WAM™ Arm
User's Guide

Barrett Technology® Inc.

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Getting Started

This section is meant to help you develop a familiarity with the WAM™Arm system. Use this Getting Started section as a supplement to the Quick Start Guide, included separately.

Unpacking

Figure 1 below illustrates everything that is shipped with a standard 4 degree-of-freedom WAM™Arm. Please ensure that all components are accounted for. ***In addition to the components shipped, you will need a computer monitor and keyboard to connect to the supplied PC.***

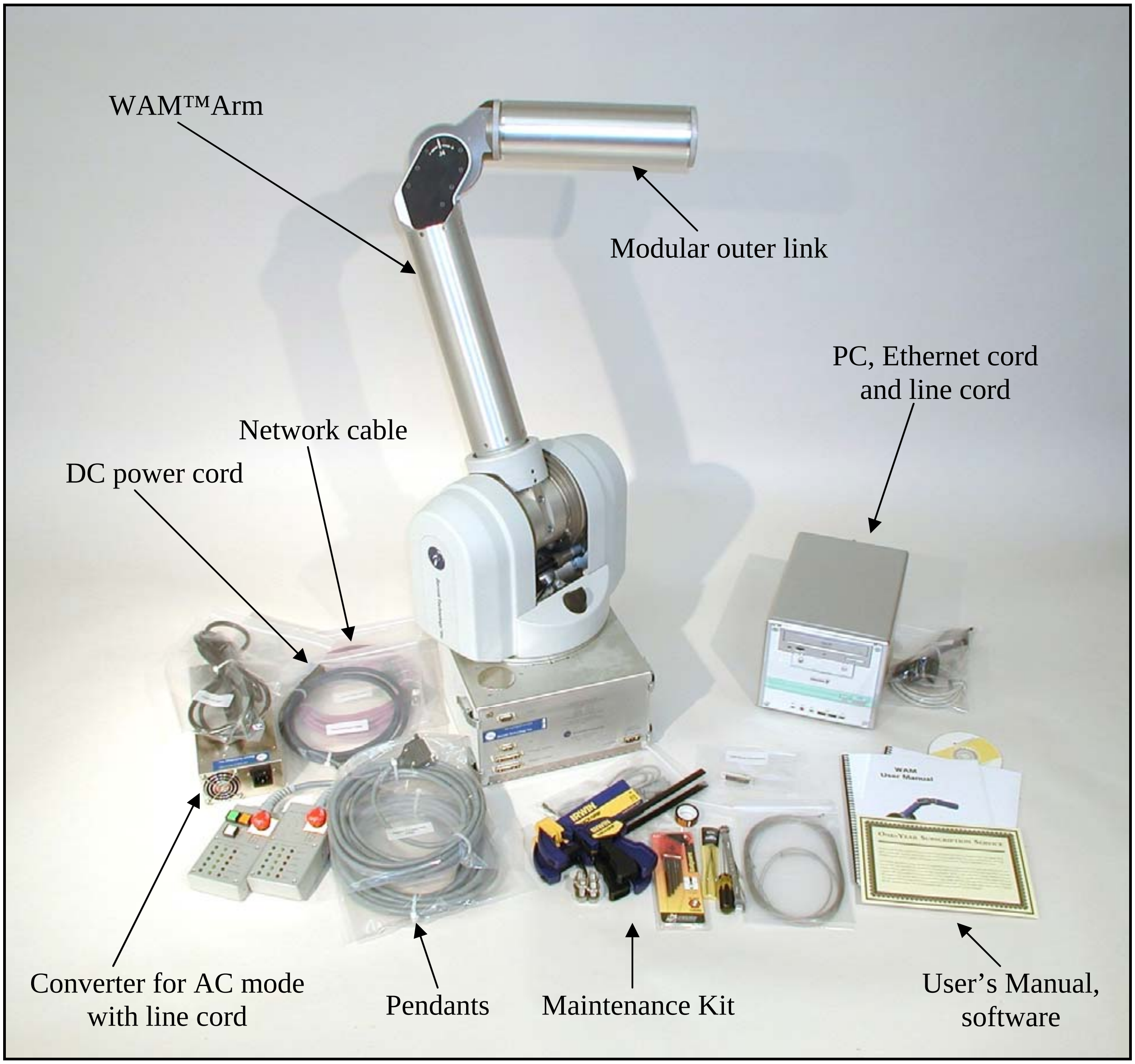


Figure 1: WAM Arm components

Details

WAM Arm – Four degree-of-freedom robotic arm

WAM PC – Shuttle PC including CAN card, used to communicate with the WAM

AC mode converter – For optional AC power, this connects the WAM to 50-60 Hz, 100-240V outlet power

Control Pendant – Used to activate and deactivate the WAM, show the safety status of the system, and has an emergency stop button

Display Pendant – Like the Control pendant, this displays the safety status of the components and has an emergency stop button, but cannot activate the WAM Arm

WAM DC power cable (blue) – Connects the WAM to DC power, or to the AC converter for AC power

Network cable (purple) – for use in communication between the PC and the WAM

Ethernet cable (for PC) – Standard Ethernet cable, for use in connecting PC to a local network

Computer AC line cord (6') – Standard AC line cord, shorter and thinner of the two line cords

AC converter line cord (10') – Standard heavy-gauge AC line cord, longer and thicker of the two line cords

Maintenance kit – kit containing replacement parts, maintenance tools, clamps for recabling, and mounting hardware for the WAM

Documentation – Includes this manual, a cable maintenance manual, a quick-start guide, and a 1-year warranty

WAM Wrist (not shown, optional) – replaces the Outer Link on the WAM, adds three additional powered degrees-of-freedom

Passive Gimbals (not shown, optional) – replaces the Outer Link on the WAM, adds three additional un-powered degrees-of-freedom

System Setup

This section describes in detail the steps required to interconnect the components of the WAM system, power up the system, and perform some routine system checks. Unless explicitly noted, all setup instructions referencing the optional WAM Wrist can be ignored if the user is setting up only the 4-DOF WAM.

Power Source

The standard WAM system requires an input voltage of 18-90VDC. The Wattage requirements for both 4-DOF and 7-DOF WAMs are summarized in Table 1. For AC operation, a converter for AC mode is supplied. The converter requires 50-60 Hz single-phase 100-120 VAC @ 7A or 200-240 VAC @ 3.5A for proper operation

Table 1 - Power Requirements

4-DOF	7-DOF
Q: 18W	Q: 27W
Typ: 28W	Typ: 45W
Peak: 600W	Peak: 800W
(Q: Quiescent = powered up, no torques applied; Typ: Typical operation with 2kg payload)	

Mounting Requirements

The mounting-surface for the WAM should be designed to handle the large reaction forces generated at the base of the arm during high-acceleration operation. The WAM can be fastened to the prepared mounting-surface via the four bolt holes in the base plate. Use four M10 or 3/8" screws. The holes are located on the base of the WAM according to Figure 2 and Figure 3.

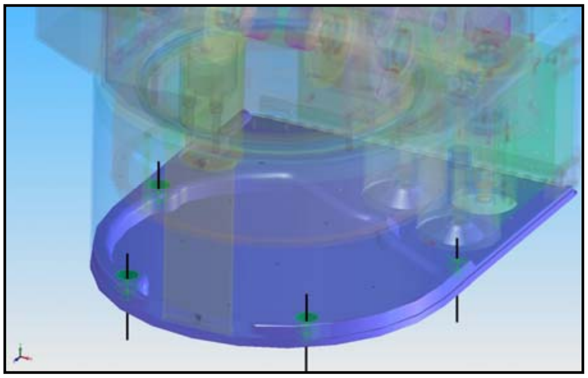


Figure 3 – Screw-hole locations

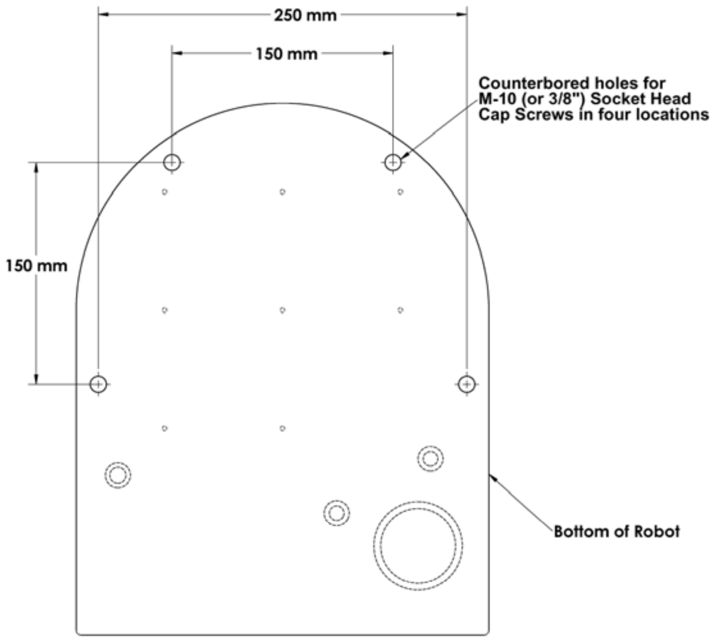


Figure 2 – Mounting-Hole Locations

General Safety

Proper precautions should be taken when selecting the location and setup of your WAM system. DO NOT set up the system such that any part of the robot's workspace (resembling a sphere with a ~1m radius, Figure 4, below) reaches into a pedestrian pathway in the lab space. The WAM is an unusually quiet mechanism thereby providing very little intrinsic warning of its enabled state (i.e. little or no servo or transmission noise). Shown below is a model of the WAM + tool workspace.

