are seven (7) fibers arranged in a close-packed bundle (forming a hex pattern in the transverse plane) and twisted axially into a helix of uniform pitch. Then seven (7) of these bundles are similarly twisted in to a larger bundle. Then this is repeated a third time until the cable (~1-mm in diameter) contains $7 \times 7 \times 7 = 343$ separate strands. The large number of fibers allows the overall cable to bend to a radius of about 15X the cable radius.

Following the Three Rules of handling drive cables during installation will keep them healthy. While the first may be obvious, the other two are subtle.

Rule 1: Avoid crushing a cable.

Rule 2: Never twist the cable.

Rule 3: Pinch is fine, and slip is fine; but never pinch+slip a cable through your fingers.

1.1 Rule 1: Avoid Crushing Cables

This rule, represented graphically in Figure 3, should be obvious. Crushing the cables has a tendency to fold and crease the cable, causing permanent damage to the cable.



Figure 3 -- Rule 1: Avoid crushing cables

1.2 Rule 2: Do Not Twist Cables

This rule is perhaps the subtlest of the 3 rules. Few people realize, nor would they care in general, that coiling or uncoiling a rope, string, or cable in a most intuitive manner will impose one full turn of axial twist in the cable per coil turn if the free end of cable is constrained. This can damage cables and is worst for the longest, stage-1, cables because the end (sitting under a coil on the floor) may be constrained.

Figure 4 illustrates the point. To make the effect clear, we use flat tape rather than a round cable because it is easier to mark the outside and the inside of the tape.

Figure 5 shows a typical scenario, where someone is removing a cable off the end of a pulley. The more common cases come when uncoiling a fresh cable or during cabling first stages in the WAM arm. This problem is minimized by uncoiling the cables with care and allowing the cable to rotate freely through your fingers when uncoiling.

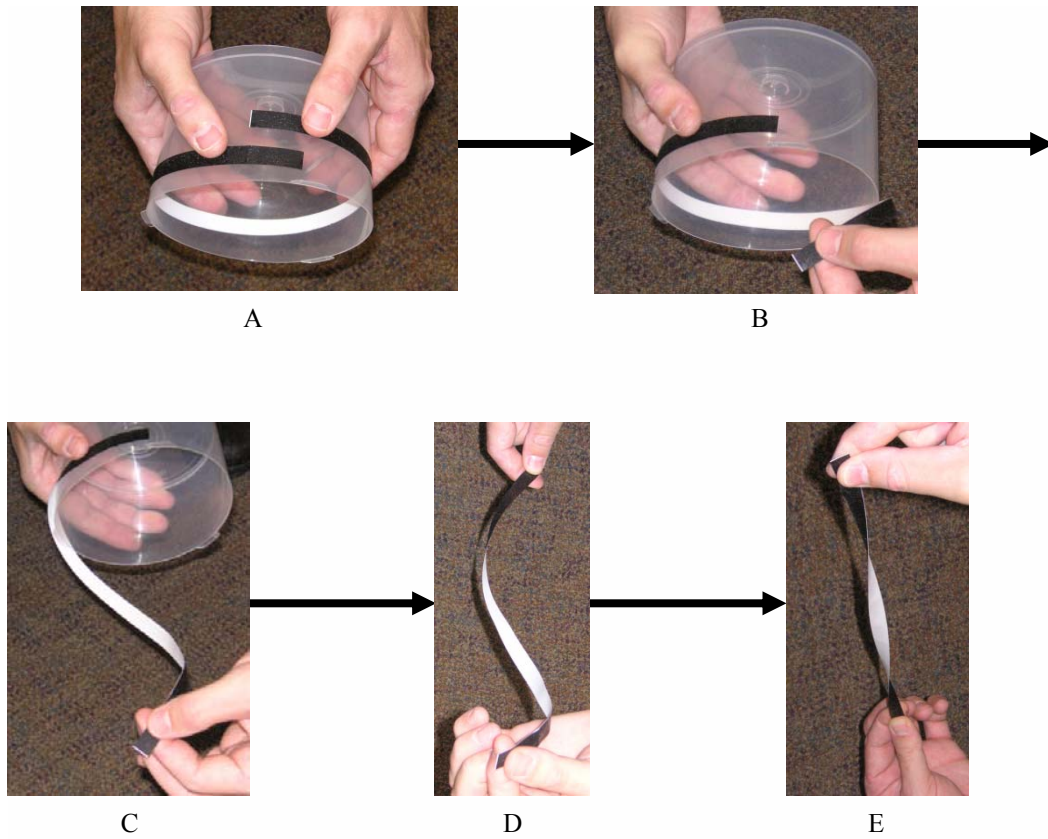


Figure 4 -- A ribbon, painted black on one side, illustrates the subtlety of creating large torsion loads while winding on/off cables. Note that the problem comes primarily from constraining twist at the ends of the ribbon.

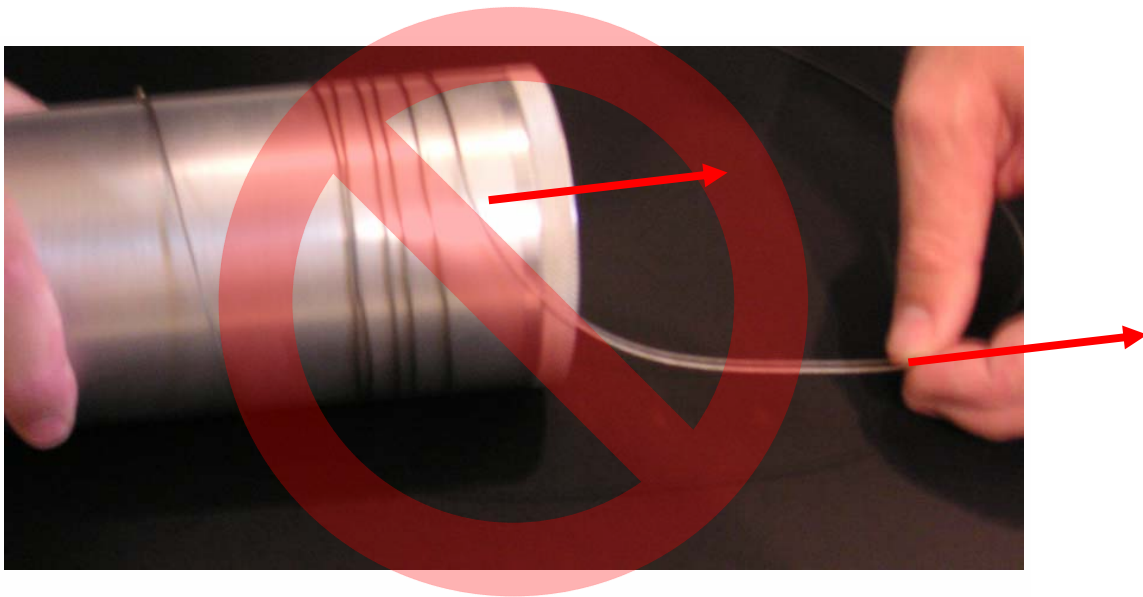


Figure 5 -- This seemingly-harmless technique of removing a cable introduces significant axial cable torque.

1.3 Rule 3: Do Not Pinch+Slip

This rule is also subtle. People learn instinctively to pinch and slip fingers over a cable, tape, or string to straighten it. Pinching the cable hard will *not* damage the cable nor will allowing the cable to slip across or through open fingers (as long as you also do not violate Rule 2). It is only the case where you both pinch *and* slide the cable under tension through your closed fingers for several centimeters that a (sudden) cable failure will occur, appearing similar to the damaged cable in Figure 2. In order to properly straighten a cable, hold one end of the cable (or, for longer cables, hold the middle of the cable) high in the air and allow the cable to unwind itself in the air. Remember that in order for this method to satisfy Rule 2, you must ensure that the end of the cable is not being constrained on the ground by the weight of coils above it.

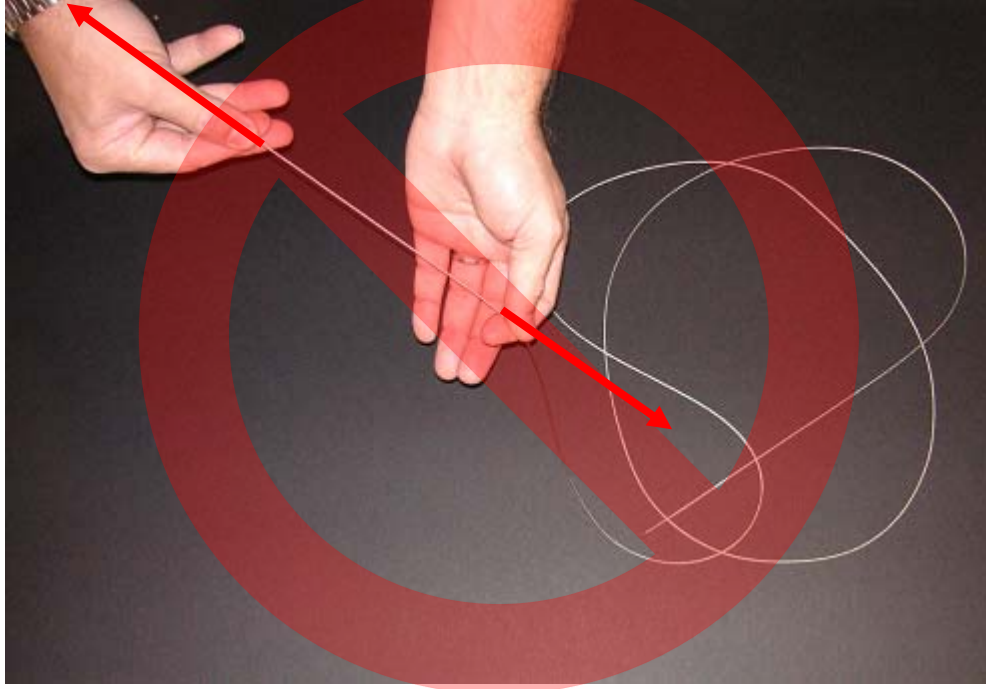


Figure 6 -- Rule 3: Do not pinch+slip the cable simultaneously to straighten a cable.

2 Terminology

Before this manual discusses the cabled transmissions in the WAM Arm or Wrist, it will be helpful to define some general terms common to cabled systems.

Anchor – location on the pulleys or pinions that the cable terminations are inserted into for retention and tensioning.

Cable – a “wire rope” typically made from very fine strands of stainless steel. The composite tensile strength and stiffness is very high in a stranded cable yet it maintains flexibility in bending.

Cable circuit – the cables and cable paths through a transmission from input (motor) to output joint.

Cross wrap – when spanning the distance between two parallel transmission elements (pinions or pulleys) the drive cable crosses the plane that contains the axes of both elements. This wrap results in the elements rotating in opposite directions when cabled (see Figure 7).

