Human arm mechanism

The goal of this thesis was to design and analyse a tensegrity mechanism which mimics human arm.The proposed model has two 4-SPS-S tensegrity structures ,as shown in Figure 1, base and the top platforms which mimic shoulder and wrist and both the structures are connected by a 2-SPS-R structure which mimics the elbow part of an arm.As you can see two types of mechanisms have been shown one of which has a 4-SPS-S structure at both ends and as for the other one. A tetrahedral structure is place with 4-SPS limbs as shown in the Figure 6. The total dof of the structure is 7 , where 3 is from moving platform,3 is from fixed platform and 1 from the 2-SPS-R structure.

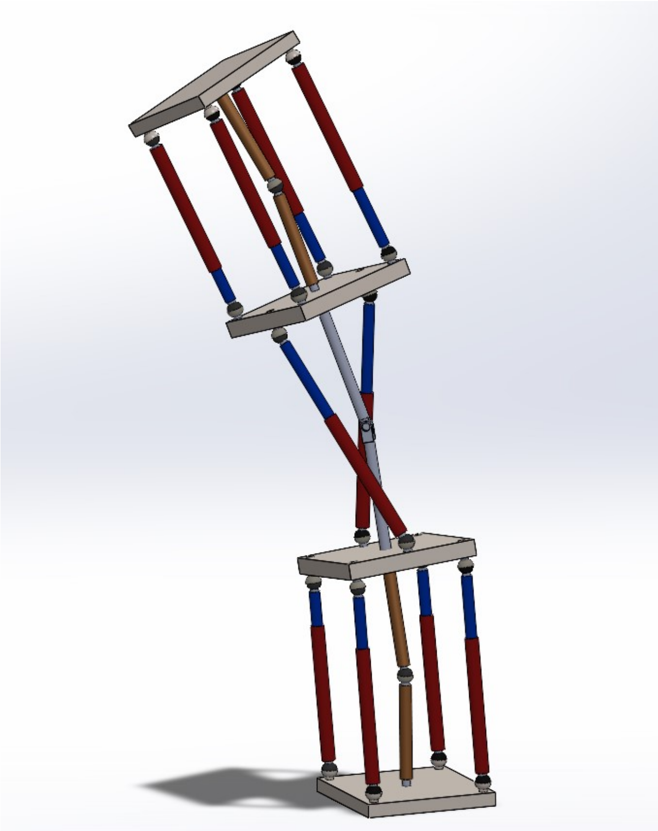

Figure 1: Human arm mimic mechanism 1

Kinematics Analysis of the Shoulder Joint

To derive the relationship between the lengths of the joint, a kinematics model of shoulder joint is established. As shown in Figure, fixed coordinate frame $B_{O-X_bY_bZ_b}$ and moving coordinate frame $C_{O-X_cY_cZ_c}$ are located in the center of the base frame and the end frame of the shoulder section , and frame C also acts as base frame for the elbow joint. Note that the Base frame B is connected to frame C by 4 leg joints which each constitutes of a spherical joint connected to base frame B and a prismatic joint and a spherical joint connected to the frame C, along with a central joint which connects the pyramid structure to the base frame B with a spherical joint.

For both the coordinate frames B and C the x and y axis are parallel to the sides of the base structure B_1, B_2, B_3, B_4 and C_1, C_2, C_3, C_4 respectively and z axis normal to the frame. The shoulder joint has the following 3 rotational DOFs: rotating the yaw angle η_x around the X-axis, rotating the pitching angle ϕ_y around the Y-axis, and rotating the roll angle θ_z around the Z-axis. The rotating Euler angle of roll-pitch-yaw is used to describe the transform matrix Rotz and rotXY as shown in the equations,for the moving coordinate frame C relative to the fixed coordinate frame B.

