Voltage/PWM versus angle calibration notes:

(no θ_1 yet)

α_1 is 1.5 degrees off 90.

Measured θ_2 off the horizontal plane.

Measured θ_3 off the horizontal plane with $\theta_2 = 90$.

(No θ_4 yet)

Measured θ_5 from 90 deg counterclockwise (seen from top).

Measured l_6 between body and back of insertion assembly.

Scott's to-do: **DONE** **IN PROGRESS**

- Make mounting disk bore 0.2 mm bigger, higher quality.
- Make robot-servo adapter mounting peg 3 mm shorter and 0.5 mm wider, higher quality.
- Mount webcam

- MATLAB webcam stuff.
- Calibrate webcam.

- AprilTags for socket

- Finish inverse kinematics, both configurations.
- End effector Jacobian for camera.

Movement procedures/algorithms:

Homing:

- Occurs on power up and task completion.
- Home prismatic (6).
- Home (1) (2) (3) (4) (5).

First approach (using inverse kinematics):

- Occurs after startup homing.
- Camera detects AprilTag(s) and makes a homogenous transform to the AprilTag(s).
- This is modified to become a homogenous transform to the outlet frame (the center of the two sockets).
- A negative z-axis translation in the socket frame yields the desired position for o_4/o_5 in socket coordinates. This is converted to camera coordinates, then to frame 5

coordinates, then to frame 0 coordinates (using the home joint parameters). The socket origin is also converted to frame 0.

- Inverse kinematics is used to calculate the joint parameters to place o_4/o_5 in the desired position. The parameter for (4) is equal but opposite to the sum of (2) and (3) to maintain level, and the parameter for (5) is calculated by the difference in angle in the frame 0 xy plane between the vector from origin 0 to the desired position for o_4/o_5 and the vector from the desired position for o_4/o_5 and the socket origin, measured from the first to the second, plus 90 degrees to account for the starting position (all with respect to counter-clockwise from top).
- The prismatic link is first deflected (5) *away from the wall* by almost 90 degrees. The negated z axis of socket frame will point either left or right in the camera frame (compared to the camera x axis), which determines which way the link should swing.
- Joints (1) (2) (3) (4) (5) are finally moved to their positions in sequence.
- (4) is aligned with socket origin (see alignment subroutine).
- If the camera detects that it is in the acceptable zone for insertion (AZ, below), it continues to fine adjustment (below). Else, it moves to coarse adjustment.

Acceptable zone (AZ) and adjustment determination:

- To insert the prongs, the position of o_4/o_5 must be within a certain small volume in front of the outlet. It must remain a safe distance from the wall, but close enough to reach, and it must not exceed a certain angle of incidence away from the socket's z axis (this may be different in the x and y directions—this will either use a deformed infinity metric, taxicab metric, or Euclidean metric for mixed angles).
- The camera will use a new measurement of the AprilTag to convert the position of o_4/o_5 into socket coordinates.
- If this point is found to be within the acceptable range, this algorithm returns True and an empty vector.
- If this point is not found to be within the acceptable range, this algorithm returns False. The difference between the center of the acceptable range and o_4/o_5's position in socket coordinates is converted into a vector in frame 0 and returned.

Joint (4) alignment subroutine:

- The camera measures the AprilTag and uses (4) to rotate the xy plane of frame 4 such that it includes the socket origin. The angle is calculated by projecting the socket point (in frame 4) onto the frame 4 xz plane and calculating the angle off the x axis, the negative of which is added to the current (4) angle.
- This may be repeated to tolerance.

Coarse Jacobian "open loop" adjustment:

- Having determined that o_4/o_5 is outside of the acceptable zone and calculated the required position delta (see AZ), the Jacobian consisting of DoFs (1) (2) and (3) will be solved for a linear combination that sums to the delta (all in frame 0).
- (4) will be automatically adjusted to counter the rotation change from (2) and (3).

- (4) is aligned with socket origin (see alignment subroutine).
- If the AZ algorithm finds that it is adequately positioned, continue to fine adjustment. If not, repeat coarse adjustment.

Fine pre-insertion adjustment:

- (4) should already be aligned with the socket origin.
- (5) is adjusted to face socket origin. The angle is calculated by projecting the socket origin onto the frame 5 xz plane and measuring off the z axis.
- (4) is aligned with the socket origin (see alignment subroutine).
- If the alignment is satisfactory (<1mm hopefully), continue to insertion. If not, repeat.

Insertion:

- Extend (6) slowly until desired distance is reached. This translation is calculated based on the desired insertion depth and the position of the prongs (calculable from position of (6)), which can be converted into socket coordinates, and the difference is taken.
- Remain in position for several seconds.
- Call homing sequence.
- End program.