Inboard & Outboard – Inboard refers to the direction towards the shoulder center of the WAMArm and Outboard refers to the direction away from the shoulder center of the WAMArm.

Open wrap – when spanning the distance between two parallel transmission elements (pinions or pulleys) the drive cable does not cross the plane that contains the axes of both elements. This wrap results in both elements rotating in the same direction when cabled (see Figure 7).

Pinion – the smaller-diameter, higher-speed cylinder in a pair of cabled transmission elements. A pinion has guide grooves for cables cut into its surface.

Pre-tension – cable tension, internal to a cable circuit, which is present even when the drive has no external loading. Pre-tension is added to eliminate backlash (in this case, cable slack) in the transmission.

Pulley – the larger-diameter, slower-speed cylinder in a pair of cabled transmission elements. A pulley’s surface is typically smooth and has no cable guide grooves.

Side-A & Side-B – directions often used in this text to identify an item. Each motor and cable circuit has an explicit definition for these directions that is given at the start of each motor's cabling instructions.

Stages – as with gear trains, cable circuits can be composed of several transmission stages, each contributing its part to the final transmission ratio. Stage 1 is from the motor to the first set of pulleys and stage 2 is from the pinions attached to the first pulleys to the second set of pulleys.

Tensioner – the mechanism in a cabled transmission, which applies and maintains pre-tension in the drive cables. Barrett’s patented single-point tensioner uses split motor pinions that counter-rotate via an integrated clutch to pre-tension entire cable circuits.

Termination – a brass sphere swaged or crimped onto the end of a cable, that engages an anchor.

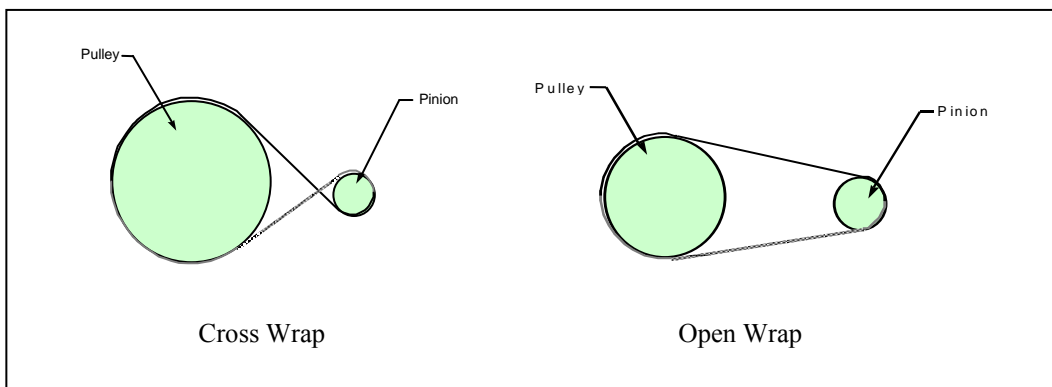


Figure 7 – Pinion-to-Pulley Transition Types

3 Cable circuits and tensioning mechanisms

3.1 Pre-tensioning Mechanisms At Motor Shafts

For re-cabling, the important point is that the autotensioner (cylindrical cup part only) must be removed before cabling begins and re-installed after cabling is complete.

This paragraph describes the *operation* of the autotensioner. One cylindrical-cup shaped pre-tensioning mechanism (aka autotensioner), pictured in Figure 8, is located at each motor of the 4-DOF WAM arm. Figure 9 gives an enhanced graphical view of the motor shaft that works with the autotensioner. Under normal operation the motor shaft acts like a solid shaft. However, the pinion is actually split laterally between an inner part (rigidly connected to the motor's rotor) and an outer part that (under special circumstances) can rotate independently from the inner pinion. During pretensioning, a steel finger is deployed from the autotensioner that engages the tang (see Figure 10) at the end of the motor shaft, blocking rotation of the “outer” pinion. You can find the split easily when the autotensioner is removed and there is no cable on the shaft because the “inner” pinion is scalloped and the “outer” pinion has a simpler cylindrical surface. Also, with the cable removed, you can rotate the outer pinion (only in the direction that would tend to add cable tension) with your fingers while the inner pinion remains fixed. Once cables are (manually) installed in the WAM (as described in this document), the motor can build torque against the tang, causing slight relative motions and thereby removing slack from the cable circuit and ultimately placing the entire cable circuit in a constant state of tension. This state of uniform cable “pre”-tension ensures that, even with torque applied, none of the cables in a circuit goes slack.

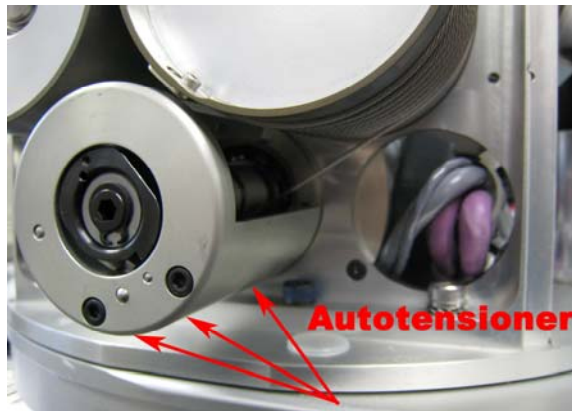


Figure 8 -- Autotensioner with cup installed over motor shaft.

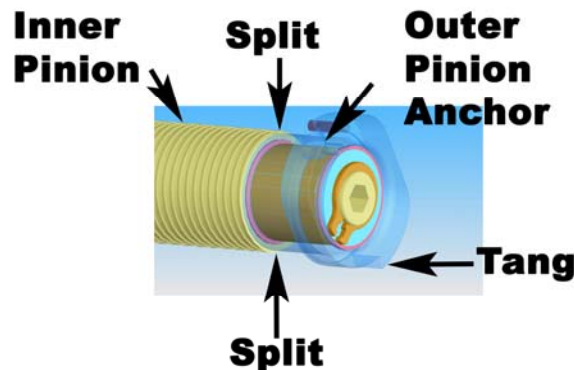


Figure 9 – Motor shaft showing split between counter-rotating parts.

Before ever attempting to remove the autotensioner, ensure that the WAM is fully powered down and that all electrical cables have been disconnected from the backplate of the WAM.

In order to remove the autotensioner (meaning only the cylindrical cup), one must first align the motor tang with the small pin, as pictured in Figure 10, by rotating the motor shaft manually.



Figure 10 -- Align motor with tang to remove cylinder cup.

If the serial number of your WAM is 1 through 32, and therefore does *not* have the three holes pictured in Figure 11, but instead looks like the autotensioner in Figure 10 or Figure 12, then grasp the cylindrical body of the autotensioner, press inwards and rotate about 5 degrees counterclockwise as illustrated in Figure 12.

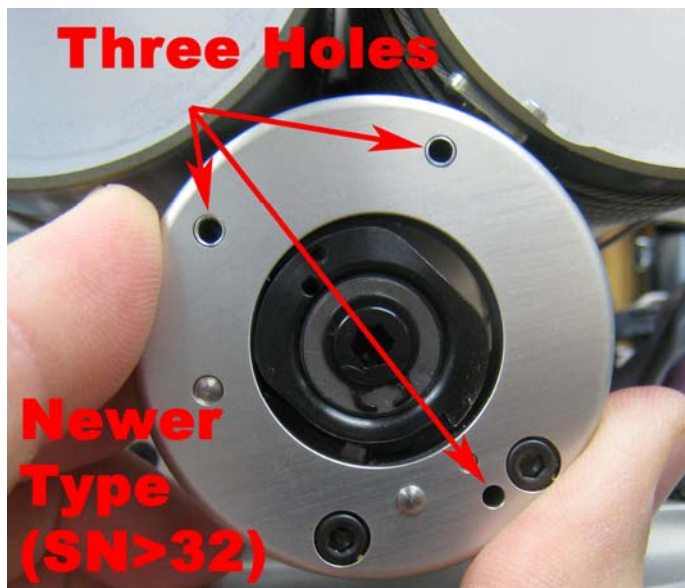


Figure 11 -- Removing newer-type autotensioner.

If the serial number of your WAM is 33 or higher, then use a 2-mm hex wrench to loosen the 3 captured screws that are accessed via the three holes shown in Figure 11. Once the screws are fully loosened the autotensioner will come off freely.



Figure 12 -- Removing old-type tensioner.

Reverse the steps above to re-install either the old or the new type of autotensioner.

3.2 General Arm Cable Circuit Descriptions (Optional Reading)

This section describes the parts of various cable circuits and the elements that they have in common. Subsequent sections explain how to replace worn drive cables as a part of standard WAM arm maintenance.

There are a total of 20 drive cables in the 4 degree-of-freedom (DOF) WAM arm and 16 more cable drives in the 3-DOF Barrett wrist. All four WAM motor axes have similar cable circuits, each of which reduces the motor shaft speed in two stages. Additionally, the cabled differential uses four 2.38mm diameter cables to couple the output to the inputs driven by motors 2 and 3.

Each cable circuit 1st-stage uses two 1.12mm diameter cables. Each 2nd-stage uses two 1.37mm diameter cables. The 2nd-stage cables are each doubled-over to run in parallel and handle the higher forces in the 2nd-stage. See Figure 13 for a schematic representation of a typical cable circuit.

Each stage has a grooved pinion driving a larger-diameter ungrooved pulley. The first and second stages are coupled through a matching pair of pulley/pinions (see Figure 21 and Figure 28) that proportionately and automatically propagate the pre-tension, applied in the first-stage pre-tensioner, to the second stage.

The pulley/pinions in the first three drives are identical (although mounted slightly differently). In each case these identical pulley/pinions are mounted on parallel shafts in such a way that the free cable lengths (and therefore the compliances) spanning between pinions and pulleys are minimized. The two matching pulley/pinions in the fourth motor drive are mounted in the elbow

on a single shaft and share their pulley surfaces. A light preload allows relative motion between these pulley/pinions during cable installation and cable pre-tensioning.