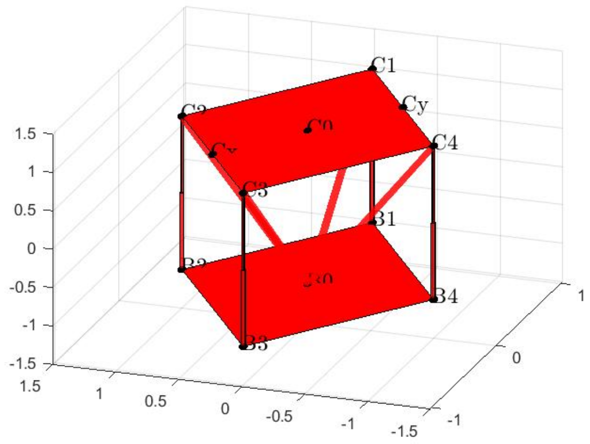

Figure 2: Shoulder Joint simulation

The coordinate system of the frame B is given as follows :

$$\begin{aligned} b0 =& [0; 0; -h] * r \\ b1 =& [cos(0 * pi/2); sin(0 * pi/2); -h] * r \\ b2 =& [cos(1 * pi/2); sin(1 * pi/2); -h] * r \\ b3 =& [cos(2 * pi/2); sin(2 * pi/2); -h] * r \\ b4 =& [cos(3 * pi/2); sin(3 * pi/2); -h] * r \\ Ori =& \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \end{aligned} \tag{1}$$

$$Rot_z = \begin{bmatrix} cos(theta) & -sin(theta) & 0 \\ sin(theta) & cos(theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$\begin{aligned} B_i =& Rotz * b_i \\ where i =& 0 - 4 \end{aligned} \tag{3}$$

The coordinates for the second plane , that is the next surface from the base C_0 to C_4 and as for C_x and C_y are the coordinates for the mid structure base as shown in the Equation 8 and Figure

$$\begin{aligned}
x =& cos(pi/4) * r \\
A1 =& [cos(0 * pi/2); sin(0 * pi/2); h] * r \\
A2 =& [cos(1 * pi/2); sin(1 * pi/2); h] * r \\
A3 =& [cos(2 * pi/2); sin(2 * pi/2); h] * r \\
A4 =& [cos(3 * pi/2); sin(3 * pi/2); h] * r \\
A0 =& [0; 0; h] * r \\
Ax =& [cos(1 * pi/2 + pi/4) * x; sin(1 * pi/2 + pi/4) * x; h * r] \\
Ay =& [cos(3 * pi/2 + pi/4) * x; sin(3 * pi/2 + pi/4) * x; h * r]
\end{aligned} \tag{4}$$

$$rotX = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(eta) & -sin(eta) \\ 0 & sin(eta) & cos(eta) \end{bmatrix} \tag{5}$$

$$rotY = \begin{bmatrix} cos(phi) & 0 & sin(phi) \\ 0 & 1 & 0 \\ -sin(phi) & 0 & cos(phi) \end{bmatrix} \tag{6}$$

$$rotXY = rotXrotY \tag{7}$$

$$\begin{aligned}
C_i =& Rotz * rotXY * A_i \\
i =& 0to4andx, y
\end{aligned} \tag{8}$$

The length of each leg is determined and developed by using matlab simulations as shown below

$$L_1 = \sqrt{l_{11} + l_{12} + l_{13}} \tag{9}$$

where

$$l_{11} = (h\,r - r\ \ c\,(\eta)\ \ s\,(\phi) + h\,r\ \ c\,(\eta)\ \ c\,(\phi))^2$$

$$l_{12} = (r(c(\phi)c(\theta) - s(\theta)s(\eta)s(\phi)) - r * c(\theta) + hr(s(\phi)c(\theta) + s(\theta)s(\eta)c(\phi)))^2$$

$$l_{13} = (r(c(\phi)s(\theta) + c(\theta)s(\eta)s(\phi)) - r * s(\theta) + hr(s(\phi)s(\theta) - c(\theta)s(\eta)c(\phi)))^2$$