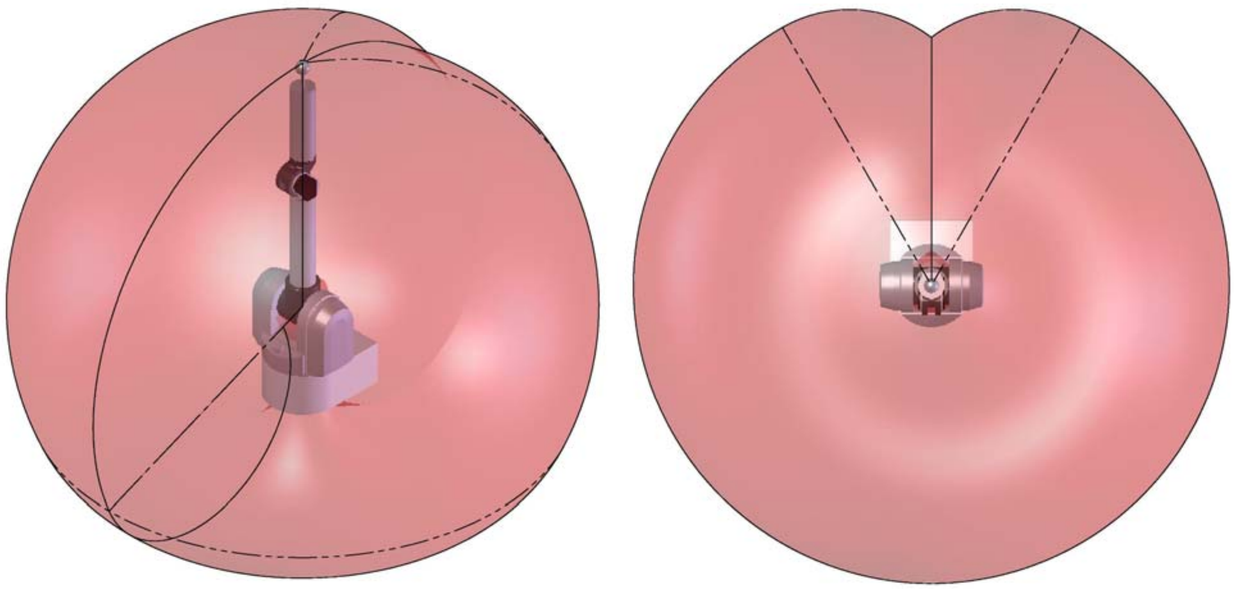
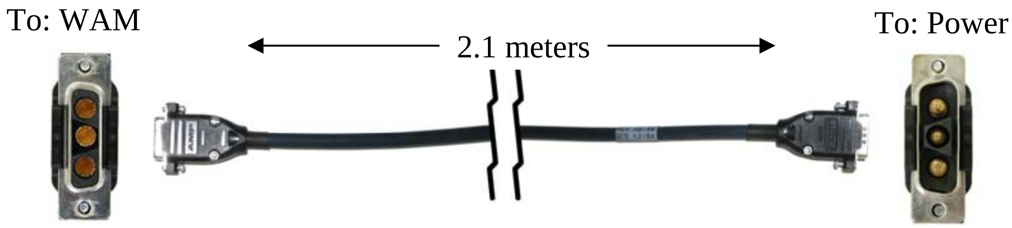


Figure 4 - WAM Workspace

Electrical Connections

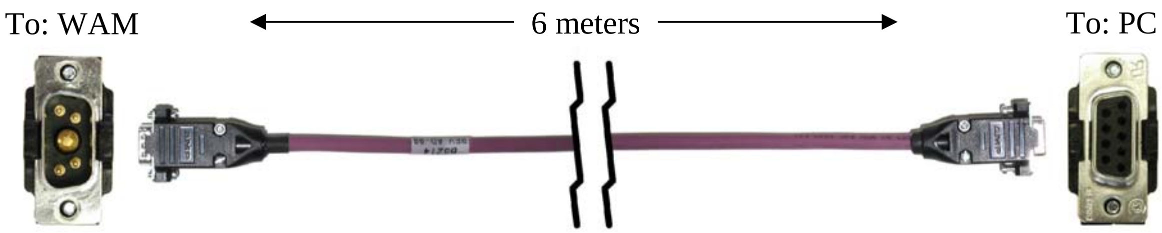
There are three types of electrical cables shipped with the WAM in addition to the standard AC lines cords and Ethernet cable.

DC Power cable (blue)



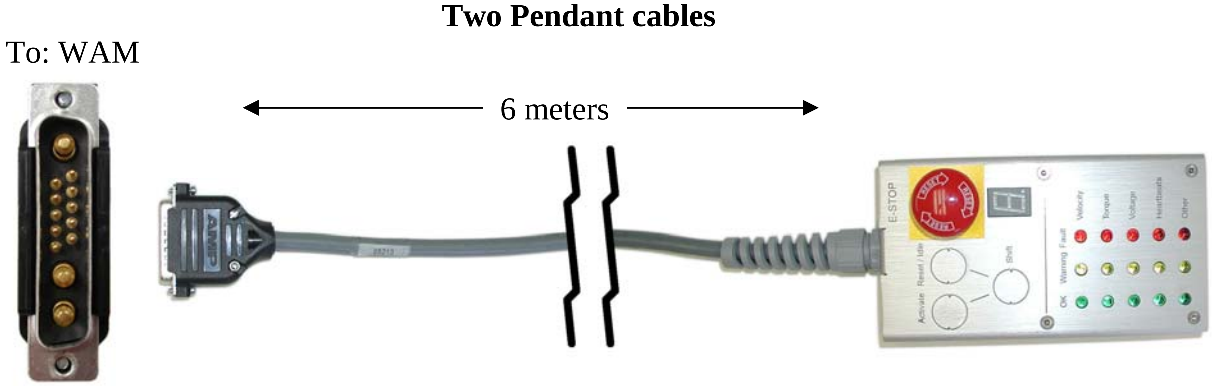
Plug this into a DC voltage source or into the AC Mode Converter.

Network cable (purple)



Plug the female end into the CAN card socket on the lower right side (viewed from back of computer). Plug the male end into the WAM socket labeled “CAN”.

Two Pendant cables



Of these two cables, connect the pendant box with three colored buttons and a red E-Stop to the socket on the WAM marked “Pendant – Control”. Connect the other pendant box (with only a red E-Stop) to the socket on the WAM marked “Pendant – Display”.

Installing the PC

Physical Installation:
Install the PC shipped with the WAM as you would any other. You will need to add a monitor and keyboard while performing initial setup of the PC. Afterwards, you may use the PC for development or remove the monitor and use remote terminal software (such as *ssh*) to operate the PC remotely.

Software installation:
The PC comes with the WAM software loaded. You will need to edit /etc/network/interfaces to set an IP address that is compatible with your network. We do not recommend using DHCP, as we have found that periodic address renegotiation interferes with the realtime operation of the WAM.
The Barrett Technology software library uses *syslogd* to log all error messages to a file. It is highly recommended to make sure that *syslogd* is running. Error messages may be found in the */var/log/syslog* text file.

Figure 5 - Shuttle PC

Connecting the WAM Wrist (optional)

Figure 7 shows that the outer link can be removed to accommodate the WAM Wrist (if the 7-DOF WAM is purchased). To avoid damaging the WAM electronics, please make sure the WAM is powered off before detaching or attaching any outer link. The WAM Wrist is connected after removing the outer link by aligning the metal shells of the integrated D-sub connectors at its base with the mating connector's shells on the end of the WAM's "elbow" and threading the quick-connect ring onto the wrist base. No special wrenches, fasteners, or tools are required. This ring should only be hand-tightened. It is normal for there to be a small number of threads left when fully tightened. This single operation also makes all electrical connections to the WAM Wrist. Figure 6 shows the electrical connector at the end of the WAM.

Figure 6 – Wrist Connector

Figure 7 - Separating the Outer Link

Final Setup

Once all components are connected, your system should look as shown in Figure 8. Although the WAM is intrinsically safer than other robotic systems, you may wish to integrate standard safety measures such as mats, gates, light curtains, etc. into the lab space surrounding the WAM.

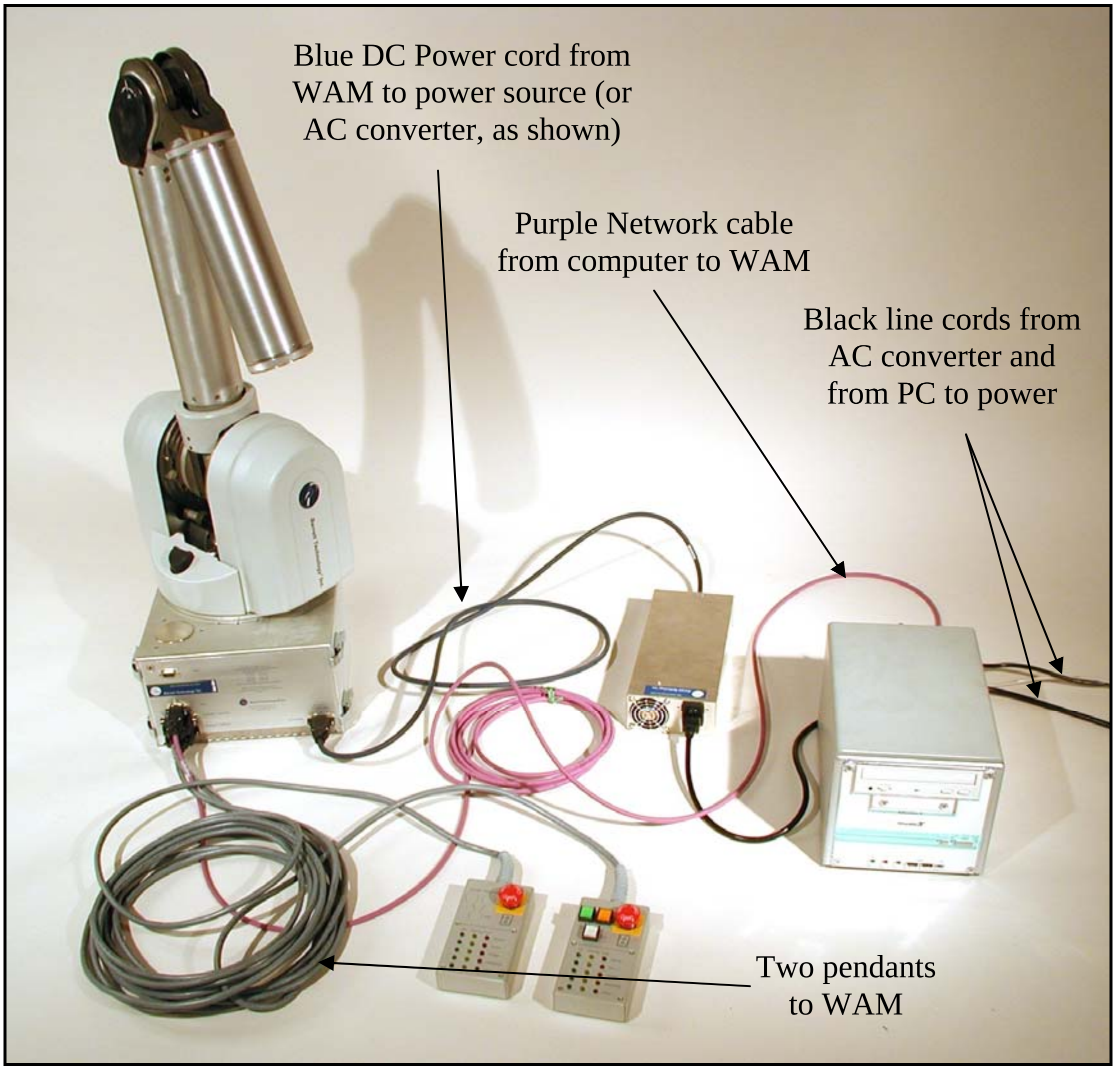


Figure 8: Typical system setup

System Startup

You are now ready to start controlling the motors in the robot. Before C code is written, the functionality of the WAM should be verified. Refer to the QuickStart sheet for instructions on how to Use the *btdiag* application located in */root/btclient/src/btdiag/* to confirm the WAM is properly set up and to demonstrate some of the basic functionality of the software library.

Hardware

WAM Arm

<u>Overview</u>

The WAM Arm is a 4-degree-of-freedom (4-DOF) manipulator with human-like kinematics. With its aluminum frame and advanced cable-drive systems, including a patented cabled differential, the WAM is lightweight with no backlash, extremely low friction, and stiff transmissions. All of these characteristics contribute to its high-bandwidth performance. The WAM Arm is the ideal platform for implementing Whole Arm Manipulation (WAM), advanced force control techniques, and high precision trajectory control.