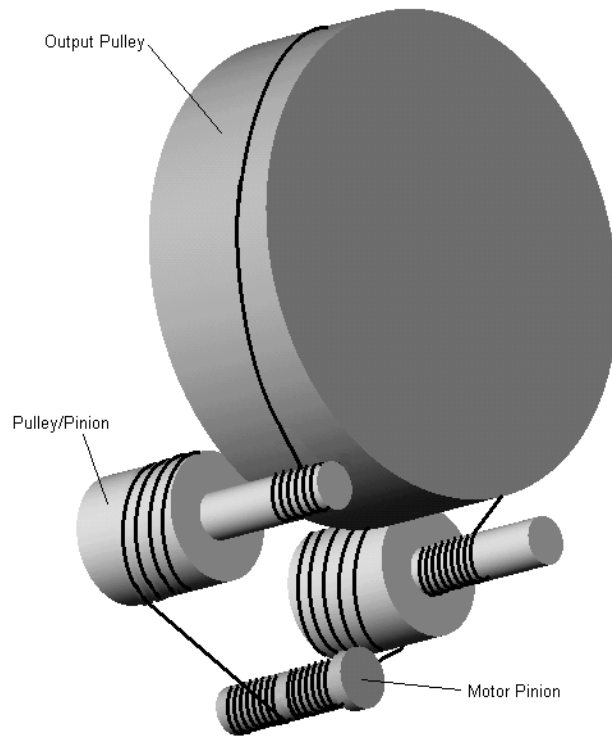


Figure 13 -- Typical Cable Circuit Arrangement

First-Stage Cable Path Description

Motor shafts drive each 1st-stage through a special split pinion. All four motor split pinions are identical. The motor pinion parts are called the inner-motor pinion (with grooves for cable guidance) and the outer-motor pinion (no grooves). The outer-motor pinion can rotate relative to the inner pinion in one direction only via the tensioner to add pre-tension to a cable circuit. Each outer-motor pinion (“outer pinion”) has a cable termination at its end. Each inner-motor pinion (“inner pinion”) has a cable termination at its root.

After a first-stage cable is attached to one of these inner pinion terminations, the cable is wound neatly into the guide grooves. The cable then spans across to the pulley section of a pulley/pinion with an open wrap such that the pinion and the pulley rotate in the same direction. The cable is then wound with a right-handed pitch, which matches the tight pitch angle of the cable wound on the motor pinion. After several winds, the cable's brass termination is attached to the anchor at the end of the pulley.

1st-stage cabling in the first three motor axes is similar. The cable attached to the inner pinion connects to the outside anchor of the appropriate pulley. The cable attached to the outer pinion connects to the inside pulley anchor.

The two 1st-stage cables of the fourth motor axis span a large (~510 mm) distance down the inside of the inner arm link. Slightly different from the first three drives, the 1st-stage cable on the fourth motor drive is connected to an anchor machined into the side of the pulley.

Second-Stage Cable Path Description

Cable circuits in the 2nd-stage consist of cables connecting the two grooved pinions of the pulley/pinions to the output pulley for that drive. The tension stresses in the 2nd-stage are about three times higher than in the 1st-stage. Therefore, slightly larger-diameter cables are used (in parallel pairs to double their capacity).

Each parallel pair is actually a single cable that is folded in half so that both termination lugs are at one end and a U-shaped loop is at the other end. The advantage of using this configuration, rather than two separate cables, is that, as the parallel pair is pre-tensioned, the stresses in the two halves of the pair automatically propagate around the loop to share the load equally. In all four 2nd-stages the brass lugs of a cable are attached to two anchor slots at one end of a grooved (pulley/pinion) pinion (1/2 turn apart). The groove is actually a double-pitch groove to accommodate the parallel pair of cables. U-slots, islands, or anchor-post features are included to the 2nd-stage pulley(s) in order to secure the U-shaped loop.

4 Important Tools & Tips

4.1 Time Allotment

Allow roughly 1-4 hours per motor axis when re-cabling for the first time. Subsequent re-cablings are generally much shorter (approximately 45 minutes per motor axis). Often, not all of the cables need to be replaced at once, thereby further reducing future re-cabling times.

One important point to keep in mind is that **each cable of a given drive must be held in place at all times until the entire circuit is pre-tensioned**. The wrapped cables act like light torsion springs which, when released even momentarily, may quickly unravel your work back to your starting point. Pre-tensioning, which prevents this unraveling, cannot be done until all cables in that circuit have been installed. The 1/2-inch masking tape provided in the maintenance kit with the WAM™ is a tremendous aid in preventing this unraveling. As a cable is wound or threaded onto each pulley or pinion, hold each wrap with your fingers to keep the cable from unwinding. At the end of each cabling step, one or two pieces of masking tape are effective in keeping cables in place temporarily.

4.2 Before Cabling

Before cabling, turn power off to the WAM and disconnect its power supply or blue power cord. When power is off, the joints will feel viscous and are difficult to move. This is because the motor phase leads are tied together electrically for safety in a power-off condition. You will need to disconnect the motor phase leads from the black “puck” motor controllers installed at the back end of the motor that is driving the joint(s) you are cabling. For example, for joint 4 disconnect the connector with three wires (white, red, black) as shown in Figure 14. You may have to cut a tie-wrap to access the connector.

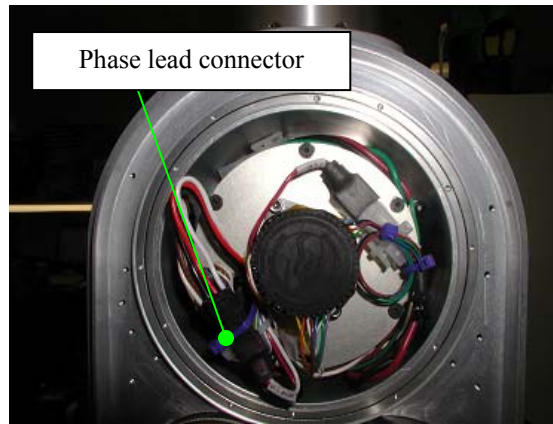


Figure 14 – J4 Puck and electrical connections

Re-cabling can be a difficult task for someone inexperienced with the process. It requires good mechanical dexterity. If you are re-cabling one of the WAM™'s cabled drives for the first time, thoroughly read the relevant sections of this manual on WAM™ cabling and pre-tensioning, make sure that you have the proper tools and cable parts, and observe good safety procedures. The cabling instructions have numbered checkboxes next to each step.

While it is possible for an experienced technician to complete the cabling process quickly without assistance, it is ideal for the inexperienced technician to work with a partner who should help keep tension on the circuits, guide the primary technician through instructions, provide assistance in watching for crossed or twisted cables, and adjust cables that may begin slipping out of place during the process.

4.3 Tools Necessary

The following tools are used for almost every cabling process (the differential has its own set of tools which are listed at the beginning of Section 7):

- Tweezers
- Pull Hook (WAM™)/Push-Pull Hook (Wrist)
- Kapton Tape (always specified as “Kapton tape”)
- Masking Tape (simply “tape”)
- Clamps (can be done with masking tape too)

4.4 After Cabling

When manually tensioning any cable circuit on the WAM™ (before autotensioning), a creaking sound is normal the first time you bring the joint through a certain range of motion. However, if the creaking persists several times through the same range of motion, check to see if any cables are crossed or otherwise interfering. Also while tensioning, listen to see if the cable attached to the outer section of a pinion makes a soft popping sound as it begins to be wrapped onto the grooved portion of the pinion. If so, move the cable slightly laterally and repeat the motion.

4.5 Cable Specifications

Table 1 lists the specifications of each type of cable. Contact Barrett Technology for additional spare cables.

Table 1 - Cable Specifications

Barrett P/N	Barrett Description	Qty per WAM	Qty per Maintenance Kit	length between terminations (mm)
B2308	ArmCable-Differential	4	2	340 +/- 0.5
B2311	ArmCable-Stage1-M1,M2,M3,M4	8	4	2300 +/- 13
B2314	ArmCable-Stage2-M1,M2,M3	6	2	1850 +/- 13
B2316	ArmCable-Stage2-M4	2	2	750 +/- 13

5 Cable Installation for Motor 1

5.1 Remove Covers

5.1.1 U-Shaped Plastic Base Cover

First remove the U-shaped base cover by unfastening the 4 clasps that secure it to the backplate, as shown in Figure 15.



Figure 15 -- Removing four clasps that secure the U-shaped plastic base cover.

5.1.2 Remove Autotensioner Cover

Expose the autotensioner cover by sliding a corner of the base plate off the edge of a table (or other means depending on your setup). Use a flat screwdriver to pry off the cover, as shown in Figure 16.

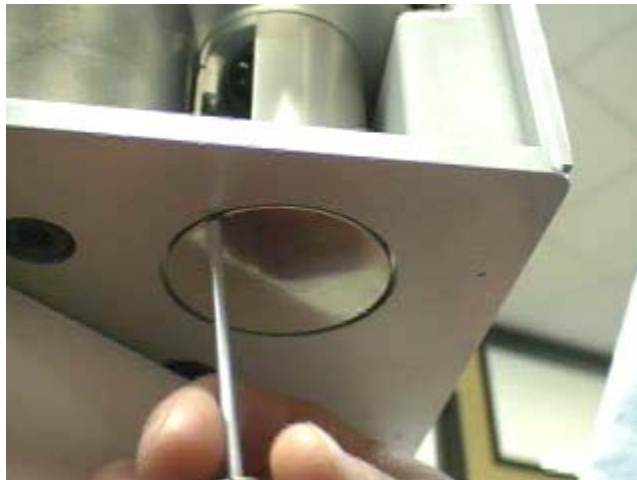


Figure 16 -- Remove autotensioner cover from baseplate of WAM.

5.1.3 *Open Hinged Backplate*

Remove any cables remaining on the backplate (except power for the wireless router). Remove the only screw that retains the hinged backplate with a 4-mm hex wrench as shown in Figure 17, then swing open the backplate as shown in Figure 18.



Figure 17 -- Remove single screw from backplate with 4-mm hex wrench.



Figure 18 -- Swing open backplate.

5.2 Remove Autotensioner

Remove the autotensioner as described in Section 3.1.

5.3 Detach Motor-1 Phase Leads

Find the leads on the base motor (Motor 1) which are the black, red, and white leads, as shown in Figure 19. The connector has a positive-locking latch, so press the plastic tab and pull the two halves apart, as shown in Figure 20.



Figure 19 -- Black, red, and white motor phase-leads as connected.



Figure 20 -- Phase leads disconnected.

5.4 Remove Any Damaged (Mechanical) Cables

Remove any damaged cables that are to be replaced. This can be a difficult exercise if the cables become badly tangled, so approach the job thoughtfully. Also, beware that frayed cables can act like sharp needles if they jab your finger tips.

5.5 Orientations:

Figure 21 distinguishes Sides A and B and identifies the Pulley-Pinions. Figure 22 identifies the motor pinion and output pulley. Figure 23 shows the Inboard and Outboard directions across the pulley and pinion faces, where Inboard is the direction towards the WAM shoulder, away from the base plate.