$$L_2 = \sqrt{l_{21} + l_{22} + l_{23}} \tag{10}$$

$$l_{21} = \left(h\,r + r\,\sin(\eta) - \frac{var1\,r\,\cos(\eta)\,\sin(\phi)}{var2} + h\,r\,\cos(\eta)\,\cos(\phi)\right)^2$$
$$l_{22} = \left(\frac{var6}{var2} - r\,\cos(\theta) - \frac{var1\,r\,\sin(\theta)}{var2} + r\,\cos(\eta)\,\cos(\theta) + h\,r\,var7\right)^2$$
$$l_{23} = \left(\frac{var8}{var2} - \frac{var1\,r\,\cos(\theta)}{var2} + r\,\sin(\theta) - r\,\cos(\eta)\,\sin(\theta) + h\,r\,var9\right)^2$$

$$L_3 = \sqrt{l_{31} + l_{32} + l_{33}} \tag{11}$$

$$l_{31} = \left(h\,r + \frac{var1\,r\ \ s\,(\eta)}{var3} + r\ \ c\,(\eta)\ \ s\,(\phi) + h\,r\ \ c\,(\eta)\ \ c\,(\phi)\right)^2$$
$$l_{32} = \left(var11 + \frac{var1\,r\ \ c\,(\eta)\ \ c\,(\theta)}{var3} + h\,r\,(\ s\,(\phi)\ \ s\,(\theta) -\ c\,(\phi)\ \ c\,(\theta)\ \ s\,(\eta))\right)^2$$
$$l_{33} = (var12 + h\,r\,(\ c\,(\theta)\ \ s\,(\phi) +\ c\,(\phi)\ \ s\,(\eta)\ \ s\,(\theta)))^2$$

$$L_4 = \sqrt{l_{41} + l_{42} + l_{43}} \tag{12}$$

$$l_{41} = \left(h\,r - r\ \ s\,(\eta) + \frac{var4\,r\ \ c\,(\eta)\ \ s\,(\phi)}{var5} + h\,r\ \ c\,(\eta)\ \ c\,(\phi)\right)^2$$
$$l_{42} = (var13 - r\ \ c\,(\eta)\ \ c\,(\theta) + h\,r\,(\ s\,(\phi)\ \ s\,(\theta) -\ c\,(\phi)\ \ c\,(\theta)\ \ s\,(\eta)))^2$$
$$l_{43} = (var14 - r\ \ s\,(\theta) + r\ \ c\,(\eta)\ \ s\,(\theta) + h\,r\,(\ c\,(\theta)\ \ s\,(\phi) +\ c\,(\phi)\ \ s\,(\eta)\ \ s\,(\theta)))^2$$

The variables used to shorten the equations above mentioned are as follows

$$\text{var1} = 4967757600021511$$

$$\text{var2} = 81129638414606681695789005144064$$

$$\text{var6} = var1\, r\, (\cos(\phi)\ \sin(\theta) + \cos(\theta)\ \sin(\eta)\ \sin(\phi))$$

$$\text{var8} = var1\, r\, (\cos(\phi)\ \cos(\theta) - \sin(\eta)\ \sin(\phi)\ \sin(\theta))$$

$$\text{var11} = r\ \ s(\theta) - \frac{var1\, r\ \ c(\theta)}{var3} - r\,(\ c(\phi)\ \ s(\theta) +\ c(\theta)\ \ s(\eta)\ \ s(\phi))$$

$$\text{var12} = r\ \ c(\theta) - r\,(\ c(\phi)\ \ c(\theta) -\ \ s(\eta)\ \ s(\phi)\ \ s(\theta)) + \frac{var1\, r\ \ s(\theta)}{var3} - \frac{var1\, r\ \ c(\eta)\ \ s(\theta)}{var3}$$

$$\text{var13} = r\ \ c(\theta) - \frac{var4\, r\,(\ c(\phi)\ \ s(\theta) +\ c(\theta)\ \ s(\eta)\ \ s(\phi))}{var5} + \frac{var4\, r\ \ s(\theta)}{var5}$$

$$\text{var14} = \frac{var4\, r\ \ c(\theta)}{var5} - \frac{var4\, r\,(\ c(\phi)\ \ c(\theta) -\ \ s(\eta)\ \ s(\phi)\ \ s(\theta))}{var5}$$

Kinematics Analysis of the Elbow Joint

The elbow joint is a single-DOF structure, and its kinematics model is established as shown in Figure. Fixed coordinate frame $C_{OXcYcZc}$ and moving coordinate frame $C_{OXqYqZq}$ are located in the center of the two coordinate frames .