Various areas of the robot are user-accessible via the easy removal of a few protective covers. The motor and the drive cables for the base motor are accessed by releasing the four draw latches on the Base Cover and sliding the cover toward the front of the robot. Access to the mechanical cables for joints 2, 3, and 4 is achieved by pulling off the plastic covers from the robot "shoulder".

A quick-connect mechanism is located at the output of the "elbow" on the WAM Arm allowing the user to make all electrical and mechanical connections with the optional 3-DOF WAM Wrist in a single step (see Figure 6). This interface can also be made to accommodate a wide range of other powered or unpowered components for attachment to the WAM Arm.

<u>Safety System: Pendants</u>

The WAM Arm system comes standard with two safety pendants, a control pendant and a display pendant. Both pendants show the present safety status of the WAM Arm, with status lights for the velocity, torque, voltage, and heartbeats of the robot. There is also a 7-segment LED single-character display which shows additional information related to any existing errors. Each pendant has a large mushroom-type emergency stop button, which can be reset (popped up) by rotating the button face clockwise. The control pendant has three additional buttons: Shift, Idle, and Activate.

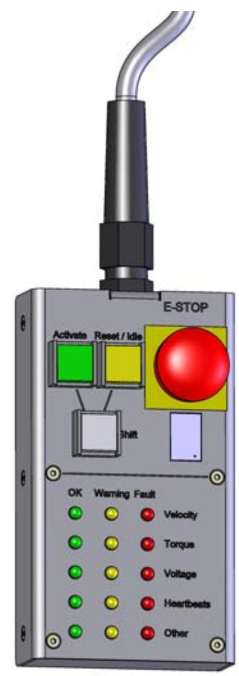


Figure 9 - Pendants

The WAM Arm has three safety states: E-STOP, IDLE, and ACTIVATED:

E-STOP means there is no motor bus voltage, in fact the motor bus power and ground lines are tied together, resulting in a "resistive braking" effect on the joints of the WAM Arm. The motor controllers are off line and do not keep track of their motor positions in this state. E-STOP is achieved by pressing the E-STOP button on either pendant.

IDLE means there is voltage applied to the motor bus and the motor controllers are on line and keeping track of their motor positions, but they are commanded to tie their motor phase leads together (also resulting in a braking effect), and they will ignore any command torque sent to them. To put the WAM Arm into the IDLE state (which will also reset any existing faults), press and hold the Shift button on the control pendant, then press the Reset/Idle button (yellow) and release both buttons. The yellow Idle button will light up, indicating that the WAM Arm is now in the IDLE state. Make sure both E-STOP buttons are reset (popped up) before attempting to change modes.

ACTIVATED means the motor controllers are actively applying any commanded torque they receive from the control PC. To put the WAM into the ACTIVATED state, press and hold the Shift button on the control pendant, then press the Activate button (green) and release both buttons. This state may only be reached when *all* of the status lights are showing OK (green). All warnings or faults must be cleared before activating the WAM. The green Activate button will light up, indicating that the WAM Arm is now in the ACTIVATED state.

Before the WAM Arm's joint positions are initialized by the PC control software, the velocity status lights indicate the state of the 4-DOF's angular joint speed. By default, there is a yellow LED warning when any joint exceeds 0.5 radians/sec and a red LED fault when any joint exceeds 2 radians/sec. The joint number responsible for the warning/fault is indicated by the single-character display on each pendant. After the WAM Arm's joint positions are initialized, the safety system begins calculating and monitoring the 4-DOF elbow and endpoint velocities in Cartesian space instead of monitoring individual joint velocities. By default, there is a warning when either the elbow (single-character "E") or arm endpoint (single-character "A") exceeds 0.5 m/s and a fault when either one exceeds 2 m/s. These defaults are modifiable in software.

The torque status lights indicate the state of the torque commands being received by the WAM Arm from the PC control software. If the PC sends non-zero torques while the WAM is in the IDLE state (the yellow Reset/Idle button is lit), the safety system will display a torque warning- prohibiting the WAM Arm from being activated. If the WAM Arm is in the ACTIVATED state (the green Activate button is lit) and the PC sends torques which exceed the default torque warning or fault levels, the torque warning or fault light will be lit- and the offending motor number will be shown in the single-character display.

The voltage status lights indicate the state of the WAM Arm's motor bus voltage. When the system is first powered up, the bus is off (there is no motor power), and the safety system registers a voltage fault. This fault is cleared by pressing Shift-Idle on the control pendant. Placing the WAM Arm into the IDLE state applies a DC voltage (18-90V, depending on input voltage) on the motor bus and clears the fault. If the voltage approaches the limits, the voltage warning light is lit. If the voltage exceeds the limits, the voltage fault light is lit.

The heartbeat status lights indicate the state of the communication between the PC and each motor controller in the WAM Arm. If the WAM is in the IDLE state and no control loop is active between the PC and robot, the pendants will display a heartbeat warning. If the WAM is in the ACTIVATED state and any controller or the PC fails to issue any communication for at least 16ms, a heartbeat fault is registered.

The "Other" status lights presently only indicate whether an E-STOP has occurred. If this is the case, the fault light will be lit and the single-character display will show "E".

ERROR	Error occurs in state		
	E-STOP	IDLE	ACTIVE
Velocity exceeds VL1	No action	Warn	Warn
Velocity exceeds VL2	No action	Fault, E-STOP	Fault, IDLE, Wait 1/4s
Torque exceeds TL1	Warn for non-zero	Warn for non-zero	Warn
Torque exceeds TL2	Fault	Fault	Fault, IDLE
Heartbeat missing	Warn	Warn	Fault, E-STOP
Voltage lower than VOLTL1	No action	Warn	Warn
Voltage lower than VOLTL2	Fault	Fault	Fault, IDLE
Voltage higher than VOLTH1	No action	Warn, Bleed voltage	Warn, Bleed voltage
Voltage higher than VOLTH2	No action	Fault, E-STOP	Fault, E-STOP
E-Stop pressed	Fault, E-STOP	Fault, E-STOP	Fault, E-STOP
NOTE: Warnings are cleared automatically, critical faults are cleared through a RESET			

REQUEST	Request occurs in state		
	E-STOP	IDLE	ACTIVE
E-STOP	E-STOP	E-STOP	E-STOP
RESET / IDLE	Clear faults, power up bus, enumerate, IDLE	Clear faults	IDLE
ACTIVATE	No Action	If no warnings or faults, ACTIVE	No Action

AC Converter

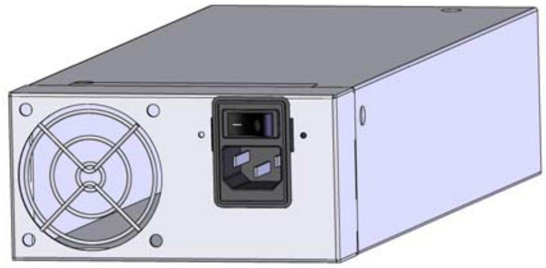


Figure 10 - AC Power Converter

Covers

There may be occasions to remove one or more of the covers for maintenance or upgrades. Typical reasons include for cover removal include: cable replacement or tensioning, firmware upgrades, and access to baseplate mounting holes.

The base cover is removed by opening all four latches. If necessary, the hinged back door may be swung down by removing the single M6 flat head screw in the upper left of the back door. To reinstall the base cover, first make sure the hinged back door is in place and the screw is secure. Wrap the cover in place, swing the lower two latch hooks away from the backplate, and place the upper two latch hooks in the grooves on each side of the backplate. Hold the upper latches, one in each hand, and align the cover such that there is an equal gap between the cover edges and the edge of the hinged door. With equal pressure, slowly close the two upper latches. They should snap into place. Repeat with the upper two latches.

The plastic side covers or shoulder covers snap into place. To remove, wrap hands around the sides about halfway down and lightly pull the sides apart. Pull the cover out and up to remove. To reinstall, pull the sides out slightly and feed the sides through the gaps formed by the Joint 2 stop covers and the large vertical aluminum plates.

To access the motor controller for Joint 1, the silver-colored disc on top of the upper base plate must be removed. Use a flat-head screwdriver with a sharp tip and gently pry the cover off. To reinstall, ensure that all electrical wires are away from the sides of the hole in the upper plate, align the silver-colored disc, and snap into place.

WAM Wrist:

The servomotors for axes 4 & 5 (this discussion assumes the wrist is connected to the 4-DOF WAM) are located at the base of the wrist to minimize their inertial effects on the host robot arm. The final roll joint in the WAM Wrist, motor axis 6, is the only geared axis. Since cable circuits generally have a size versus torque relationship that limits the minimum characteristic size of a transmission, gears were an appealing trade-off (in this axis only) for the significant decrease in distance between the grasp-center of an attached end-effector and the wrist-center.

The 1st and 2nd stage transmission cables for motor axes 4 & 5 are accessed by sliding the cover clamp off the Transmission Cover and pulling the cover around the wrist. To access the final stage cables, the user is required to remove 4 socket cap screws from each black nylon guard at the top of the wrist and then to pull off each guard. Since the final cable stages for motor axes 4 & 5 require infrequent maintenance, removal of these guards will rarely be necessary.

The threaded base of the WAM Wrist is fully compatible with the mechanical and electrical quick-connect features on the WAM Arm.

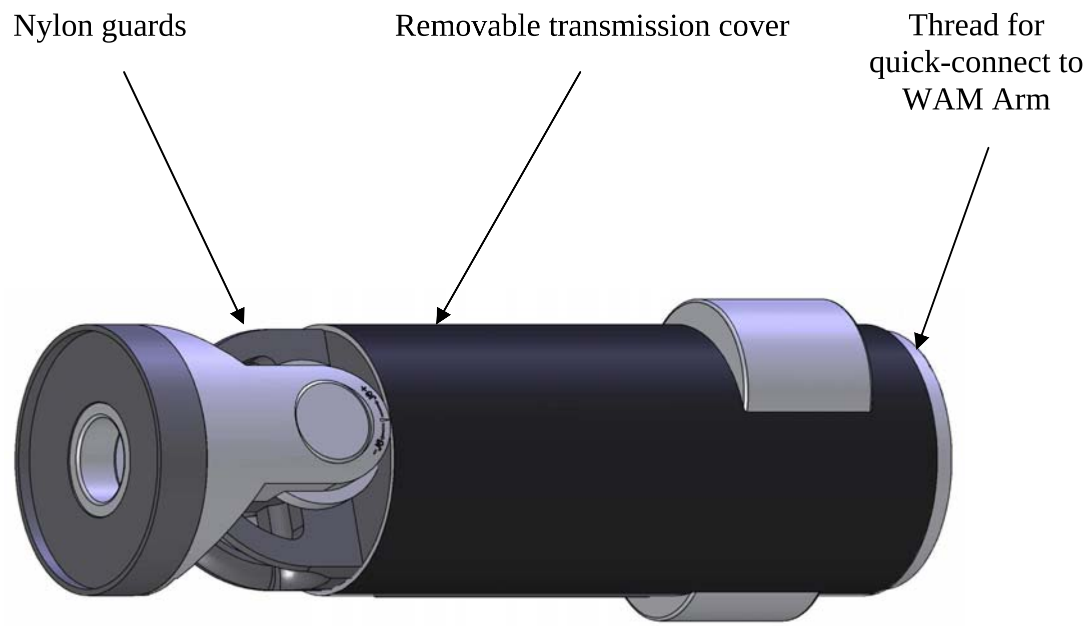


Figure 11 – WAM Wrist Components

PC & Control Software

PC Specs
Mainboard: Shuttle SK43G
Processor Type: AMD Duron Applebred x86 @ ~1.8GHz
Memory: 128MB (16MB of that is used as a video framebuffer).
Hard drive: 80GB, but only a fraction of that is partitioned and formatted
Optical: Standard CD-ROM
Kernel: Linux 2.6 and the Real-Time Application Interface (RTAI) patches
Distro: Zenwalk (slackware-based)
PCI: One slot, used by CAN network card
AGP: One slot, free