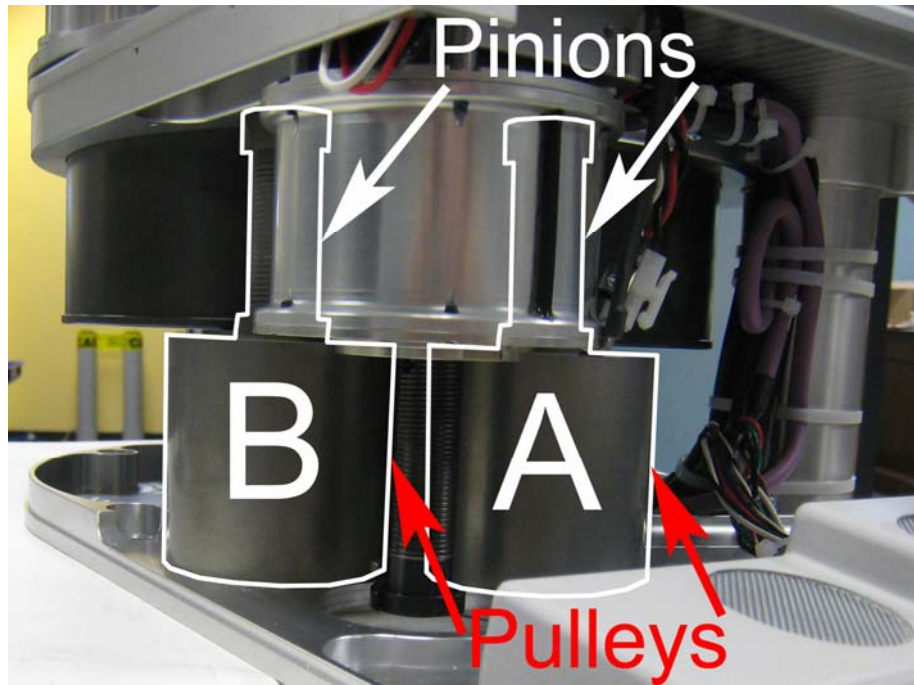


Figure 21 – Definition of Side A and Side B in the WAM base.

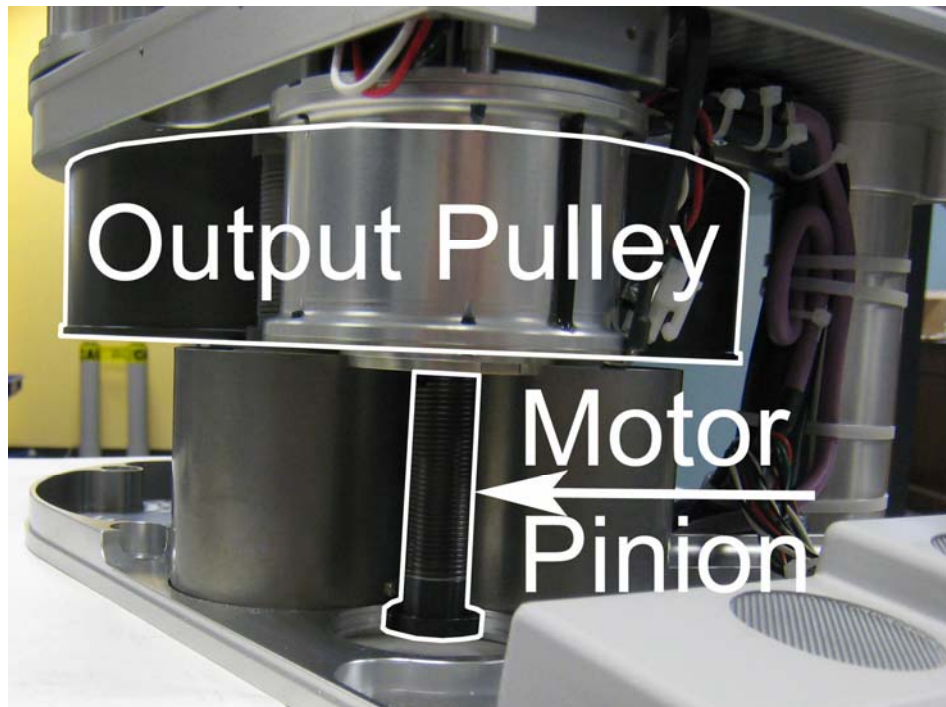


Figure 22 -- Output Pulley and Motor Pinion Identified.

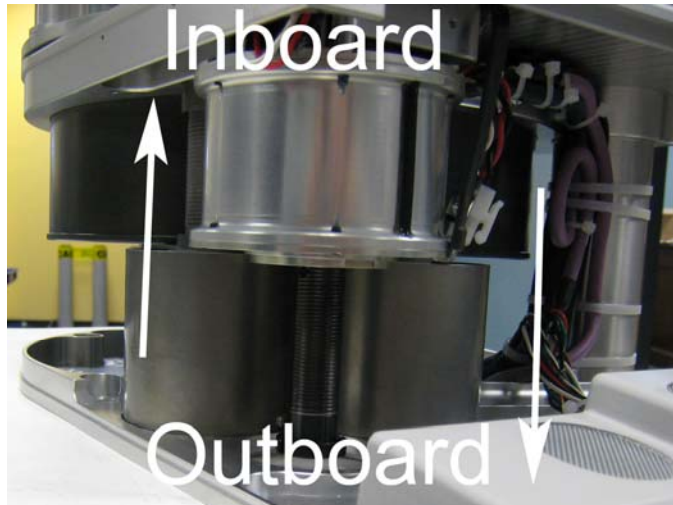


Figure 23 -- Inboard and Outboard Directions Defined for Motor-1 Cable Drive

5.6 Motor 1 - Stage 2

5.6.1 Side-A stage-1-cable pre-install

- 1. Take one stage-1-cable (B2311) and install its termination into the **Side-A** stage-1-pulley-anchor.
- 2. Hold the free end of the cable in your left hand to keep tension on the cable, rotate the pulley with your right hand to wind the cable onto the pulley in a right-handed helix, like in **Figure 24**. When all of the cable has been wrapped onto the pulley, tape the cable in place.



Figure 24 – Pre-Wrap Pulley

5.6.2 Side-B stage-2-cable

- 3. Rotate J1 fully clockwise (negative J1 direction) until it contacts the stop, tape J1.
- 4. Loop a stage-2-cable (B2314) around the stage-2-pulley-Outboard-anchor-post (like in **Figure 25**) such that the ends are uneven by 30 to 40 mm.

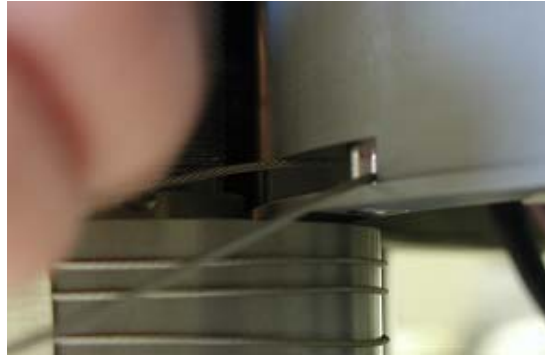


Figure 25 – Around Outboard Anchor Post

- 5. Thread both sides of the cable behind both stage-2-pinions such that the longer cable is on bottom (see **Figure 26**) – do not cross the cables.



Figure 26 – Wrap behind Motor Pinions

- 6. Insert the Outboard strand of the cable pair into the **Inboard** stage-2-pinion-anchor that is in line with (on the same side as) the stage-1- pulley-anchor. See Figure 27 and Figure 28 for reference. With a small square piece of tape, fix the ball termination in the anchor point.

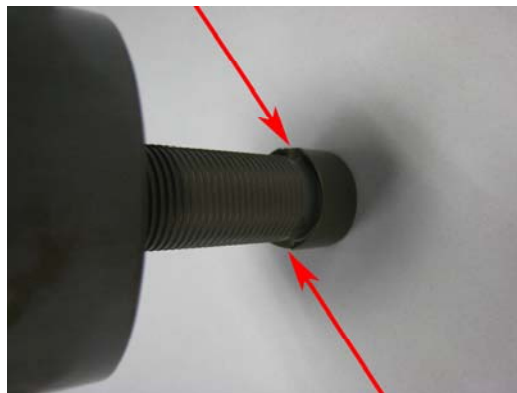


Figure 27 -- Twin termination anchors at the Inboard end of the pinion.



Figure 28 – First use the Pinion Anchor that is in line with the Pulley Anchor.

- 7. Rotate the pulley 180 degrees counter-clockwise. Attach the second termination to the other Inboard anchor and tape it there.
- 8. Wind the cable onto the pinion, filling the non-grooved portion first, such that all the slack is taken up, as in Figure 29. Tape the pinion into place by applying tape between the *Side-B stage-1-pulley* and the motor body, as shown in Figure 30.



Figure 29 – Guide on cable.



Figure 30 – Tape in Place to Secure

5.6.3 Side-A stage-2-cable

- 9. Loop a stage-2-cable (B2314) around the **Inboard** stage-2-pulley-termination-post, as shown in Figure 31. Tape the ends of both sides of the cable together so that they are uneven by 20 to 30 mm.



Figure 31 – Looping Cable around the Inboard Stage-2-Pulley Termination Post

- 10. Wrap the cable onto the stage-2-pulley in the counter-clockwise direction with the longer side above the shorter side, taping the cable in place as necessary. Continue the wrap behind the stage-2-pinions and above the first cable pair.
- 11. Attach the Inboard strand of the cable pair to the Outboard stage-2-pinion-anchor inline with (on the same side as) the stage-1-pulley-anchor. See Figure 32 and Figure 33 for reference. Place a small square of tape over the anchor and some of the pinion to keep the termination from falling out.



Figure 32 -- Twin termination anchors at Outboard end of pinion.



Figure 33 -- First use pinion anchor that is aligned with the Pulley anchor.

- 12. Rotate the pulley 180 degrees clockwise, and attach the second termination ball to the other Outboard anchor.
- 13. Wind the cable onto the pinion (start at and fill only the grooved area) such that all the slack is taken up. Tape the pinion into place by applying tape between the *Side-A* stage-1-pulley and the motor body, as shown in **Figure 34**.



Figure 34 – Securing the Side-A Stage-1-Pulley

5.7 Motor 1 - Stage 1

5.7.1 Side-B stage-1-cable

- 14. Place one end of a stage-1-cable (B2311) into the anchor located on the motor-pinion near the body of the motor.
- 15. Wind the cable onto the inner-motor-pinion as shown in **Figure 35**, taking care not to let the cable slide through your fingertips. Make sure the cable does NOT cover its termination after one loop around – it should be one groove below the termination.
- 16. When the cable is approximately two grooves above the un-grooved section of the pinion, tape the cable in place on the pinion, and wrap it onto the pulley, inserting the termination ball into the anchor point (use tweezers). Rotate the motor pinion to take up the slack in the **Side-B** stage-1-cable. If the wire spills over onto the non-grooved section, ensure that it is wrapped only loosely there.



Figure 35 – Wrapping Stage-1-Cable onto Pinion

5.7.2 Side-A stage-1-cable

- 17. Unwrap the minimum amount of the **Side-A** stage-1-cable to insert the **Side-A** stage-1-cable-termination into the outer-pinion-anchor (this should be about one wrap).
- 18. Insert the **Side-A** stage-1-cable-termination into the outer-pinion-anchor.
- 19. Holding the motor pinion in place, rotate the outer-pinion clockwise to take up the remaining cable.
- 20. Remove all large pieces of tape except for that holding the Side-B stage-1-pulley. Using a finger to maintain tension in the **Side-B** stage-1-cable (as shown in **Figure 36**), remove the remaining large piece of tape and rotate J1 counter-clockwise slightly until the split between the motor and outer pinions is showing (“tensioning position”), as shown in **Figure 37**.