For both the coordinate frames Q and C the x and y axis are parallel to the sides of the base structure Q_1, Q_2, Q_3, Q_4 and C_1, C_2, C_3, C_4 respectively and z axis normal to the frame. The Elbow joint has the following 1 DOF: rotating the angle β.

Transform matrix R1 for the moving coordinate frame Q relative to the fixed coordinate frame C is given as rot_{y2}.

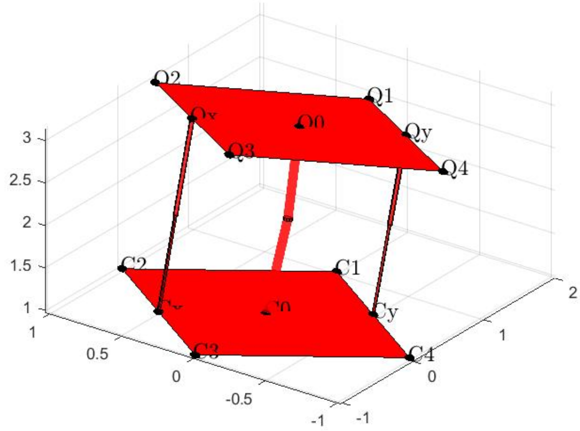

Figure 3: Elbow Joint simulation

The coordinate system of the frame Q is given as follows :

$$\begin{aligned}
P1 =& [cos(0 * pi/2); sin(0 * pi/2); 3 * h] * r \\
P2 =& [cos(1 * pi/2); sin(1 * pi/2); 3 * h] * r \\
P3 =& [cos(2 * pi/2); sin(2 * pi/2); 3 * h] * r \\
P4 =& [cos(3 * pi/2); sin(3 * pi/2); 3 * h] * r \\
P0 =& [0; 0; 3 * h] * r \\
Ori_2 =& [0; 0; 2 * h] * r \\
Px =& [cos(1 * pi/2 + pi/4) * x; sin(1 * pi/2 + pi/4) * x; 3 * h * r] \\
Py =& [cos(3 * pi/2 + pi/4) * x; sin(3 * pi/2 + pi/4) * x; 3 * h * r]
\end{aligned} \tag{13}$$

$$rot_{z2} = \begin{bmatrix} cos(gamma) & -sin(gamma) & 0 \\ sin(gamma) & cos(gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$rot_{x2} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(alpha) & -sin(alpha) \\ 0 & sin(alpha) & cos(alpha) \end{bmatrix} \tag{15}$$

$$rot_{y2} = \begin{bmatrix} cos(beta) & 0 & sin(beta) \\ 0 & 1 & 0 \\ -sin(beta) & 0 & cos(beta) \end{bmatrix} \tag{16}$$

$$Q_i = rotY2 * P_i; i = 0to4andx, y \tag{17}$$

The length of each leg is determined and developed by using matlab simulations as shown below

$$L_5 = \sqrt{l_{51} + l_{52} + l_{53}} \tag{18}$$

$$l_{51} = \left(\frac{r\ \ s\,(\eta)}{2} - \frac{r\ \ s\,(\beta)}{2} + \frac{r\ \ c\,(\eta)\ \ s\,(\phi)}{2} - 3\,h\,r\ \ c\,(\beta) + h\,r\ \ c\,(\eta)\ \ c\,(\phi)\right)^2$$
$$l_{52} = \left(var15 + \frac{r\ \ c\,(\eta)\ \ s\,(\theta)}{2} - h\,r\,(\ c\,(\theta)\ \ s\,(\phi) + \ c\,(\phi)\ \ s\,(\eta)\ \ s\,(\theta))\right)^2$$
$$l_{53} = (var16 - h\,r\,(\ s\,(\phi)\ \ s\,(\theta) - \ c\,(\phi)\ \ c\,(\theta)\ \ s\,(\eta)))^2$$