The Barrett Technology robot control client software (btclient) is divided into multiple parts:

- examples/ - example source code for robot control software development
- doc/ - source code documentation, Doxygen (HTML/RTF)
- lib/ - location of library binaries
- include/ - common include directory for libraries
- src/btsystem/ - software library with general robot routines
- src/btwam/ - software library with WAM-specific routines
- src/btutil/ - utility for enumerating the motor controllers, restoring defaults, updating firmware
- src/btdiag/ - a full-featured robot diagnostic application (and example program)

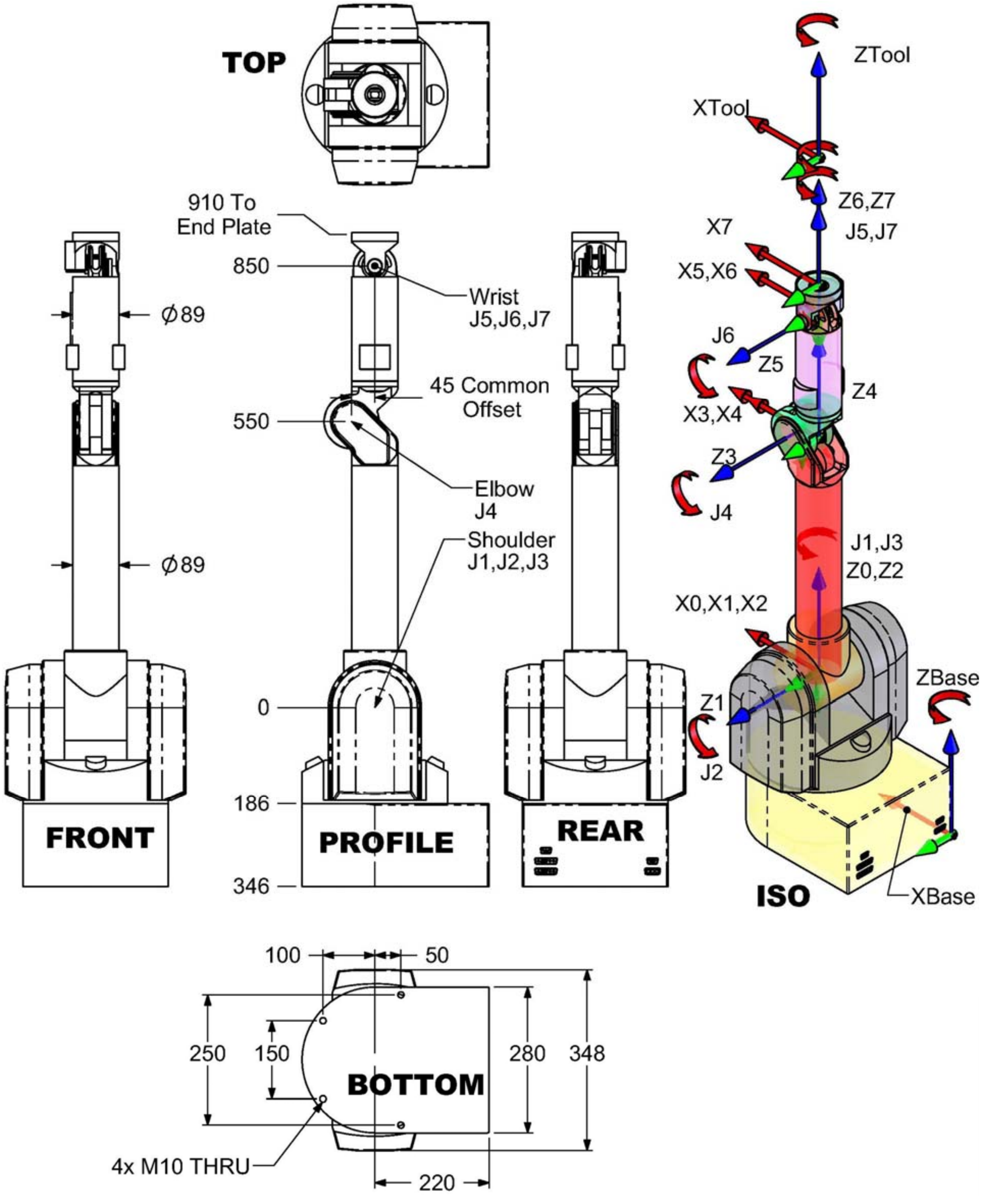
If you edit the btsystem or btwam libraries, the procedure to recompile is: **`make lib; make install`**

In the examples, the PC closes a 500Hz position/torque control loop with the WAM over the CAN bus. The PC asks the motor controllers for their present positions, converts the received encoder counts into joint angles, calculates the desired joint torques, converts these into motor torque commands, then sends out the calculated torques to the motors. All force or position control is calculated on the PC and converted to motor torques as a final step- the WAM itself is entirely motor torque controlled. For a source code example of this process, see the WAMControlThread() function in src/btwam/btwam.c.

Please note that (as of Nov 2005) the CAN card driver used under LinuxRTAI is not realtime. If interrupts occur while the CAN driver is processing data, the WAM may jitter slightly. Common sources of interrupts are DHCP renegotiation, and XWindows GUI processing. To minimize the chance of jitter, please use only static IP addressing, and run the PC in terminal mode- or log in via SSH.

When the WAM is first powered on, the motor controllers use hall effect sensors and six-step commutation for control until an initial hall transition occurs. Then they switch to using the incremental encoders for smoother commutation until the encoder index pulse is observed (once per motor revolution). Then they begin a factory-calibrated commutation loop for precise torque control.