Figure 36 – Using Finger to Maintain Tension

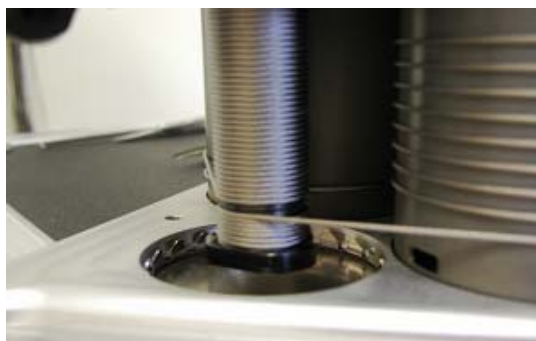


Figure 37 – Motor Pinion Split

- 21. While maintaining tension in the cable, hold the inner pinion still with one hand while twisting the outer pinion counter-clockwise.

5.8 Manual Tensioning

- 22. Push parts of the cable wrapped around both stage-1-pulleys so that they are both fairly uniform helices.
- 23. Slowly move J1 approximately 15 degrees counter-clockwise. Move back to the tensioning position. Counter-rotate the pinions to take up slack and add tension to the system.
- 24. Slowly move J1 approximately 30 degrees counter-clockwise. Move back to the tensioning position. Counter-rotate the pinions to take up slack and add tension to the system.
- 25. Repeat Step 24, adding ~15 degrees each time until you move J1 to the extreme of its range.
- 26. Move J1 to the extreme of its range and back. Add tension by counter-rotating the inner and outer pinions at the tensioning position.
- 27. Check to see if cables on the stage-2-pulley are grinding – if they are, move the all of the cables on the Side-A stage-2-pinion up by one groove before tensioning further.
- 28. Move J1 its full range 6 more times and tension as in Step 26. Note: Only turn the outer pinion with your fingers. As you move J1, pull off the small pieces of tape over cable termination slots and anchors – pull the tape away from the cables so it does not pull them out of their positions.

Repeat step 28 until all of J1's cable are in a uniform spiral around their respective paths.

6 Cable Installation for Motors 2 & 3

6.1 Remove Covers

Remove the plastic side cover on the side you will be cabling by spreading their flanges slightly and tugging away from the WAM shoulder. Remove both J2 covers by curling your fingers over their tops and popping the bottom out first. Never remove the actual J2 stop.

6.2 Remove Autotensioner

Follow the instructions in Section 3.1 to remove the autotensioner.

6.3 Detach Motors 2&3 Phase Leads

Detach the black, red, and white phase leads between the motor and its Puck drive. The connector has a positive lock, so you depress a plastic tab while uncoupling the connector. See Figure 19 and Figure 20 for reference.

6.4 Loosen Differential M3x6 Screws by a Couple Turns

Use a 2-mm hex wrench to loosen the two M3x6 screws, shown in Figure 38 and Figure 39, by a couple of turns.

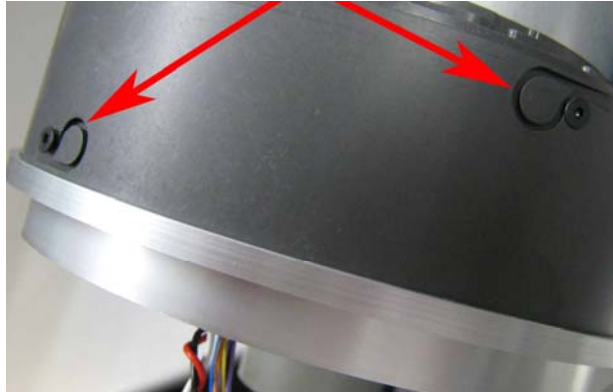


Figure 38 -- Two M3x6 screw locations.

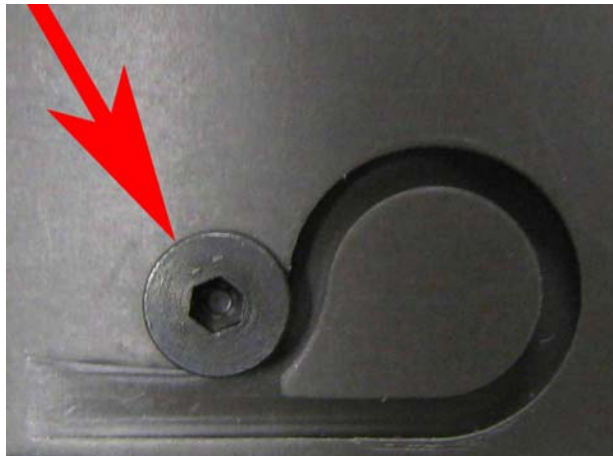


Figure 39 -- Closeup of the M3x6 screw.

6.5 Remove Any Damaged Cables

Remove any damaged cables that are to be replaced. This can be a difficult exercise if the cables become badly tangled, so approach the job thoughtfully. Also, beware that frayed cables can act like sharp needles if they jab your finger tips.

6.6 Orientation

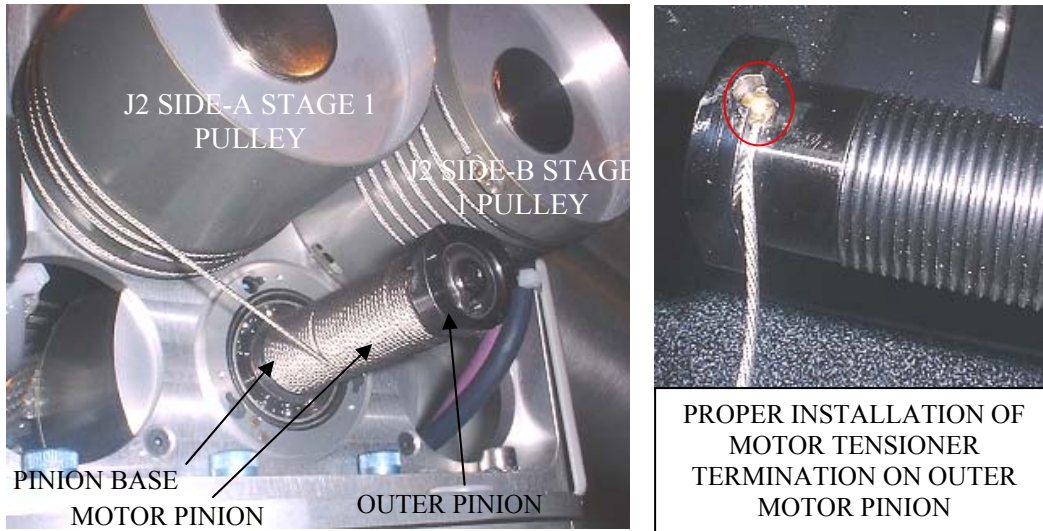


Figure 40 -- Motor Shafts

The cable circuits for M2 and M3 are very similar to the cable circuits of M1. Figure 40 shows locations of Side A and Side B. Figure 41 and Figure 42 respectively define Inboard and Outboard directions relative to the center plane of the shoulder.

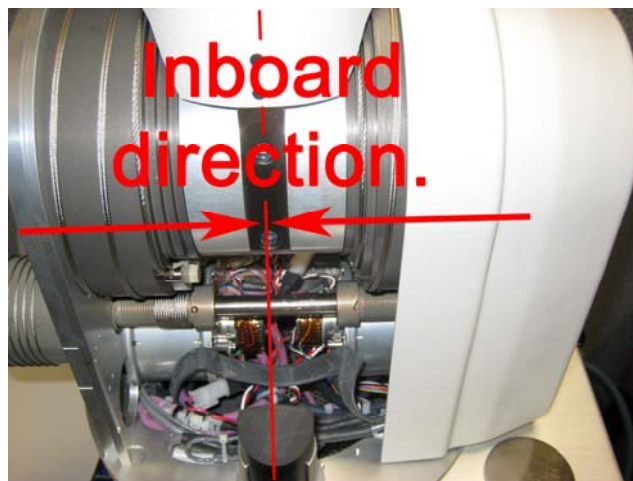


Figure 41 -- Inboard direction points towards the center plane of the shoulder.

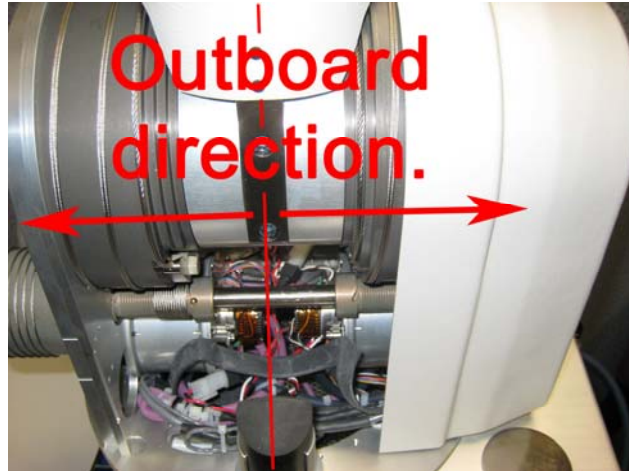


Figure 42 -- Outboard direction points away from the center plane of the shoulder.

6.7 Motors 2 & 3 Stage 2

- 1. While facing the side to be cabled, rotate the stage-2-pulley fully counter-clockwise until joint-2 and joint-3 contact their stops. See **Figure 43** for reference. The arm links should be on your left and J3 against its positive (+) stop.

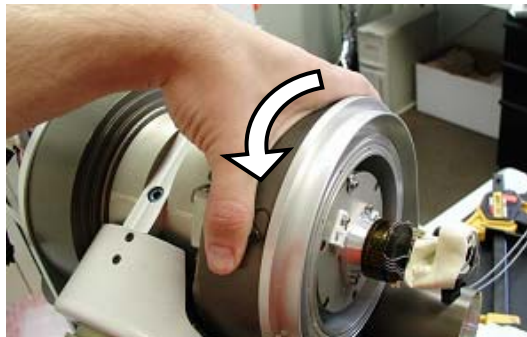


Figure 43 – Rotating J2 and J3 until Joint Stop

- 2. Tape or clamp the stage-2-pulley in place.

6.7.1 Side-A stage-1-cable pre-install

- 3. Take one stage-1-cable (B2311) and install its termination into the **Side-A** stage-1-pulley-anchor.
- 4. Using one hand to keep tension on the cable, spin the pulley with your other hand to wind the cable onto the pulley in a right-handed helix, as shown **Figure 44**. When all of the cable has been wrapped onto the pulley, tape it in place.



