# Head-Neck model

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## 1 Head-Neck system

## 2 Literature Review

The oculomotor system is studied in detail for almost 5 decades. During that time, some authors suggested and contributed with some models of the eye-head system (including the neck). However, the majority of those models simplified the kinematics and dynamics too much. In [1] a simplified model of the head, vertebrae and torso was made. They considered that the neck was simply the stacking of seven vertebrae. Even though their dimensions of each component of the system was accurate, they did not account for the translation of the head. In [2], a careful analysis of the neck was made, accounting for every single muscle present in the human body in that region. In [3], a simplified model of the neck muscles was made, with just enough muscles to allow for 3 degrees of freedom. *Mention [4] and [5]*

## 3 Model

### 3.1 Neck muscles

The objective of this model is to simulate neck and gaze movements, with the least complexity possible. In order to do that, instead of having 6 rotational and translational DoF, it was decided to keep only 4: horizontal, vertical and torsional rotation for the neck and vertical rotation of the head. With this, it is possible to emulate all movements the human body can perform using only head and neck muscles. Hence it is possible to group the modeled muscles into 4 groups:

- Muscles responsible for head torsional rotation: Sternocleidomastoid
- Muscles responsible for head vertical rotation: Sternhyoid and spine. These muscles are also responsible for keeping the head upright and looking at infinity.

- Muscles responsible for head horizontal rotation: Sternocleidomastoid and Trapezius
- Muscles responsible for neck vertical rotation: Support muscles

Full list of the muscles implemented:

- Left Sternocleidomastoid
- Right Sternocleidomastoid
- Sternhyoid
- Spine (simplified as a muscle)
- Front neck support muscle (created to keep the head and neck upright in resting orientation)
- Left Trapezius (attached on the head)
- Right Trapezius (attached on the head)
- Back neck support muscle (created to keep the head and neck upright in resting orientation)
- Left Trapezius (attached on the neck)
- Right Trapezius (attached on the neck)

## 3.2 SolidWorks Model

In order to simulate the neck and head systems, a prototype is meant to be built. This prototype was modeled resorting to SolidWorks software and it can be seen in the figure below.

The model has, for a base, a wooden block as the torso that is fixed in the world frame. This block is where the cables that emulate the neck muscles will have their starting points. Inside the "torso" a sphere joint is located. This joint is responsible for giving the neck 3 degrees of rotational freedom (horizontal, vertical and torsional). Attached to the sphere joint, there is a small cone that has the role of supporting the cylinder that represents the spine. However, this cylinder also possesses two openings at the top where a revolute joint fits, accommodated by ball bearings. This revolute joint allows the head to perform vertical rotations, or in other words, it allows for a nodding motion. This last joint is encompassed by the head, that is hollow and possesses a socket for an eye.

Regarding the most pertinent measures:

- Height of the cylinder: 0.0994 m;
- Torso base to cylinder base: 0.0744 m;

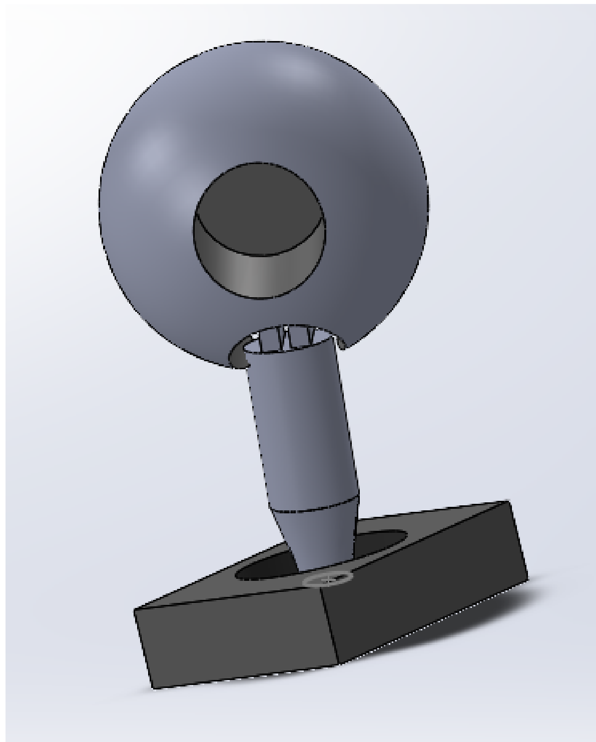


Figure 1: SolidWorks model

- Torso base to head base: 0.163 m;
- Radius of the head: 0.143 m;
- Radius of the cylinder: 0.0275 m;