Appendix A – Dimensions & Joint Ranges



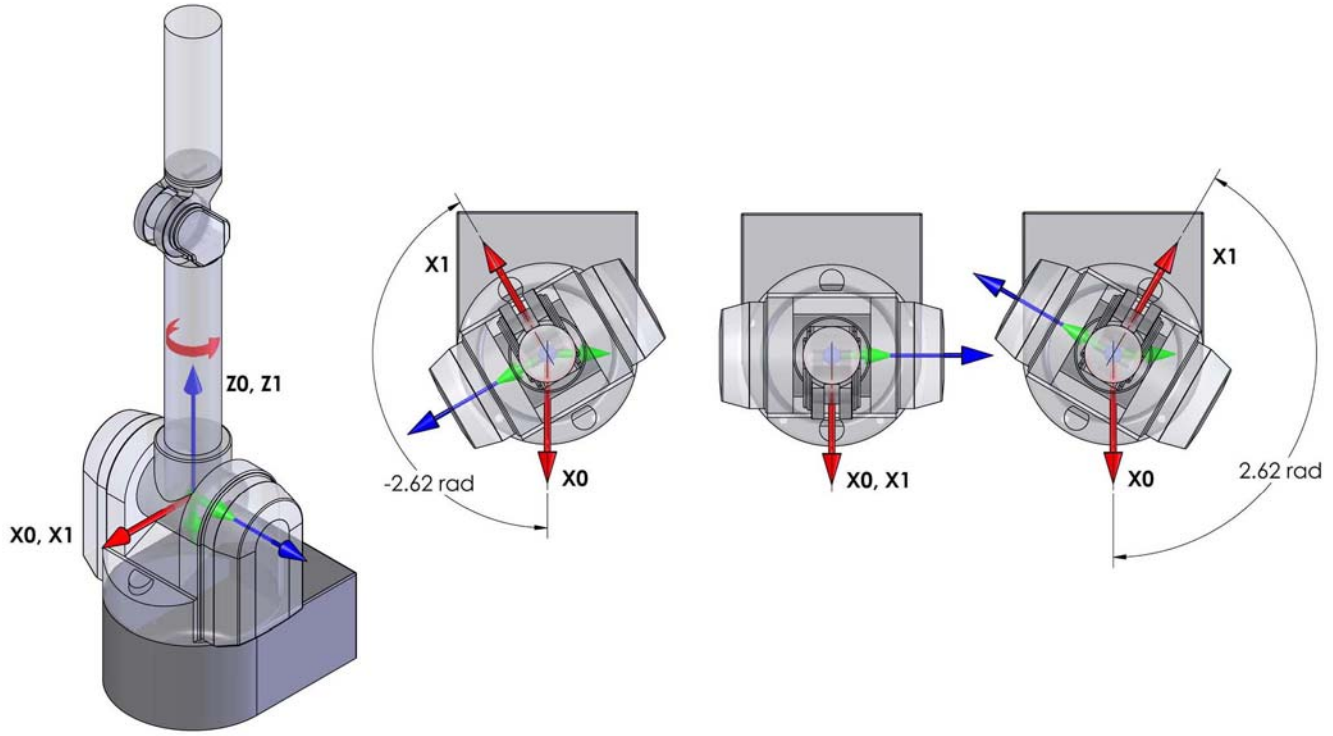


Figure 12 – WAM Arm Joint 1 Frame and Limits

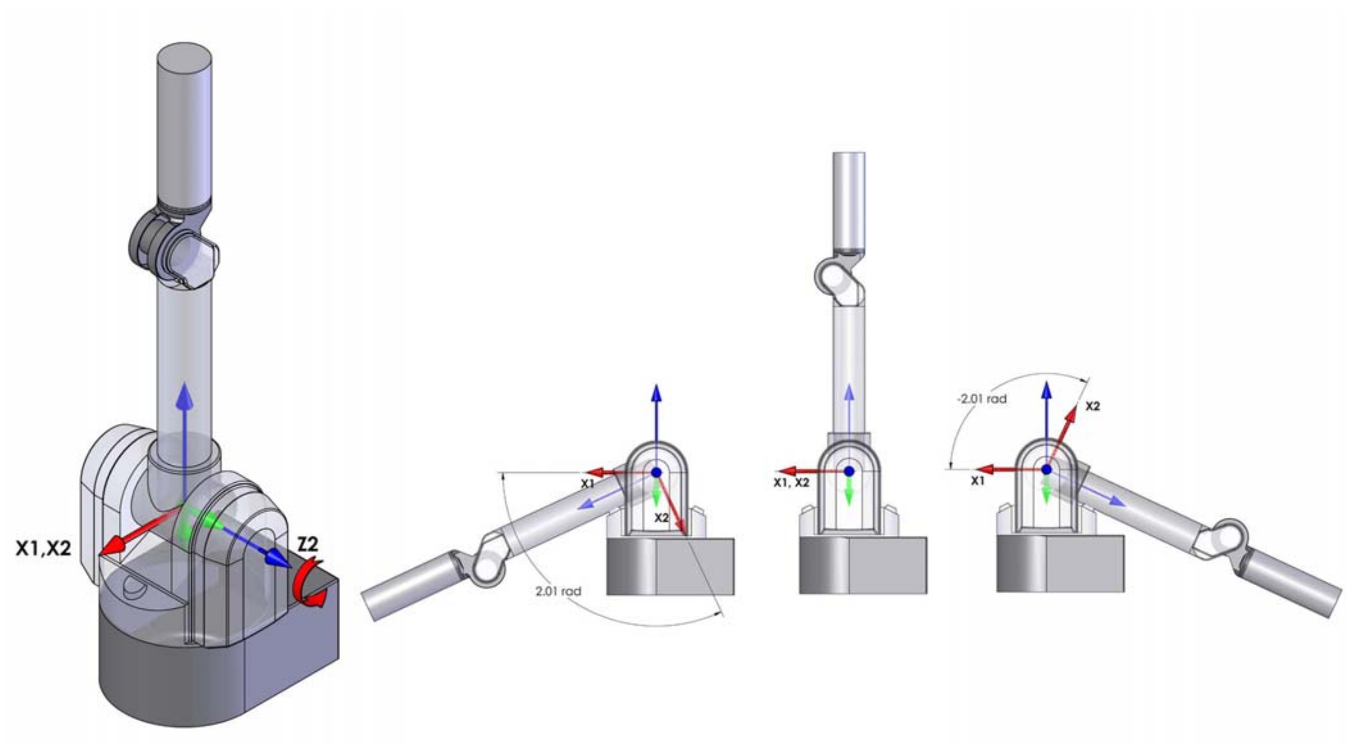


Figure 13 – WAM Arm Joint 2 Frame and Limits

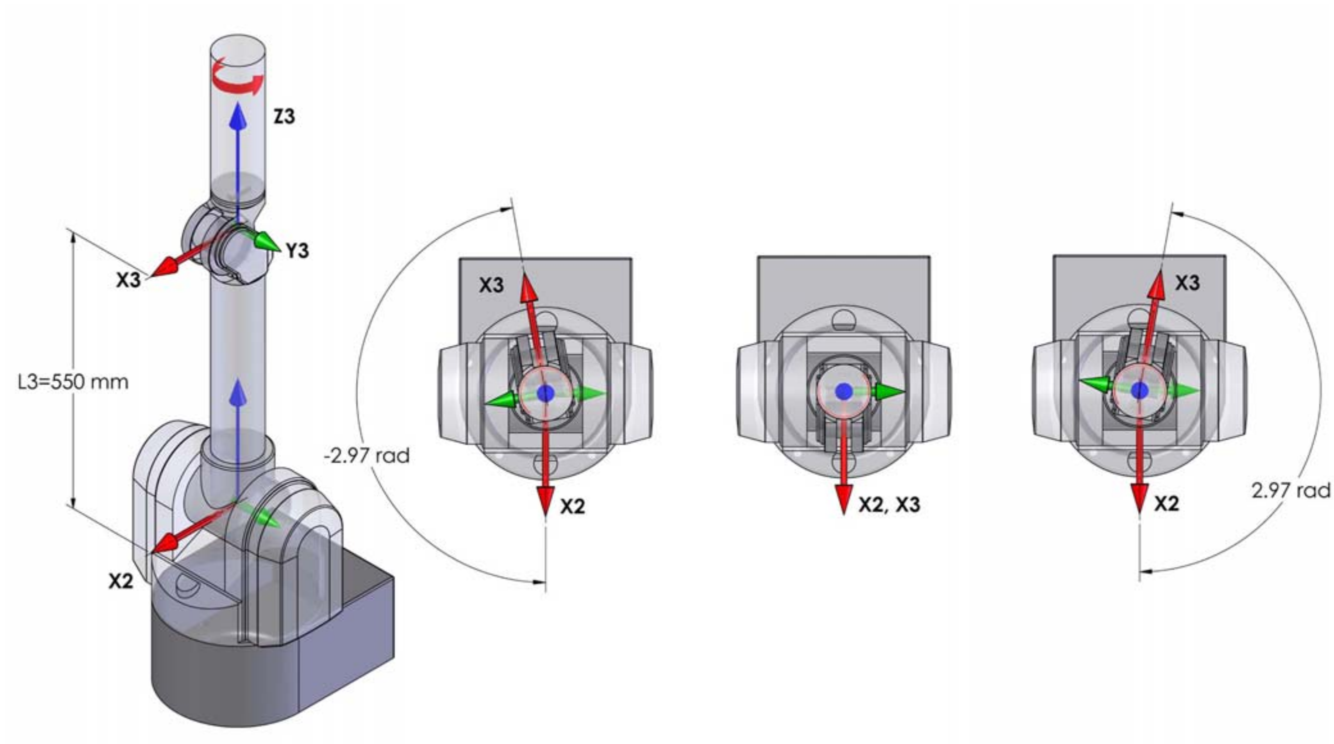


Figure 14 – WAM Arm Joint 3 Frame and Limits

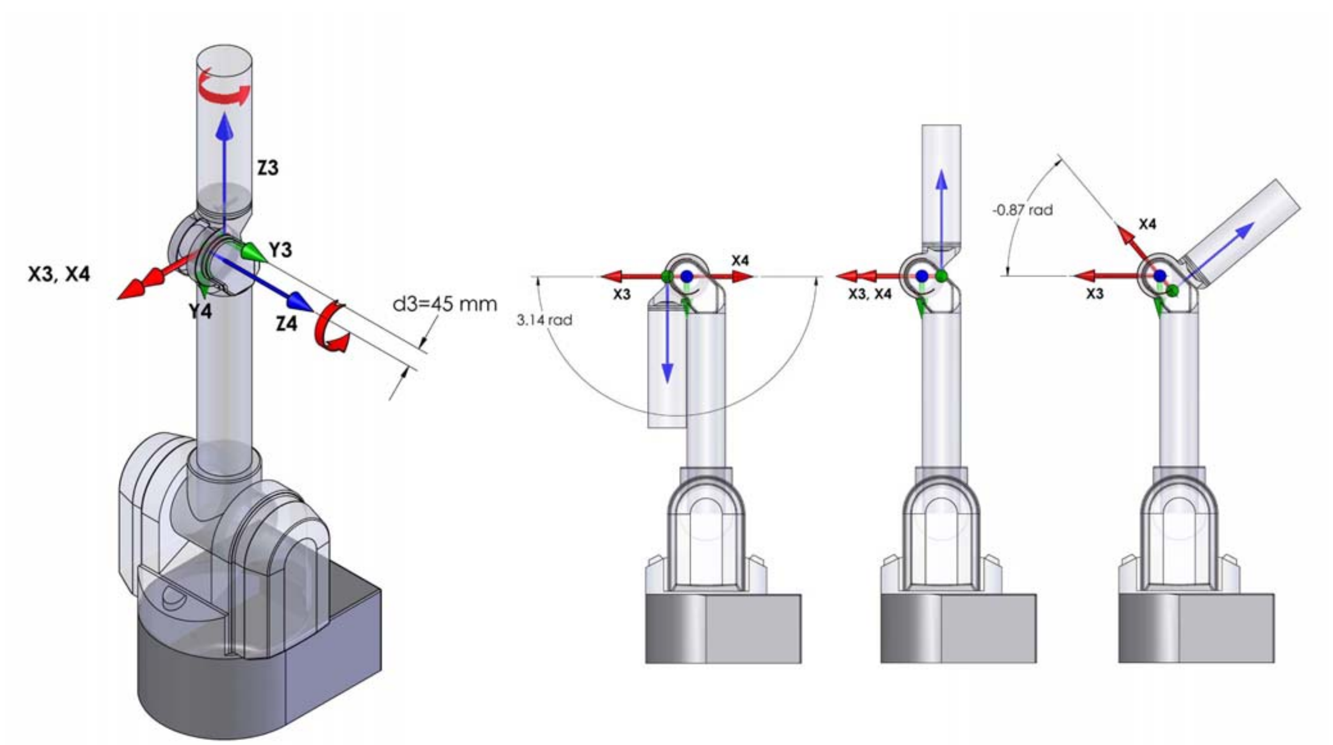


Figure 15 - WAM Arm Joint 4 Frame and Limits

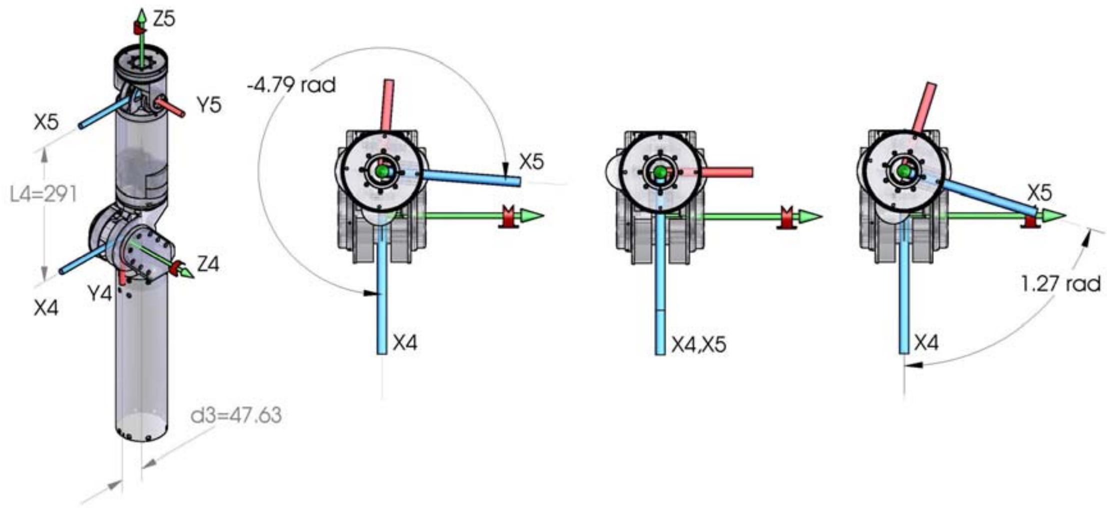


Figure 16 - WAM Arm Joint 5 Frame and Limits

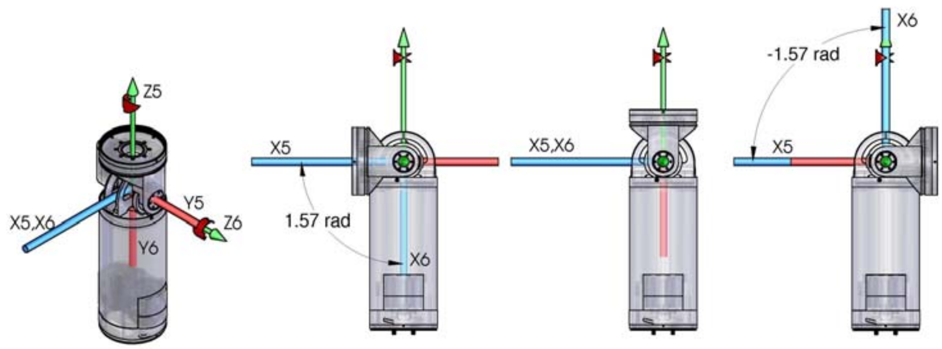


Figure 17 – WAM Arm Joint 6 Frame and Limits

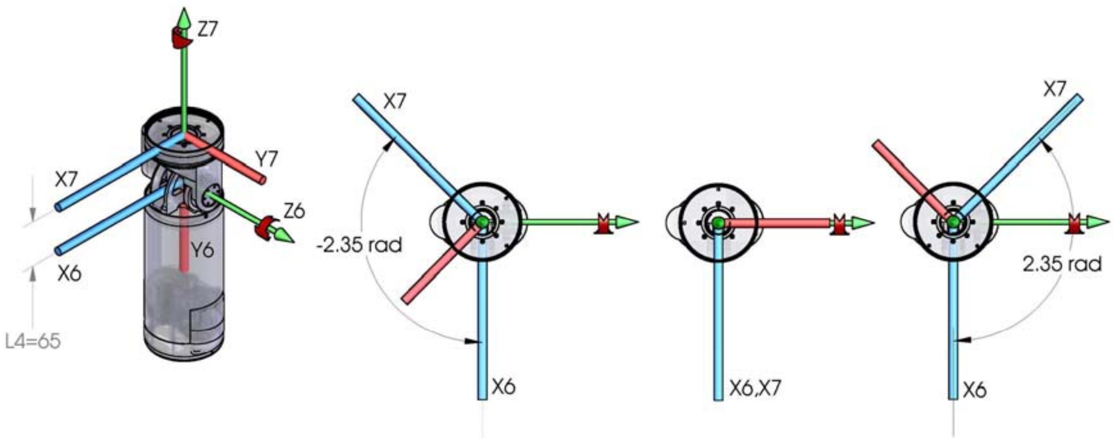


Figure 18 – WAM Arm Joint 7 Frame and Limits

Appendix B - Kinematics

Motor-Joint Transformations

Motor-to-Joint Position Transformations

The following transformations show the change in joint positions as a function of motor positions. The input transmission ratios and the differential transmission ratios are calculated from known pulley, pinion, and cable diameters.

Table 2 - Arm Transmission Ratios

Parameter	Value
N_1	42.0
N_2	28.25
N_3	28.25
n_3	1.68
N_4	18.0
N_5	10.27
N_6	10.27
N_7	14.93
n_6	1

$$\begin{pmatrix} J\theta_1 \\ J\theta_2 \\ J\theta_3 \\ J\theta_4 \end{pmatrix} = \begin{pmatrix} \frac{-1}{N_1} & 0 & 0 & 0 \\ 0 & \frac{1}{2N_2} & \frac{-1}{2N_2} & 0 \\ 0 & \frac{-n_3}{2N_2} & \frac{-n_3}{2N_2} & 0 \\ 0 & 0 & 0 & \frac{1}{N_4} \end{pmatrix} \begin{pmatrix} M\theta_1 \\ M\theta_2 \\ M\theta_3 \\ M\theta_4 \end{pmatrix}$$

Equation 1 - WAM Motor-to-Joint position transformations

$$\begin{pmatrix} J\theta_5 \\ J\theta_6 \\ J\theta_7 \end{pmatrix} = \begin{pmatrix} \frac{1}{2N_5} & \frac{1}{2N_5} & 0 \\ \frac{-n_6}{2N_5} & \frac{n_6}{2N_5} & 0 \\ 0 & 0 & \frac{-1}{N_7} \end{pmatrix} \begin{pmatrix} M\theta_5 \\ M\theta_6 \\ M\theta_7 \end{pmatrix}$$

Equation 2 - Wrist Motor-to-Joint position transformations

The motor position can also be derived from joint space by taking the inverse of the multiplying matrix. For convenience they are as follows:

$$\begin{pmatrix} M\theta_1 \\ M\theta_2 \\ M\theta_3 \\ M\theta_4 \end{pmatrix} = \begin{pmatrix} -N_1 & 0 & 0 & 0 \\ 0 & N_2 & \frac{-N_2}{n_3} & 0 \\ 0 & -N_2 & \frac{-N_2}{n_3} & 0 \\ 0 & 0 & 0 & N_4 \end{pmatrix} \begin{pmatrix} J\theta_1 \\ J\theta_2 \\ J\theta_3 \\ J\theta_4 \end{pmatrix}$$

Equation 3: Arm Joint-to-Motor position transformations

$$\begin{pmatrix} M\theta_5 \\ M\theta_6 \\ M\theta_7 \end{pmatrix} = \begin{pmatrix} N_5 & \frac{-N_5}{n_6} & 0 \\ N_5 & \frac{N_5}{n_6} & 0 \\ 0 & 0 & -N_7 \end{pmatrix} \begin{pmatrix} J\theta_5 \\ J\theta_6 \\ J\theta_7 \end{pmatrix}$$