Figure 44 – Wrapping Stage-1-Pulley-Anchor

6.7.2 Side-B stage-2-cable

- 5. Take one stage-2-cable (B2314). Form it into a U shape. The ends should be uneven by approximately 30-40mm, as shown in **Figure 45**.



Figure 45 – Uneven Stage-2-Cable Ends

- 6. If you did not already do so, loosen the M3x6 screw on the *outboard* loop-anchor-groove. Install the U-loop such that the longer end rides on the *outboard* edge of the stage-2-pulley. Gently push the cable into the slot, as shown in **Figure 46**. With only a light torque, snug the screw against the cable so that the cable cannot pop out of the groove but can slide along the groove.



Figure 46 – Installing Cable in Outboard Loop-Anchor-Groove

- 7. Wrap the cable 1/2 turn around the pulley in a left-handed helix. The cable will pass between the pulley and both stage-2-pinions.
- 8. Attach the outboard cable of the cable pair to the *inboard Side-B* stage-2-pinion-anchor that is in line with (on the same side as) the stage-1-pulley-anchor. See Figure 27 and Figure 28 for reference.

- 9. Using a small piece of sticky tape, fix the ball termination in the anchor point.
- 10. Rotate the pinion 180 degrees clockwise. Attach the second ball in the same manner.
- 11. Wind the cable onto the pinion (fill the non-grooved area first) such that all the slack is taken up. Tape the pinion into place by applying tape between the Side-B stage-1-pulley and the WAM's body, as shown in **Figure 47**.



Figure 47 – Securing the Stage-1-Pulley

6.7.3 Side-A stage-2-cable

- 12. Take the other *stage-2-cable* (B2314). Form it into a U shape. The ends should be uneven by 30-40 mm with the inboard cable longer. See **Figure 48** for reference.
- 13. Install the U-bend into the inboard *loop-anchor-groove* such that the longer end rides on the inboard edge of the *stage-2-pulley*. Gently push the cable into the slot.
- 14. Wrap the cable 1+3/4 turns around the pulley in a left-handed helix. The second time underneath the pulley the cable will pass between the tombstone support and the first installed cable, as in **Figure 48**.

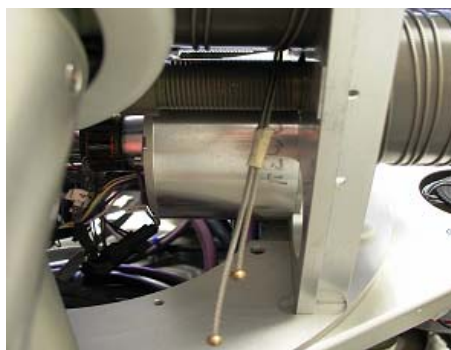


Figure 48 – Area between Tombstone and First Cable

- 15. Attach the inboard cable of the cable pair to the outboard Side-A *stage-2-pinion* anchor that is in line (on the same side as) with the *stage-1-pulley-anchor*. See Figure 32 and Figure 33 for reference.
- 16. Rotate the pinion 180 degrees counter-clockwise. Attach the second termination ball in the same manner.

- 17. Wind the cable onto the pinion such that all the slack is taken up (skipping the grooved section this time), as in **Figure 49**. Tape the pinion into place by applying tape between the Side-B *stage-1-pulley* and the motor body.

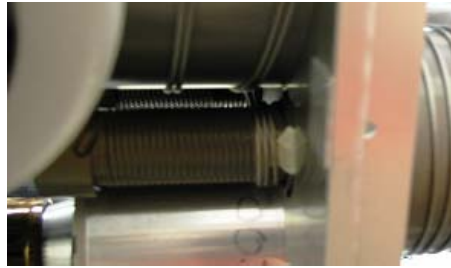


Figure 49 – Wrapping Stage-2-Pinion

- 18. If there is a significant amount of slack in the cables on the stage-2-pulley, tighten the pinion again before continuing.
- 19. Tighten the loop anchor screws so that they are snug against the cable but not crushing.

6.8 Motors 2 & 3 Stage 1

6.8.1 Side-B stage-1-cable

- 20. Place one end of the *Side-B stage-1-cable* (B2311) into the anchor located on the base of the motor pinion. Secure with tape if necessary.
- 21. Rotate the pinion clockwise, winding the cable onto the motor pinion as shown in **Figure 50**, taking care not to let the cable slide through your fingertips.



Figure 50 – Wrapping Inner Pinion

- 22. Once the cable is wound most of the way, use tape to secure the wrapped section to the pinion. Wind the end of the cable 1 wrap around the Side-B stage-1-pulley and insert the termination (using tweezers) into the cable anchor. Rotate the motor pinion to take up the remainder of the slack in the Side-B stage-1-cable, as shown in **Figure 51**.



Figure 51 – Wind 1+1/2 Times onto Pulley

6.8.2 Side-A stage-1-cable

- 23. Unwind the minimum amount of the Side-A stage-1-cable (B2311) needed to insert it into the motor outer pinion anchor. Remember not to constrain the cable as you unwrap (Rule 2).

- 24. Insert the Side-A stage-1-cable termination into the motor outer pinion anchor.
- 25. Holding the motor pinion in place, rotate the outer pinion to take up the remaining cable. (Note: you may need to rotate the motor pinion to move the other cable off the outer pinion.)
- 26. Remove all large pieces of tape but that holding the Side A stage-2-pulley. Using a finger to maintain tension in the Side-A stage-1-cable, remove the remaining large piece of tape and move the *stage-2-pulley* clockwise until the split between the motor and outer pinions is showing.
- 27. While maintaining tension in the cable, hold the inner pinion and rotate the outer pinion counter-clockwise. After completing this step, it should look like Figure 52.



Figure 52 – Final Tension and Configuration

6.9 Manual Tensioning

- 28. Slowly move the *stage-2-pulley* ~15 degrees counter-clockwise. Move back to the tensioning position. Counter-rotate the pinions to take up slack and add tension to the system.
- 29. Slowly move the *stage-2-pulley* ~30 degrees counter-clockwise. Move back to the tensioning position. Counter-rotate the pinions to take up slack and add tension to the system.
- 30. Repeat Step 28, adding ~15 degrees each time until you move the *stage-2-pulley* to the extreme of its range, J2 and J3 will both contact their stops. As you are turning, adjust the Side-A stage-1-cable so that it is in a uniform spiral.
- 31. If you are cabling M3, ensure that, when the stage-2-pulley is at the extreme of its range, the level-4 differential cable does not touch a stage-2-cable as it comes off of the stage-2-pinion.
- 32. Move the *stage-2-pulley* to the extreme of its range and back. Add tension by holding the inner pinions still and turning the outer pinion counter-clockwise.
- 33. Move the *stage-2-pulley* its full range 6 more times and tension. Note: Only tension with your fingers on the outer pinion. Do NOT use two wrenches because you risk breaking the cable.
- 34. The circuit is tight enough when you can move it through its range of motion several times without the cable coming noticeably loose. Tighten the stage-2-pulley screws to complete the cabling. The finished circuit should look like Figure 53.

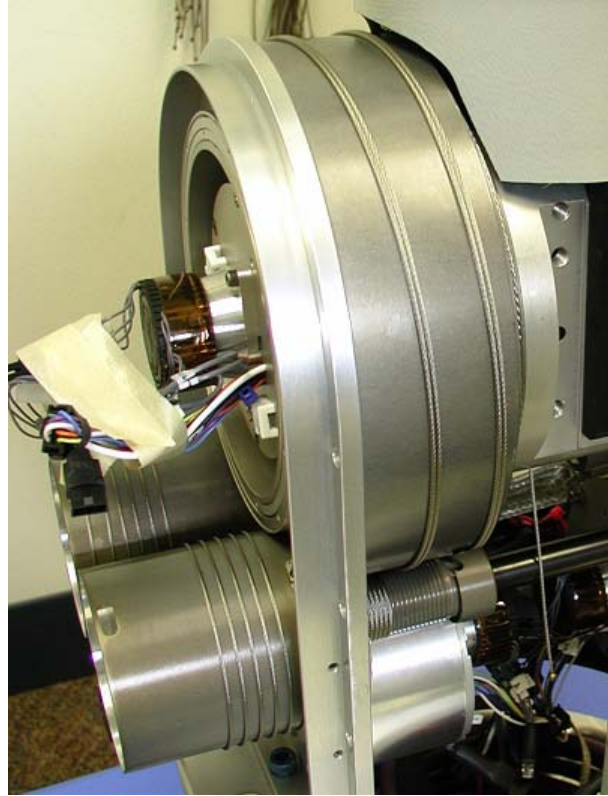


Figure 53 – Complete Cabled Transmission

Cable Installation for Motor 4



Figure 54 – Joint 4

6.10 Preparation

- 1. If you have any attachments (e.g. wrist, arm) on J4, remove these before beginning.
- 2. Remove the shoulder cover on the side to be cabled.
- 3. Remove both J2-stop covers.
- 4. Remove the motor (2 or 3) tensioning mechanism (the cylinder that surrounds the motor pinion).
- 5. Disconnect phase leads for joints 2 and 3.
- 6. Review Figure 55 through Figure 40 and note the terminology used for J4 cabling.
- 7. Remove the J4 covers at the elbow using a Phillips (+) type screwdriver (see Figure 58). Remove the black J4 pinion cover at the base of the arm by reaching your hand inside and pressing on the center of the back of the cover.
- 8. Orient the arm so that J1, J2, and J3 are all centered. J4 should begin in the far negative (-) orientation.
- 9. Prepare several short pieces of masking tape and several 1-cm pieces of Kapton tape for convenient use later. Use tweezers and not your fingers to handle the Kapton tape. Note that all Kapton tape is permanent and should not be removed even after the cabling is complete.

6.11 Orientation

Clockwise and Counter-Clockwise: View the WAM™ Arm from the side you are working on.
Side-A & Side-B: Refer to **Figure 55**.