$$L_6 = \sqrt{l_{61} + l_{62} + l_{63}} \tag{19}$$

$$l_{61} = \left(\frac{r\ \ s\,(\eta)}{2} - \frac{r\ \ s\,(\beta)}{2} + \frac{r\ \ c\,(\eta)\ \ s\,(\phi)}{2} + 3\,h\,r\ \ c\,(\beta) - h\,r\ \ c\,(\eta)\ \ c\,(\phi)\right)^2$$
$$l_{62} = \left(var17 - 3\,h\,r\ \ s\,(\beta) + \frac{r\ \ c\,(\eta)\ \ s\,(\theta)}{2} + h\,r\,(\ c\,(\theta)\ \ s\,(\phi) + \ c\,(\phi)\ \ s\,(\eta)\ \ s\,(\theta))\right)^2$$
$$l_{63} = \left(var18 - \frac{r\ \ c\,(\eta)\ \ c\,(\theta)}{2} + h\,r\,(\ s\,(\phi)\ \ s\,(\theta) - \ c\,(\phi)\ \ c\,(\theta)\ \ s\,(\eta))\right)^2$$

The variables used to shorten the equations above mentioned are as follows

$$\text{var15} = \frac{r\,(\ c\,(\phi)\ \ c\,(\theta) - \ s\,(\eta)\ \ s\,(\phi)\ \ s\,(\theta))}{2} - \frac{r\ \ c\,(\beta)}{2} + 3\,h\,r\ \ s\,(\beta)$$
$$\text{var16} = \frac{r}{2} + \frac{r\,(\ c\,(\phi)\ \ s\,(\theta) + \ c\,(\theta)\ \ s\,(\eta)\ \ s\,(\phi))}{2} - \frac{r\ \ c\,(\eta)\ \ c\,(\theta)}{2}$$

$$\text{var17} = \frac{r\,(\ c\,(\phi)\ \ c\,(\theta) -\ s\,(\eta)\ \ s\,(\phi)\ \ s\,(\theta))}{2} - \frac{r\ \ c\,(\beta)}{2}$$
$$\text{var18} = \frac{r}{2} + \frac{r\,(\ c\,(\phi)\ \ s\,(\theta) +\ c\,(\theta)\ \ s\,(\eta)\ \ s\,(\phi))}{2}$$

Kinematics Analysis of the wrist Joint

To derive the relationship between the lengths of the joint, a kinematics model of shoulder joint is established. As shown in Figure, fixed coordinate frame $Q_{OXqYqZq}$ and moving coordinate frame $S_{OXsYsZs}$ are located in the center of the base frame and the end frame of the shoulder section , and frame Q also acts as base frame for the wrist joint. Note that the Base frame S is connected to frame Q by 4 leg joints which each constitutes of a spherical joint connected to base frame S and a prismatic joint and a spherical joint connected to the frame Q, along with a central joint which connects the pyramid structure to the base frame S with a spherical joint.

For both the coordinate frames S and Q the x and y axis are parallel to the sides of the base structure S_1, S_2, S_3, S_4 and Q_1, Q_2, Q_3, Q_4 respectively and z axis normal to the frame. The shoulder joint has the following 3 rotational DOFs: rotating the yaw angle η_x around the X-axis, rotating the pitching angle ϕ_y around the Y-axis, and rotating the roll angle θ_z around the Z-axis. The rotating Euler angle of roll-pitch-yaw is used to describe the transform matrix Rotz and rotXY as shown in the equations,for the moving coordinate frame Q relative to the fixed coordinate frame S.