Equation 4: Wrist Joint-to-Motor position transformation

Motor-to-Joint Torque Transformations

Similar to the position transformations the following equations determine the joint torque from the motor torque:

$$\begin{pmatrix} J\tau_1 \\ J\tau_2 \\ J\tau_3 \\ J\tau_4 \end{pmatrix} = \begin{pmatrix} -N_1 & 0 & 0 & 0 \\ 0 & N_2 & -N_2 & 0 \\ 0 & \frac{-N_2}{n_3} & \frac{-N_2}{n_3} & 0 \\ 0 & 0 & 0 & N_4 \end{pmatrix} \begin{pmatrix} M\tau_1 \\ M\tau_2 \\ M\tau_3 \\ M\tau_4 \end{pmatrix}$$

Equation 5: Arm Motor-to-Joint torque transformation

$$\begin{pmatrix} J\tau_5 \\ J\tau_6 \\ J\tau_7 \end{pmatrix} = \begin{pmatrix} N_5 & N_5 & 0 \\ \frac{-N_5}{n_6} & \frac{N_5}{n_6} & 0 \\ 0 & 0 & -N_7 \end{pmatrix} \begin{pmatrix} M\tau_5 \\ M\tau_6 \\ M\tau_7 \end{pmatrix}$$

Equation 6: Wrist Motor-to-Joint transformations

The following equations determine motor torque from the joint torque:

$$\begin{pmatrix} M\tau_1 \\ M\tau_2 \\ M\tau_3 \\ M\tau_4 \end{pmatrix} = \begin{pmatrix} \frac{-1}{N_1} & 0 & 0 & 0 \\ 0 & \frac{1}{2N_2} & \frac{-n_3}{2N_2} & 0 \\ 0 & \frac{-1}{2N_2} & \frac{-n_3}{2N_2} & 0 \\ 0 & 0 & 0 & \frac{1}{N_4} \end{pmatrix} \begin{pmatrix} J\tau_1 \\ J\tau_2 \\ J\tau_3 \\ J\tau_4 \end{pmatrix}$$

Equation 7: Arm Joint-to-Motor torque transformations

$$\begin{pmatrix} M\tau_5 \\ M\tau_6 \\ M\tau_7 \end{pmatrix} = \begin{pmatrix} \frac{1}{2N_5} & \frac{-n_6}{2N_5} & 0 \\ \frac{1}{2N_5} & \frac{n_6}{2N_5} & 0 \\ 0 & 0 & \frac{-1}{N_7} \end{pmatrix} \begin{pmatrix} J\tau_5 \\ J\tau_6 \\ J\tau_7 \end{pmatrix}$$

Equation 8 - Wrist Joint-to-Motor torque transformations

WAM Kinematics

Denavit-Hartenberg Frames for the WAM

Appendix A defines a standard set of coordinate frames to use while working with the WAM. A good introduction the coordinate frames, transformations and kinematics is beyond the scope of this document. There are several good introductory robotics books available. We recommend *Spong,M.;Vidyasagar, M.* *Robot Dynamics and Control ; 1989 John Wiley & Sons*. We use the Denavit-Hartenberg (D-H) method to establish the coordinate frames; particularly the variant used in Spong.

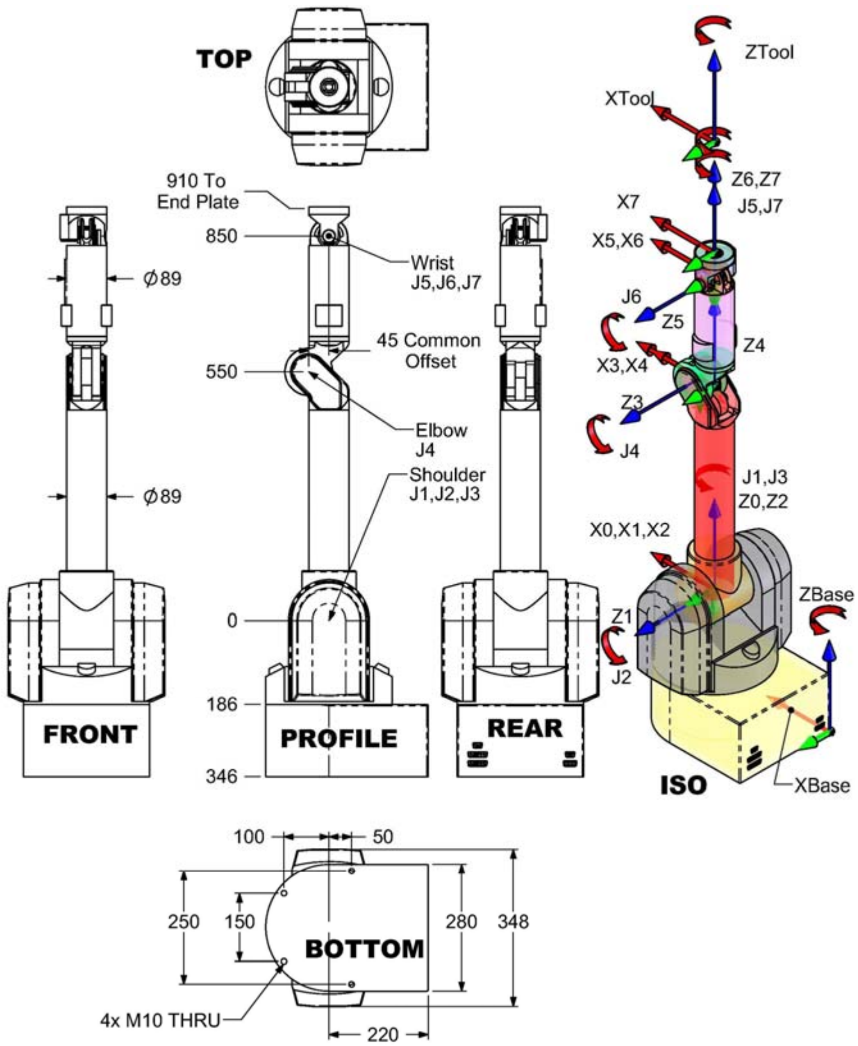


Figure 19 - Denavit-Hartenberg Frames – 7-DOF WAM

Figure 19 shows the entire 7-DOF WAM system in the zero position. A positive joint motion is based on the right hand rule for each axis.