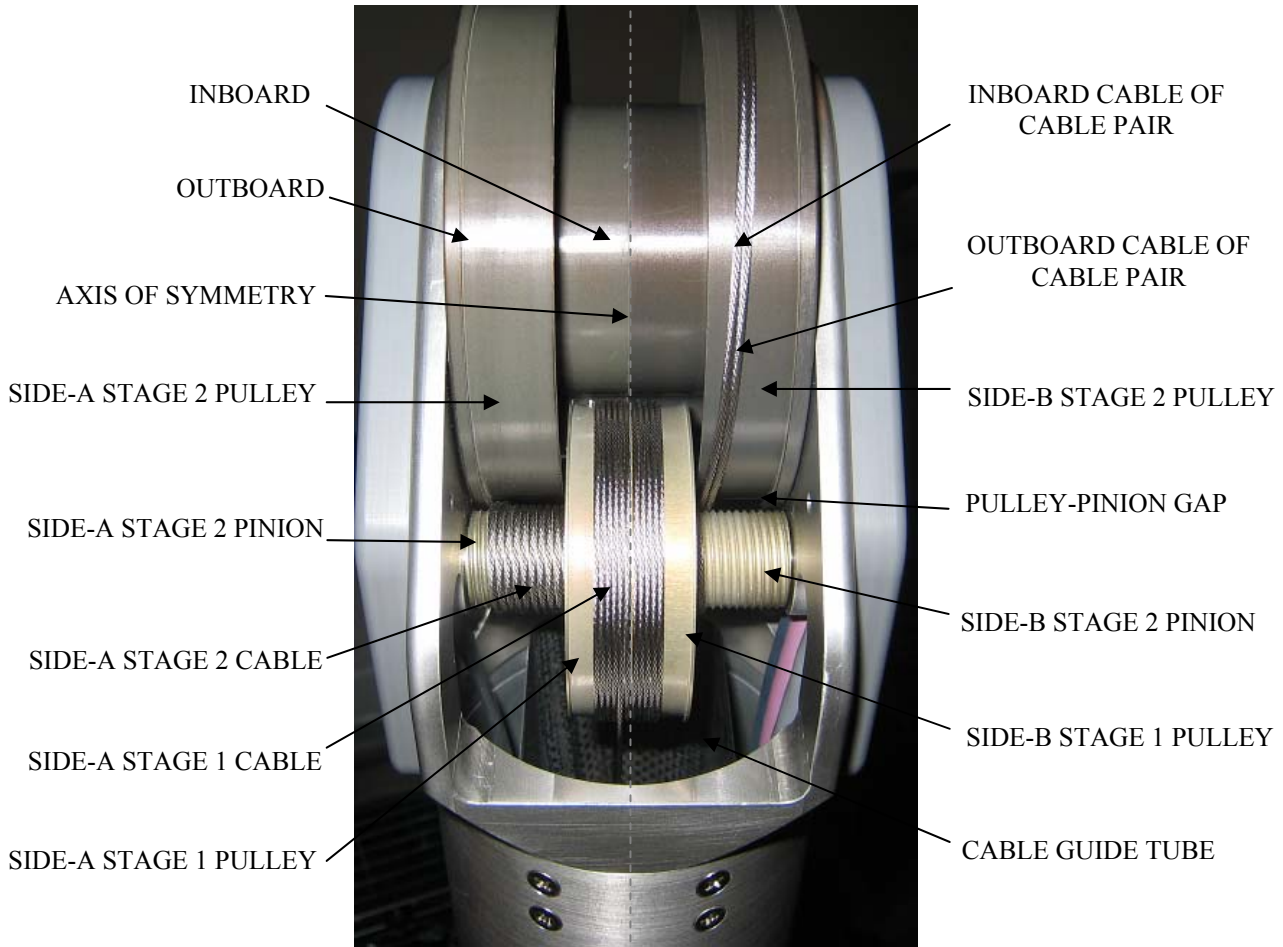


Figure 55 -- View of Joint 4 (elbow)



Figure 56 -- Side Views of Joint 4

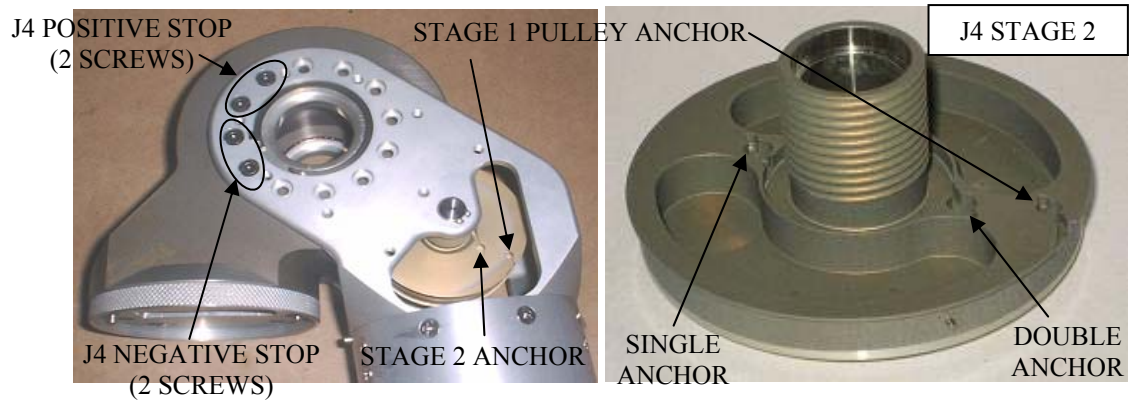


Figure 57 -- Joint 4 Components



Figure 58 – Removing J4 Covers

6.12 Motor 4 Stage 2

6.12.1 Side-A Stage-2-Cable

- 1. Remove the Side-A stage-2-anchor-post screw and washer (using M3 hex wrench or small fingers). Bend a J4-stage-2 cable (B2316) in half forming a U-loop (do not pinch it). Install it around the anchor post. Use masking tape to temporarily secure the cable in place.
- 2. Replace the screw and washer, as in Figure 59, and remove the tape before continuing. Wrap the cable around the pulley.
- 3. Insert the cable terminations through the back of the elbow and out the front (not between the pulley and pinion).
- 4. Move J4 to the far positive stop.
- 5. Insert the outboard cable termination into the Side-A stage-2-single-anchor as in Figure 60. The cable termination should fit snugly into the groove on the anchor. Use a piece of Kapton tape to hold it in the slot.
- 6. Rotate the Pulley Pinion 180° clockwise (view from left side) and insert the inboard cable termination into the stage-2-double-anchor. Use Kapton tape to hold in place.
- 7. Gently adjust the inboard and outboard sides so that they are even in length. Rotate the pinion clockwise (from left) to wind the cable onto the grooved pinion (see Figure 61). Use tweezers to push the cables towards the center of the pinion and fill up the entire un-grooved portion of the pinion first. Keep tension on the cables throughout and continue winding until the cable is fully wound. Pulling J4 forward temporarily will assist in completing the winding process.
- 8. Secure the stage-2-pulley as shown in Figure 62 so that the cable is secured.



Figure 59 – Replacing Anchor Screw



Figure 60 – Inserting the Terminations into the Side-A Anchors



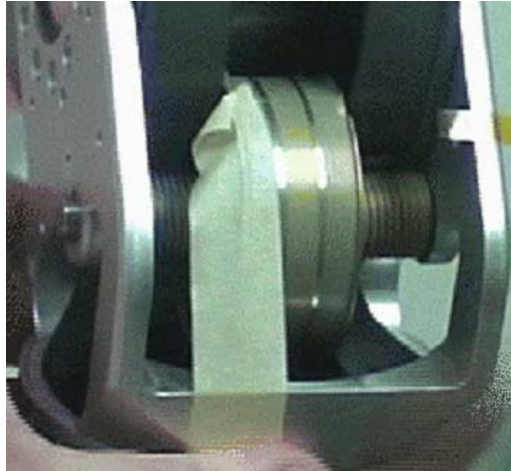


Figure 62 – Securing the Stage-2 Pulley

6.12.2 Side-B stage-2-cable

- 9. Make a U-loop of the Side-B stage-2-cable (B2316). Push the loop between the pulley and pinion and around to the anchor-post as shown in Figure 63. Loop the cable around anchor post as in Figure 64.
- 10. Adjust the terminations so that the outboard side is pulled 30-40mm longer than the inboard and secure with a piece of masking tape.
- 11. Pull the ends of the cable to the back of the joint under the pulley and pinion.
- 12. Insert the outboard termination into the Side-B stage-2-double-anchor. Once again, the cable should nest into the anchor in the direction of the groove.
- 13. Rotate the Side-B half of the pinion and insert the inboard termination into the Side B stage-2-single-anchor (see Figure 66).
- 14. Wind cable onto pinion by rotating only the Side-B half of the Stage-2- pinion. Again, make sure the ungrooved portion of the pinion is full before winding on to the grooves.



Figure 63 – Feeding the U-loop between Pinion and Pulley



Figure 64 – Looping Cable around Side-B Anchor

- 15. Tighten stage 2 by counter-rotating Side-A and Side-B in opposite directions as indicated in Figure 65. Remove all masking tape; the internal friction in the pinion/pulley should keep the cables from unwinding. The setup should now look like Figure 67.
- 16. Move J4 through its full range of motion and inspect the cables to ensure that they are not crossing at any point.



Figure 65 – Tightening Stage-2



Figure 66 – Inserting Cable into Side-B Single Anchor

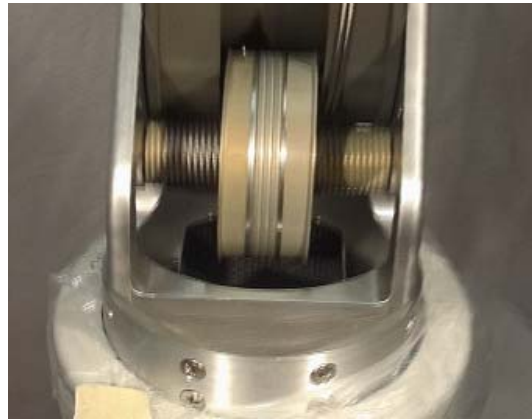


Figure 67 – View of Completed Stage-2

6.13 Motor 4 Stage 1

6.13.1 Side-B stage-1-cable

- 17. Bring J4 to the far negative position. Install one end of a stage-1-cable (B2311) in the Side-B stage-1-pulley-anchor and secure with Kapton tape. While keeping tension on the cable, rotate J4 to the far positive (+) direction so that the cable wraps around the Stage 1 pulley. Be sure that the cable wraps around the pulley on the inside of the retainer pin.
- 18. Carefully wrap the cable around the pulley by inserting the loose termination between the pinion and pulley and pulling it out the front (see Figure 68). Be careful not to twist or cross the cable and make sure the cable wraps only around the section of pulley inside the pin; place one finger through the hole in the side of J4 to check the back of the pulley. Use masking tape after each wrap to keep the cables in place. Continue until you see six (6) wraps of cable on the side of the joint that is visible. Keep the tape in place after the last wrap.
- 19. Feed the loose termination between the pulleys and drop the remainder of the Side-B stage-1-cable down through the central tube and out the bottom. Be sure that the cable goes through all of the arm's interior tubes.



Figure 68 – Wrapping Side-B Cable 6 Times

6.13.2 Side-A stage-1-cable

- 20. Install one end of another Stage-1-cable (B2311) through the back of the joint and into the Side-A stage-1-pulley-anchor; secure it with Kapton tape.
- 21. Loop the cable around the pulley until you see five (5) wraps of cable on the side of the joint that is visible, by feeding it underneath the pulley and up through the gap above the Stage 1 pulley. Use masking tape after each wrap to keep the cables in place. It may be useful to feed the cable completely out the back prior to feeding it out the front. Be careful not to impart any unnatural twists on the cable and make sure that the cable does not cross itself or wind outside of the pin. While looping, keep one finger through the hole in the side of J4 and on the back of the pulley to ensure that the cables do not cross each other.
- 22. Drop the remainder of the Side-A stage-1 cable down through the arm tube and pull it out the bottom. The joint should now look like Figure 69.