The coordinate system of the frame S is given as follows :

$$
\begin{aligned}
R1 =&[cos(0*pi/2);sin(0*pi/2);5*h]*r\\
R2 =&[cos(1*pi/2);sin(1*pi/2);5*h]*r\\
R3 =&[cos(2*pi/2);sin(2*pi/2);5*h]*r\\
R4 =&[cos(3*pi/2);sin(3*pi/2);5*h]*r\\
R0 =&[0;0;5*h]*r\\
R00 =&[0;0;7*h]*r\\
Ori_3 =&[0;0;4*h]*r\\
Ori_4 =&[0;0;6*h]*r
\end{aligned}
\tag{20}
$$

$$
\begin{aligned}
R11 =&[cos(0*pi/2)*(r/3);sin(0*pi/2)*(r/3);5*h*r]\\
R22 =&[cos(1*pi/2)*(r/3);sin(1*pi/2)*(r/3);5*h*r]\\
R33 =&[cos(2*pi/2)*(r/3);sin(2*pi/2)*(r/3);5*h*r]\\
R44 =&[cos(3*pi/2)*(r/3);sin(3*pi/2)*(r/3);5*h*r]
\end{aligned}
\tag{21}
$$

$$
rot_{z3} = \begin{bmatrix} cos(gamma3) & -sin(gamma3) & 0 \\ sin(gamma3) & cos(gamma3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{22}
$$

$$
rot_{x3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(alpha3) & -sin(alpha3) \\ 0 & sin(alpha3) & cos(alpha3) \end{bmatrix} \tag{23}
$$

$$
rot_{y3} = \begin{bmatrix} cos(beta3) & 0 & sin(beta3) \\ 0 & 1 & 0 \\ -sin(beta3) & 0 & cos(beta3) \end{bmatrix} \tag{24}
$$

$$
rotXY_3 = rot_{x3}rot_{y3} \tag{25}
$$

$$S_i = Rotz3 * rotXY3 * R_i; i = 0to4 \tag{26}$$

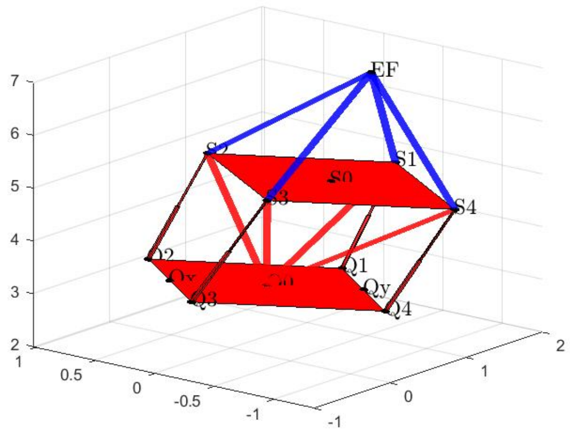

Figure 4: wrist Joint simulation

The length of each leg is determined and developed by using matlab simulations as shown below

$$L_9 = \sqrt{l_{91} + l_{92} + l_{93}} \tag{27}$$

$$l_{91} = (r\,var19 + 5\,h\,r\,(\ s(\beta_3)\ \ s(\gamma_3) - \ c(\beta_3)\ \ c(\gamma_3)\ \ s(\alpha_3)))^2$$
$$l_{92} = (r\ \ s(\beta) - r\ \ c(\alpha_3)\ \ s(\beta_3) - 3\,h\,r\ \ c(\beta) + 5\,h\,r\ \ c(\alpha_3)\ \ c(\beta_3))^2$$
$$l_{93} = (r\,var20 - r\ \ c(\beta) - 3\,h\,r\ \ s(\beta) + 5\,h\,r\,(\ c(\gamma_3)\ \ s(\beta_3) + \ c(\beta_3)\ \ s(\alpha_3)\ \ s(\gamma_3)))^2$$