Equation 9 below gives the transform between two adjacent D-H coordinate frames. The D-H parameters that were derived from Figure 19 are located in Table 3 below. Note that ***c*** and ***s*** stand for *cos* and *sin* respectively.

$$
{}^{i-1}T_i = \begin{pmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_1 c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_1 s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

Equation 9 - D-H Generalize transform matrix

Table 3 - WAM Link Parameters with units of meters and radians

i	a_i	α_i	d_i	θ_i
1	0	$-\pi/2$	0	θ_1
2	0	$\pi/2$	0	θ_2
3	0.045	$-\pi/2$	0.55	θ_3
4	-0.045	$\pi/2$	0	θ_4
5	0	$-\pi/2$	0.3	θ_5
6	0	$\pi/2$	0	θ_6
7	0	0	0.061	θ_7

For example, to generate the transform from coordinate Frame 2 to coordinate Frame 1 (i.e. the position and orientation of Frame 2 described in terms of Frame 1 which is also a rotation about joint 2), use the parameters in the second row of Table 3 above as follows:

$$
{}^{1}T_2 = \begin{pmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & 0 \\ \sin(\theta_2)\cos(-\pi/2) & \cos(\theta_2)\cos(-\pi/2) & -\sin(-\pi/2) & -\sin(-\pi/2)(0) \\ \sin(\theta_2)\sin(-\pi/2) & \cos(\theta_2)\sin(-\pi/2) & \cos(-\pi/2) & \cos(-\pi/2)(0) \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

$$
= \begin{pmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin(\theta_2) & -\cos(\theta_2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

Equation 10 - D-H Matrix Example

Each of the joints has a mechanical stop that limits the motion. Refer to Table 4 below for a complete listing of the joint limits for each axis.

Table 4 – Joint Limits

Joint	Positive Joint Limit (radians)	Negative Joint Limit (radians)
1	2.62	-2.62
2	2.01	-2.01
3	2.97	-2.97
4	3.14	-0.87
5	4.79	-1.27
6	1.57	-1.57
7	2.35	-2.35

Forward Kinematics for the 4-DOF WAM

The forward kinematics of the 4-DOF WAM system is used to determine the end tip location and orientation. These transformations are generated using the parameters in Table 3 on page 20 and the matrix in Equation 9 on page 20.

$$
{}^{4}\mathrm{T}_{Tool} = \begin{pmatrix} u_x & v_x & w_x & p_x \\ u_y & v_y & w_y & p_y \\ u_z & v_z & w_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

Equation 11: Tool frame matrix

You define the ${}^{4}\mathrm{T}_{Tool}$ frame for your specific end affecter. The forward kinematics are determined for any frame on the robot by mulitplying all of the transforms up to and including the final frame. To determine the tool end tip location and orientation use the following equation:

$$
{}^{0}\mathrm{T}_{Tool} = {}^{0}\mathrm{T}_{1}\,{}^{1}\mathrm{T}_{2}\,{}^{2}\mathrm{T}_{3}\,{}^{3}\mathrm{T}_{4}\,{}^{4}\mathrm{T}_{Tool}
$$

Equation 12: Tool end tip position and orientation equation for the 4-DOF WAM

Forward Kinematics for the 7-DOF WAM

As with the previous example, you define the ${}^{7}\mathrm{T}_{Tool}$ frame for your specific end affecter. The forward kinematics are determined for any frame on the robot by mulitplying all of the transforms up to and including the final frame. To determine the end tip location and orientation use the following equation:

$$
{}^{0}\mathrm{T}_{Tool} = {}^{0}\mathrm{T}_{1}\,{}^{1}\mathrm{T}_{2}\,{}^{2}\mathrm{T}_{3}\,{}^{3}\mathrm{T}_{4}\,{}^{4}\mathrm{T}_{5}\,{}^{5}\mathrm{T}_{6}\,{}^{6}\mathrm{T}_{7}\,{}^{7}\mathrm{T}_{Tool}
$$

Equation 13: Tool end tip position and orientation equation for the 7-DOF WAM

WAM and Gimbals Kinematics

Denavit-Hartenberg Frames for the WAM Gimbals

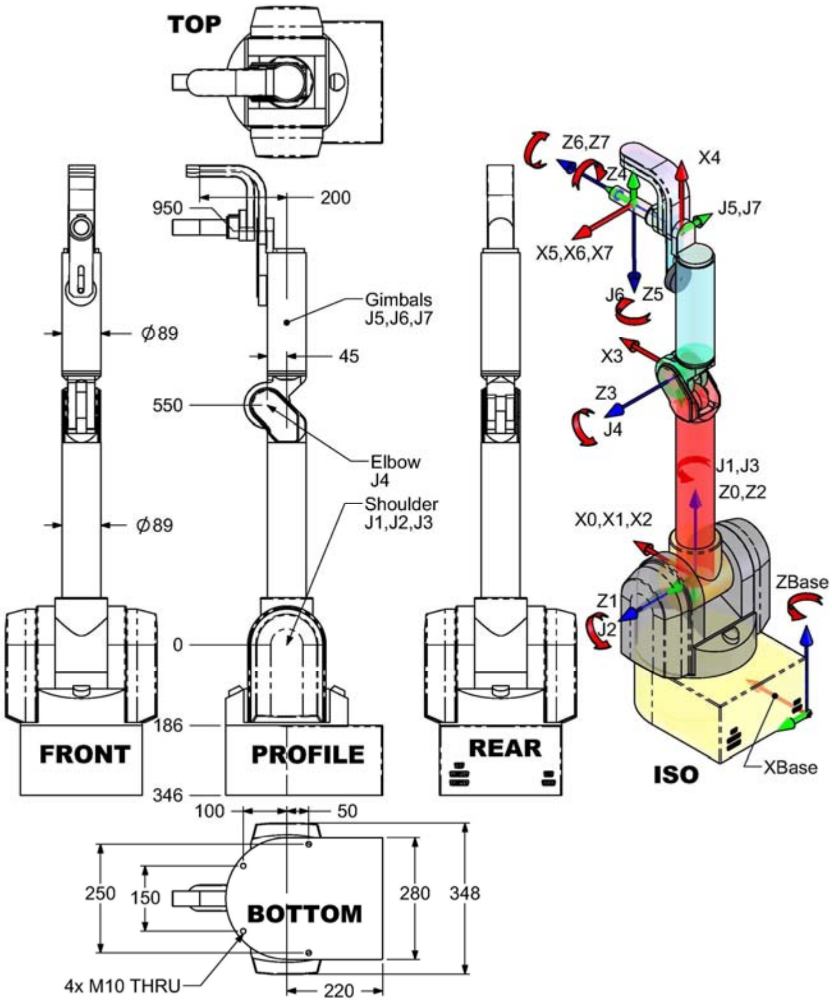


Figure 20 - Denavit-Hartenberg Frames – Gimbals

Figure 20 shows the WAM Gimbals in the zero position. A positive joint motion is based on the right hand rule for each axis. The D-H parameters that were derived from Figure 20 are located in Table 5 below.

Table 5 – 4-DOF WAM + Gimbals DH Parameters

i	a_i	α_i	d_i	θ_i
1	0	$-\pi/2$	0	θ_1
2	0	$\pi/2$	0	θ_2
3	0.045	$-\pi/2$	0.55	θ_3
4	0.4	$-\pi/2$	0	θ_4
5	0	$\pi/2$	0	$\theta_5-\pi/2$
6	0	$-\pi/2$	0.1547	$\theta_6-\pi/2$
7	0	0	0	θ_7

Appendix C - CAN Communication Spec

1Mbaud CANbus
8 time quanta per bit
75% sampling point
Sync jump width = 1 time quanta (TQ)
11-bit MsgID (standard CAN)
Proprietary protocol, not DeviceNet or CANopen
Recommended reading: Controller Area Network by Konrad Etschberger

MsgID spec:
[GFFFFFTTTTT] (11 bits, binary)
G: Group, 0 = Directed message, 1 = Group broadcast
F: From ID, Host = 00000, Motor N = N
T: To ID or group

Examples MsgIDs:
00000000011 => Directed message from host to motor 3 (3 = 00011, binary)
10001100100 => Group broadcast from motor 3 to group 4

Motor IDs and Groups:
Each motor in the robot has a unique communication ID
Each motor listens and processes messages bound for its ID
There are 32 possible groups (0..31, 00000..11111)
Each motor may be assigned to be a part of any 3 groups
Each motor also listens and processes messages bound for any of those 3 groups
Motors 1-4 listen to groups 0, 1, and 4 by default
Motors 3-7 listen to groups 0, 2, and 5 by default
Host listens to groups 3 and 6 by default
0 = All actuators
1 = Lower arm torques (motors 1-4)
2 = Upper arm torques (motors 5-7)
3 = Position feedback
4 = Lower arm property
5 = Upper arm property
6 = Property feedback

CAN frame data payload:
CAN specifies a maximum of 8 bytes/frame
[APPPPPPP] [00000000] [LLLLLLLL] [mmmmmmmm] [MMMMMMMM] [HHHHHHHH]
A: Action, 0 = Get property, 1 = Set property
P: Property (128 possible values, 0..127, 0000000..1111111)
0: Second byte (almost) always set to zero, see exceptions below
L: Low byte of data value
m: mid-low byte of data value
M: Mid-high byte of data value
H: High byte of data value
If sending a single 16-bit integer value, only LLLLLLLL and mmmmmmmm are used
The CAN frame data length code (DLC) is set to the number of bytes being transmitted

Properties:
Each motor has several properties, see property list
Most of these properties may be read and written via "Get property" and "Set property" messages

Exceptions:
1) Actual Position property is a 22-bit, 2's complement number
It is packed into a 3-byte frame payload [00MMMMMM] [mmmmmmmm] [LLLLLLLL]
It is always sent to Group 3

2) Command torque is a set of 4 14-bit, 2's complement numbers
It is sent TO motors in 8 bytes (max):

```
    0        1        2        3        4        5        6        7
APPPPPPP AAAAAAaa aaaaaaBB BBBBbbbb bbbbCCCC CCcccccc ccDDDDDD dddddddd
```

A = Action (0:Get 1:Set)
P = Property
A = Upper 6 bits of first value
a = Lower 8 bits of first value
B = Upper 6 bits of second value
b = Lower 8 bits of second value
Each motor has a property (PIDX) which tells it which torque to use from the set of 4

Full example:
3 motors with IDs 5, 6, and 7
Host with ID of zero

Host sends:
MsgID [10000000000] -> Group 0
Data [10000101] [00000000] [00000010] [0000000] -> Set property 5 (STAT) to 2 (STATUS_READY)
The motors start up with STAT = 0 (STATUS_RESET)
Setting STAT to READY gets the motors ready to receive additional data
Motors will only respond to STAT and VERS commands while in RESET (for safety)