## 4 Insertion Points

Since the torso is fixed in the world frame, the strings that simulate neck muscles are rigidly attached to the bottom part of the model and those points do not change in the world. Conversely the other insertion point of each muscle is either on the head or the neck: bodies that move. Therefore, it is necessary to find the points of insertion that minimize the overall length of the cable (for any orientation of head and neck) and hence the force produced by the motors.

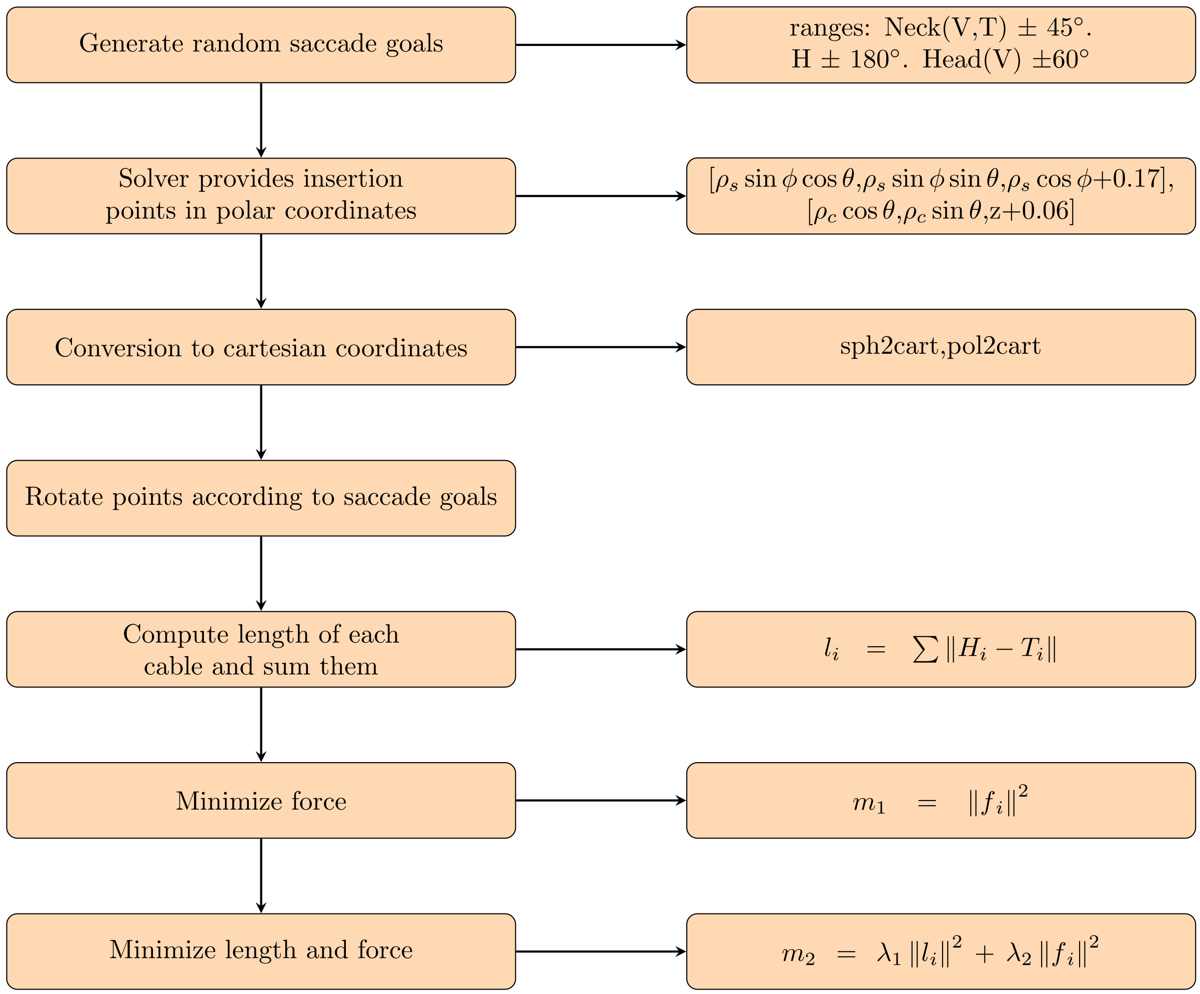
In order to get the points that minimize the force exerted, several test runs were tried, rotating the bodies to eccentric orientations. Consider the insertion points on the torso as $T_i, i = 1, ..., 5$. The insertion points on the head are represented by $H_i, i = 1, ..., 5$.