$$L_{10} = \sqrt{l_{101} + l_{102} + l_{103}} \tag{28}$$

$$l_{101} = (var21 + r\ \ c(\alpha_3)\ \ c(\gamma_3) + 5\,h\,r\,(\ s(\beta_3)\ \ s(\gamma_3) - \ c(\beta_3)\ \ c(\gamma_3)\ \ s(\alpha_3)))^2$$
$$l_{102} = \left(r\ \ s(\alpha_3) + \frac{var1\,r\ \ s(\beta)}{var2} - \frac{var1\,r\ \ c(\alpha_3)\ \ s(\beta_3)}{var2} - 3\,h\,r\ \ c(\beta) + 5\,h\,r\ \ c(\alpha_3)\ \ c(\beta_3)\right)^2$$
$$l_{103} = (var22 + 3\,h\,r\ \ s(\beta) - 5\,h\,r\,(\ c(\gamma_3)\ \ s(\beta_3) + \ c(\beta_3)\ \ s(\alpha_3)\ \ s(\gamma_3)) + r\ \ c(\alpha_3)\ \ s(\gamma_3))^2$$

$$L_{11} = \sqrt{l_{111} + l_{112} + l_{113}} \tag{29}$$

$$l_{111} = \left(\frac{var1\, r\ \ s\,(\alpha_3)}{var3} - r\ \ s\,(\beta) + r\ \ c\,(\alpha_3)\ \ s\,(\beta_3) - 3\,h\,r\ \ c\,(\beta) + 5\,h\,r\ \ c\,(\alpha_3)\ \ c\,(\beta_3)\right)^2$$
$$l_{112} = \left(r\,var23 - 5\,h\,r\,(\ c\,(\gamma_3)\ \ s\,(\beta_3) +\ c\,(\beta_3)\ \ s\,(\alpha_3)\ \ s\,(\gamma_3)) + \frac{var1\, r\ \ c\,(\alpha_3)\ \ s\,(\gamma_3)}{var3}\right)^2$$
$$l_{113} = (var24 - 5\,h\,r\,(\ s\,(\beta_3)\ \ s\,(\gamma_3) -\ c\,(\beta_3)\ \ c\,(\gamma_3)\ \ s\,(\alpha_3)))^2$$

$$L_{12} = \sqrt{l_{121} + l_{122} + l_{123}} \tag{30}$$

$$l_{121} = \left(r\ \ s\,(\alpha_3) + \frac{var4\, r\ \ s\,(\beta)}{var5} - \frac{var4\, r\ \ c\,(\alpha_3)\ \ s\,(\beta_3)}{var5} + 3\,h\,r\ \ c\,(\beta) - 5\,h\,r\ \ c\,(\alpha_3)\ \ c\,(\beta_3)\right)^2$$
$$l_{122} = (var25 - 3\,h\,r\ \ s\,(\beta) + 5\,h\,r\,(\ c\,(\gamma_3)\ \ s\,(\beta_3) +\ c\,(\beta_3)\ \ s\,(\alpha_3)\ \ s\,(\gamma_3)) + r\ \ c\,(\alpha_3)\ \ s\,(\gamma_3))^2$$
$$l_{123} = (var26 + 5\,h\,r\,(\ s\,(\beta_3)\ \ s\,(\gamma_3) -\ c\,(\beta_3)\ \ c\,(\gamma_3)\ \ s\,(\alpha_3)))^2$$

The variables used to shorten the equations above mentioned are as follows

var4 = 40564819207303340847894502572032

var3 = 40564819207303340847894502572032

var5 = 20282409603651670423947251286016

var7 = $(\sin(\phi)\,\sin(\theta) - \cos(\phi)\,\cos(\theta)\,\sin(\eta))$

var9 = $(\cos(\theta)\,\sin(\phi) + \cos(\phi)\,\sin(\eta)\,\sin(\theta))$

var19 = $(\ c\,(\beta_3)\ \ s\,(\gamma_3) +\ c\,(\gamma_3)\ \ s\,(\alpha_3)\ \ s\,(\beta_3))$