Host sends:
MsgID [10000000000] -> Group 0
Data [10001000] [00000000] [00000010] [00000000] -> Set property 8 (MODE) to 2 (MODE_TORQUE)
The motors default to MODE = 0 (MODE_IDLE)
Setting MODE to MODE_TORQUE tells the motors to apply any torque sent to them
When MODE = MODE_IDLE, motors will ignore any torque commands sent and apply braking

Host sends:
MsgID [10000000000] -> Group 0
Data [00011010] -> Get property 26 (AP)

Motors send:
MsgID [10010100011] -> From ID 5 to Group 3
Data [00000000] [00000000] [0000010] -> My position is 2 encoder cts

MsgID [10011000011] -> From ID 6 to Group 3
Data [00000000] [00000000] [0000111] -> My position is 7 encoder cts

MsgID [10011100011] -> From ID 7 to Group 3
Data [00111111] [11111111] [11111110] -> My position is -2 encoder cts

Host uses these positions to calculate a torque, then sends:
MsgID [10000000010] -> Group 2
Data [10001010] [AAAAAAaa] [aaaaaaBB] [BBBBbbbb] [bbbbCCCC] [CCcccccc] [cc000000] [00000000]
-> Set torques to new values AAAAAAaaaaaaaa, etc

Parameter	Description	Default	R/W	Saved
ACCEL	Acceleration	32	R/W	Yes
ADDR	Address to peek/poke	NONE	R/W	No
ANA0	Analog input	NONE	R/-	No
ANA1	Analog input	NONE	R/-	No
AP	Actual position	NONE	R/W	Yes
AP2	Actual position	NONE	-/-	No
B	Brake	0	R/W	No
BAUD	Baud rate	9600	R/W	No
CT	Close torque	NONE	R/W	Yes
CT2	Close torque	NONE	-/-	No
CTS	Counts per revolution	4096	R/W	Yes
CTS2	Counts per revolution	NONE	R/W	No
D	Duty cycle	0	R/W	No
DEF	Default command for CAN	NONE	-/W	No
DIG0	Digital I/O	0	R/W	No
DIG1	Digital I/O	0	R/W	No
DP	Default position	0	R/W	Yes
DP2	Default position	NONE	-/-	No
DS	Default step	10	R/W	Yes
DUMP	Log dump mode: 0=Manual, 1=Auto	0	R/W	No
E	Endpoint target	0	R/W	No
EN	Enable bitfield	0x00EE	R/W	Yes
ERROR	Error	NONE	R/-	No
GAIN1	Gimbals gain 1 (Q4.12)	0x1000	R/W	Yes
GAIN2	Gimbals gain 2 (Q4.12)	0x1000	R/W	Yes
GAIN3	Gimbals gain 3 (Q4.12)	0x1000	R/W	Yes
GRPA	Comm group A	NONE	R/W	Yes
GRPB	Comm group B	NONE	R/W	Yes
GRPC	Comm group C	NONE	R/W	Yes
HSG	High strain gage	255	R/W	Yes
ID	CANbus ID	NONE	R/W	Yes
IFAULT	Ignore fault count	0	R/W	No
IKCOR	Current sense correction factor	NONE	R/W	Yes
IKI	Current sense integral gain	NONE	R/W	Yes
IKP	Current sense proportional gain	NONE	R/W	Yes
ILOGIC	Logic current	NONE	R/-	No
IMOTOR	Motor current	NONE	R/-	No
IOFF	Initialization offset	NONE	R/W	Yes
IOFST	Current offset	NONE	R/W	Yes
IPNM	CommandedCurrent / Nm (ratio)	NONE	R/W	Yes
IVEL	Initialization velocity	20	R/W	Yes
JIDX	Joint index	NONE	R/W	Yes
KD	Differential gain	0	R/W	Yes
KI	Integral gain	0	R/W	Yes
KP	Proportional gain	4096	R/W	Yes
LOAD	Load command for CAN	NONE	-/W	No
LOCK	Lock	0	-/W	No
LOG	Log status: 0=Off, 1=Once, 2=Continuous	0	R/W	No
LOG1	Log variable address 1	0	R/W	No
LOG2	Log variable address 2	0	R/W	No
LOG3	Log variable address 3	0	R/W	No
LOG4	Log variable address 4	0	R/W	No
LSG	Low strain gage	0	R/W	Yes
MAXPWR	Max allowed power	0	R/W	No
MCV	Max close velocity	300	R/W	Yes
MD	Max duty	990	R/W	No
MDS	Max duty sum	1650	R/W	Yes
MECH	Mechanical angle	NONE	R/-	No
MECH2	Mechanical angle	NONE	-/-	No
MODE	Mode of operation	0	R/W	No
MOFST	Mechanical offset	NONE	R/W	Yes
MOV	Max open velocity	300	R/W	Yes
MPE	Max position error	5	R/W	Yes
MT	Max torque	750	R/W	Yes
MV	Max velocity	300	R/W	Yes
OD	Odometer	NONE	R/W	Yes
OFFSET1	Gimbals offset 1 (Q4.12)	0	R/W	Yes
OFFSET2	Gimbals offset 2 (Q4.12)	0	R/W	Yes
OFFSET3	Gimbals offset 3 (Q4.12)	0	R/W	Yes
OT	Open torque	NONE	R/W	Yes
OT2	Open torque	NONE	-/-	No
OTEMP	Over temperature alarm	72	R/W	No
P	Position command	NONE	R/W	No
PEN	Pendant debug	NONE	R/W	No
PIDX	Puck index for torque	NONE	R/W	Yes
PTEMP	Peak temperature recorded	NONE	R/W	Yes
PWR	Observed power	NONE	R/-	No
RATIO	Output angle multiplier	NONE	R/W	Yes
ROLE	Role	NONE	R/W	Yes
SAFE	Safety debug	NONE	R/W	No
SAMPLE	Sample time	1000	R/W	Yes
SAVE	Save command for CAN	NONE	-/W	No
SG	Strain gage	NONE	R/-	No
SN	Serial number	NONE	R/W	Yes
STAT	Status	NONE	R/W	No
TEMP	Temperature	NONE	R/-	No
TENSION	Tensioner output	0	R/W	No
TENSO	Tension offset	NONE	R/W	Yes
TENST	Tension total	NONE	R/W	Yes
THERM	Thermistor	NONE	R/-	No
TL1	Torque warning level	4731	R/W	No
TL2	Torque critical level	5204	R/W	No
TORQ	Torque command	0	R/W	No
TSTOP	Time until considered stopped	1000	R/W	Yes
UNITS	Units of input angle	DEG	R/W	Yes
UPSECS	Up seconds in operation	NONE	R/W	Yes
V	Velocity command	0	R/W	No
VALUE	Value to poke/peeked	NONE	R/W	No
VBUS	Bus voltage	NONE	R/-	No
VERS	Version	NONE	R/W	No
VL1	Velocity warning level (Q4.12)	0x0800	R/W	No
VL2	Velocity critical level (Q4.12)	0x1000	R/W	No
VLOGIC	Logic voltage	NONE	R/-	No
VNOM	Vnominal	48	R/W	No
VOLTH1	Voltage high warning level	54	R/W	No
VOLTH2	Voltage high critical level	57	R/W	No
VOLTL1	Voltage low warning level	36	R/W	No
VOLTL2	Voltage low critical level	30	R/W	No
ZERO	Zeroed status	0	R/W	No

Key	Parameter
0	VERS
1	ROLE
2	SN
3	ID
4	ERROR
5	STAT
6	ADDR
7	VALUE
8	MODE
9	D
10	TORQ
11	P
12	V
13	E
14	B
15	MD
16	MT
17	MV
18	MCV
19	MOV
20	MOFST
21	IOFST
22	PTEMP
23	UPSECS
24	OD
25	MDS
26	AP
27	AP2
28	MECH
29	MECH2
30	CTS
31	CTS2
32	DP
33	DP2
34	OT
35	OT2
36	CT
37	CT2
38	BAUD
39	TEMP
40	OTEMP
41	LOCK
42	DIG0
43	DIG1
44	ANA0
45	ANA1
46	THERM
47	VBUS
48	IMOTOR
49	VLOGIC
50	ILOGIC
51	GRPA
52	GRPB
53	GRPC
54	PIDX
55	JIDX
56	ZERO
57	IPNM
58	SG
59	HSG
60	LSG
61	DS
62	IVEL
63	IOFF
64	MPE
65	EN
66	TSTOP
67	KP
68	KD
69	KI
70	SAMPLE
71	ACCEL
72	TENSION
73	UNITS
74	RATIO
75	LOG
76	DUMP
77	LOG1
78	LOG2
79	LOG3
80	LOG4
81	GAIN1
82	GAIN2
83	GAIN3
84	OFFSET1
85	OFFSET2
86	OFFSET3
87	PEN
88	SAFE
89	SAVE
90	LOAD
91	DEF
92	VL1
93	VL2
94	TL1
95	TL2
96	VOLTL1
97	VOLTL2
98	VOLTH1
99	VOLTH2
100	MAXPWR
101	PWR
102	IFAULT
103	IKP
104	IKI
105	IKCOR
106	VNOM
107	TENST
108	TENSO

Appendix D - BarrettHand

The BarrettHand can be readily integrated into the WAM system. There are two methods by which Hand control can be integrated with Arm control. The first method allows the user to control the Hand from a separate window while the Arm is running. The second method is integration of hand commands with Arm commands within the same program. Both methods require the following setup procedure.

Setup:

- Turn power to entire system OFF
- Plug in hand connector that extends from the modular outer link or Wrist into base of Hand
- Align holes on Hand Base Ring with holes on connector strain relief plate
- Align pins on Tool Plate with holes on Hand Base Ring
- Attach Hand to modular outer link or Wrist by turning Tool Plate Attachment Ring clockwise
- The pins must engage completely for Hand to be securely attached to Wrist
- Plug 'End Effector' extension cable from base of Arm to rear of Hand Power Supply Box
- Plug power cord into Power Supply Box
- Attach a standard serial cable from COM port to rear of Hand Power Supply Box

The hand is attached and ready for operation. Read the BarrettHand User Manual before proceeding with Hand operation.

Before operating both Hand and Arm together the Hand should be tested on the end of the Arm. Place Arm in a configuration that allows the Hand to move through its full range of motion. Follow the procedures in the BarrettHand User Manual for testing Hand operation. If Hand operation is successful, the system is ready for use.

To operate the Hand separately from the Arm:

- Turn Hand Power Supply Box ON
- Open a serial terminal application (such as TeraTerm, HyperTerminal, minicom) and connect to the COM port of the BarrettHand at 9600 baud, No parity, 8 bits, One stop bit, No flow control
- Put Arm in a configuration that allows for full joint motion of the Hand
- Initialize Hand (Type "HI"). The Hand is now ready for operation while executing Arm programs
- Execute desired Arm program
- While Arm program is running, switch to the serial terminal window
- Type Hand commands (see the Grasper Control Language section of the BarrettHand manual)

To operate Hand and Arm from the same program:

Integration of the Hand and the Arm in the same program requires opening and initializing the serial port from within your WAM control application, then sending the desired Grasper Control Language (GCL) commands from the application. See the directory of example code for details about how this is implemented.