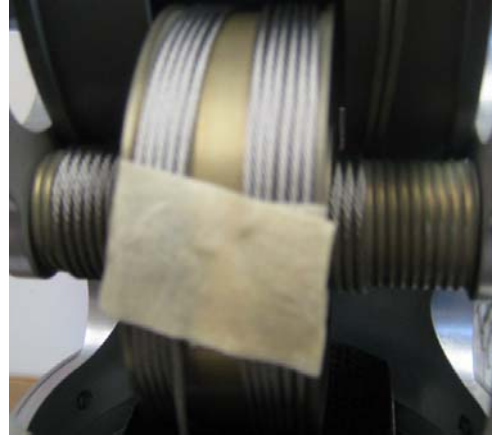


Figure 69 – J4 after Installation of Stage-1 Cables

6.13.3 Attaching the cables to the motor pinion

- 23. While holding both cables at the bottom of the arm tube to maintain tension, remove the tape on the pulley. Pull the shorter cable away from J4 and allow the longer cable to move towards J4 while maintaining tension on both to make J4 move as far back as possible. DO NOT pull the cables across the edge of the differential output tube. While J4 is rotating, ensure that the pulleys do not cross or move outside the pins. Tape all pulley cables again to maintain tension and then tape J4 so that it cannot move from this position. Tape the back of the Side-B stage-1-cable where it drops down to ensure that it does not fall off of the pulley.
- 24. Drop J2 to the far positive (+) stop. From this position, the longer of the two loose ends should be passing underneath the motor pinion, and the shorter of the two should be passing over it. Look through the length of the arm to ensure that the cables are not crossed or tangled.
- 25. Tape the Inboard cable out of the way temporarily. Connect the Outboard cable to the termination anchor on the base of the motor pinion.
- 26. While keeping tension on the cable, slowly wind the cable onto the pinion by turning it away from you (CW from right side). The cable should cross over the retaining ring on the first rotation. Then, wrap each future rotation as close to the retaining ring as possible. Continue until cable is fully wound.
- 27. Install the other cable's termination into the outer-pinion-anchor.

- 28. Wind the Side-B stage-1-cable onto the outer-pinion while holding motor-pinion stationary, and take up all the slack. Note the outer pinion is on a one-way clutch, so it can only rotate in one direction relative to the motor pinion. Once the cables are tight, remove all tape.

6.14 Manual Tensioning

- 29. To tension the joint, always put J2 in the far positive (+) direction and J4 in the far negative (-) direction. Use your fingers to turn the outer pinion, and hold the inner pinion by inserting an M4 hex wrench into the end of the pinion. Use this method to take up slack whenever it develops.
- 30. Un-tape the elbow joint and slowly move it through 30 degrees of motion. Return the elbow joint to the tensioning position and tension. As you move the joint, look for cables that are crossed, twisted, or wrapped outside of the stage-1-pulley retainer pins.
- 31. Continue to oscillate the J4 joint back and forth, adding 30 degrees of motion each time and tensioning after each cycle until you have moved J4 through its full range of motion. As you are doing so, work the Side-A stage-1-cable and the Side-B stage-1-cable on the stage-1-pulley toward the center of the stage-1 pulley so that they are next to (but not pinching) each other (in the end the two sections of cables should be within 0.5 mm of each other).
- 32. Move the elbow through its full range six times, return the elbow joint to the tensioning position, and tension the cable.
- 33. Repeat step 32 two more times.
- 34. Move J3 and J4 to combinations of each of their stops. After each, look up the arm's length to ensure that the stage-1 cables are not rubbing. They should appear to be close to each other at times, but they should not be able to contact.
- 35. Add a piece of the thick Kapton tape around the piece of cable at the base of the stage-1-pinion and then add a zip-tie at the middle of the pinion section before the retaining ring (see Figure 70).



Figure 70 – Tape and Zip-tie

7 Cable Installation for the Differential

7.1 Preparation

7.1.1 Tools and Supplies

- 4x Differential Cable (B2308)
- Differently Sized Punches and Small Plastic Mallet
- Masking Tape
- 10mm Combination Wrench

7.1.2 Cautions

- Make sure that the termination does not get caught on the edge of the anchor slots as you tap them in.
- Be careful not to kink or cut the cable.
- Make sure the differential cables stay on their respective levels – if you feel the joint suddenly stop rotating while moving, do not force it as it may be pinching a cable which has crossed levels.
- If you are rotating either of the inner pulleys and the cam-locks are not yet closed, tape them down so they do not hit the output pulley as they pass it.
- Getting cable terminations into the cam-locks should be somewhat difficult, and closing the cam-locks should require A LOT of force, and should create an exceptionally loud creaking noise. If you do not find all three of the above to be true while you are cabling the differential, check the cables as something has likely slipped out of place.
- When you insert the terminations into the anchors and the anchor slots, use a small plastic mallet and a small punch to tap the terminations into place. Always ensure that the terminations and the cables are tapped into their respective anchors and slots as far as possible.
- On the differential output pulley tape cables to their respective levels next to their anchors to prevent them from slipping off.

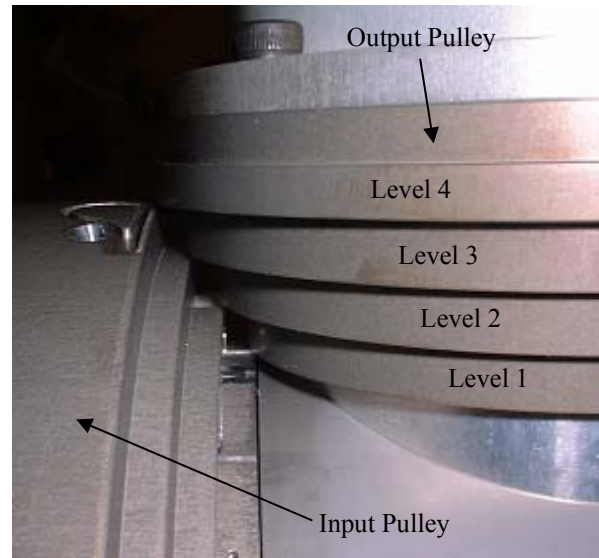


Figure 71 – WAM™ Arm Differential

7.2 Orientation

Clockwise and Counter-Clockwise: View the WAM™ Arm from the side you are working on.

Side-A & Side-B: Looking from the Rear (looking at the connector plate) **Side-A** is on the Left.

7.3 Installation

7.3.1 Level 1 and 4 (Side-A)

- 1. Rotate the Side-A input pulley so the cam-lock is as close to the output pulley as possible and thread the level-1-cable through the Side-A gap, rotating J3 as needed (see Figure 73). After this point, keep the cam-lock away from the output differential so the cable can't slide out.
- 2. Insert the level-1-cable into the Side-A input-anchor; use the punch to insert the cable into the level-1-slot. See Figure 72.



Figure 72 – Level 1 Input



Figure 73 – Sliding the Level-1-Cable down the Side-A Gap

- 3. Wrap the cable along the input-pulley, and use the punch and mallet to insert the other termination into level-1-output-anchor, and the cable into the slot. This anchor is the bottom (blue) arrow in Figure 74. It may take some force to set the termination fully into the anchor.
- 4. Insert the level-4-cable into the output pulley's level-4-slot. This is the top (yellow) arrow in Figure 74. Wrap the cable around the differential-output-pulley and onto the side-A differential-input-pulley.
- 5. Insert the other end of the level-4-cable into the cam-lock mechanism (shown in Figure 75). While ensuring the level-1-cable and level-4-cable stay on the correct pulley path, tighten cam-lock using a 10mm Box Wrench (keep cable tight by maneuvering the input-pulley against the J2-joint-stop). Both cables should be taut. The cables will ride to the edge of their levels once the cam-locks are locked. Move J3 through its full range to test the level 1 and 4 differential cables.
- 6. Thread the level-2-cable and the level-3-cable through the Side-B gaps to their respective levels as you did with the level-1-cable, rotate J3 as needed (you may thread both cables at the same time or one after the other but both must be threaded now). Afterwards, keep the cam-lock away from the output differential so the cables cannot slide out the gap.
- 7. Insert the level-2-cable into the Side-B input-anchor, and then manipulate (using punch) the cable into the level-2-slot as shown in Figure 76. Note the subtle difference between Figure 72 and Figure 76.
- 8. Wrap the level-2-cable along the input pulley, and insert the other termination into level-2-output-anchor, and the cable into the slot. This anchor is the bottom (pink) arrow in Figure 77.

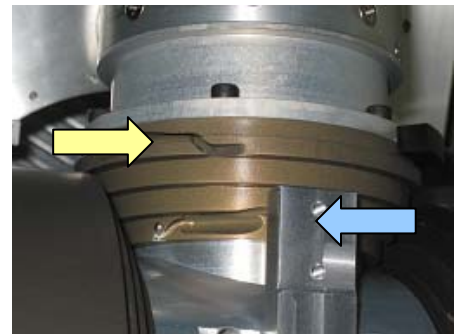


Figure 74 – Level 4, Level 1 Outputs



Figure 75 – Locked Level 4 Input

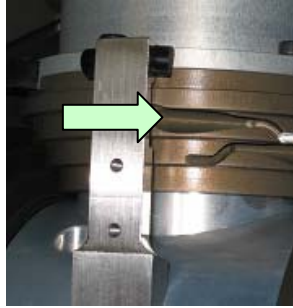
- 9. Insert the level-3-cable into the level-3-slot. This is the top (green) arrow in Figure 77. Wrap the cable around the differential-output-pulley and onto the differential-input-pulley with a cam-lock on level-3.

Insert the other end of the level-3-cable into the cam-lock mechanism (shown in

- 10. Figure 78). While ensuring that the level-2-cable and the level-3-cable stay on the correct pulley path, tighten the cam-lock using a 10mm Box Wrench (keep cables tight by maneuvering the input-pulley against the J3-joint-stop). All cables should be taut.



Figure 76 – Level 2 Input



**Figure 77 – Locked
Level 3 Input**

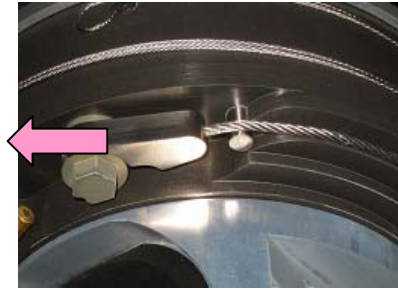


Figure 78 – Levels 2 and 3 Output

8 Autotensioning

Contact Barrett Technology for Autotensioning instructions at support@barrett.com or at US+617-252-9000. Follow-on manuals will contain complete Autotensioning instructions.