var20 = $(\ c\,(\beta_3)\ \ c\,(\gamma_3) -\ s\,(\alpha_3)\ \ s\,(\beta_3)\ \ s\,(\gamma_3))$

var21 = $\dfrac{var1\, r\,(\ c\,(\beta_3)\ \ s\,(\gamma_3) +\ c\,(\gamma_3)\ \ s\,(\alpha_3)\ \ s\,(\beta_3))}{var2} - r$

var22 = $\dfrac{var1\, r\ \ c\,(\beta)}{var2} - \dfrac{var1\, r\,(\ c\,(\beta_3)\ \ c\,(\gamma_3) -\ s\,(\alpha_3)\ \ s\,(\beta_3)\ \ s\,(\gamma_3))}{var2}$

var23 = $(\ c\,(\beta_3)\ \ c\,(\gamma_3) -\ s\,(\alpha_3)\ \ s\,(\beta_3)\ \ s\,(\gamma_3)) - r\ \ c\,(\beta) + 3\,h\,r\ \ s\,(\beta)$

var24 = $\dfrac{var1\, r}{var3} + r\,(\ c\,(\beta_3)\ \ s\,(\gamma_3) +\ c\,(\gamma_3)\ \ s\,(\alpha_3)\ \ s\,(\beta_3)) - \dfrac{var1\, r\ \ c\,(\alpha_3)\ \ c\,(\gamma_3)}{var3}$

var25 = $\dfrac{var4\, r\ \ c\,(\beta)}{var5} - \dfrac{var4\, r\,(\ c\,(\beta_3)\ \ c\,(\gamma_3) -\ s\,(\alpha_3)\ \ s\,(\beta_3)\ \ s\,(\gamma_3))}{var5}$

var26 = $r - \dfrac{var4\, r\,(\ c\,(\beta_3)\ \ s\,(\gamma_3) +\ c\,(\gamma_3)\ \ s\,(\alpha_3)\ \ s\,(\beta_3))}{var5} - r\ \ c\,(\alpha_3)\ \ c\,(\gamma_3)$

The total body simulation of Human arm mechanism is shown in the figure below

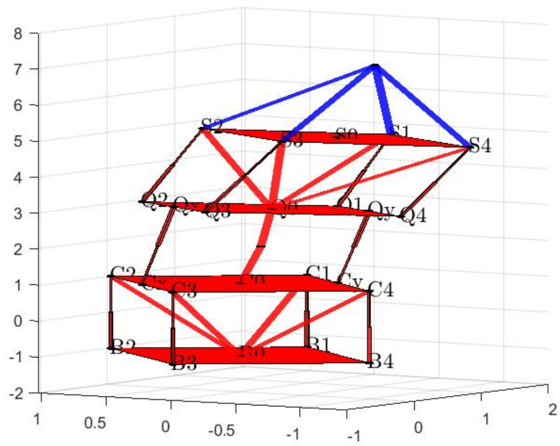

Figure 5: wrist Joint simulation

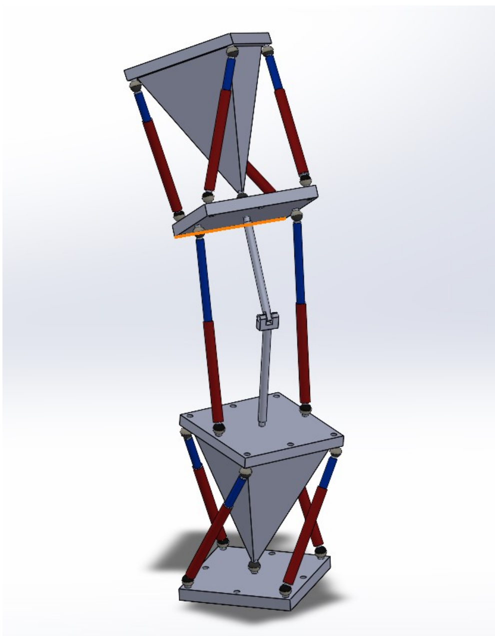

Figure 6: Human arm mimic mechanism