## 4.1 Motion Range

First, random rotations are applied to head and neck. It is important to notice that these two bodies have different movement ranges and each was defined based on the Solidworks model capabilities. So for the neck, the vertical and torsion motions were restrained between -45 degrees and positive 45 degrees. As for the horizontal component, it has a maximum range of 180 degrees and minimum of -180 degrees, since the prototype is able to fully rotate the neck. The head only provides one DoF to the system (vertical motion), and its motion range is from -60 degrees to 60 degrees.

## 4.2 Optimization

A block diagram of the optimization can be seen below.




#### 4.2.1 Insertion points rotation

Since the head is permitted to translate, rotating it with a rotation matrix alone is not enough. Hence, the concept of homogeneous matrix is introduced. Consider the following matrix $H$ that describes the rotation and translation of the head in the world frame:

$$ {}^{w}H_h = \begin{bmatrix} {}^{w}R_h & {}^{w}o_h \\ 0_{1\times 3} & 1 \end{bmatrix} \tag{1} $$

where

$$ {}^{w}R_h = {}^{w}R_n \, {}^{n}R_h \tag{2} $$

and the offset is

$$^{w}o_h = {}^{w}o_n + {}^{n}o_h \tag{3}$$

$^{n}R_h$ is the rotation matrix of the head with respect to the neck, which, in this model, can only be around one axis.

So, to rotate the points in the head, one has to follow

$$\begin{bmatrix} P_w \\ 1 \end{bmatrix} = {}^{w}H_h \begin{bmatrix} P_h \\ 1 \end{bmatrix} \tag{4}$$

In order to rotate the points on the neck, a simple rotation matrix is applied to any given point, since this component does not translate.

### 4.2.2 Cost and constraints

For the optimization at hand, MATLAB's function *fmincon* was used. Regarding the insertion points minimization, the constraints are

$$\begin{aligned}
&\underset{\mathbf{H}}{\text{minimize}}\ f(\mathbf{H}) = \lambda_1 \left\| length_i \right\|^2 + \lambda_2 \left\| force_i \right\|^2 \\
&\textbf{subject to} \\
&\qquad 2\pi \geq \theta \geq 0 \\
&\qquad \frac{\pi}{2} \geq \phi \geq -\frac{\pi}{2} \\
&\qquad z > 0.01 \\
&\qquad \vec{v_i} \cdot \vec{v}_{desired} > 0.95, \qquad i = 1, 2, 7, 8
\end{aligned}$$

In the minimization above, $\theta$ is the angle between the reference direction on the chosen plane and the line from the origin to the projection of a point P on the plane. $\phi$ is the angle between the z-axis and the vector that starts on the origin of the reference frame and ends on a point P.

$$\begin{aligned}
&\underset{\mathbf{f},\mathbf{P}}{\text{minimize}}\ f(\mathbf{P}, \mathbf{f}) = \lambda_1 (\overline{length}(\mathbf{P}, \boldsymbol{\theta}))^2 + \lambda_2 \left\| force \right\|^2 \\
&\textbf{subject to} \\
&\qquad (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = R_s^2, \\
&\qquad (x - x_0)^2 + (y - y_0)^2 = R_c^2, \\
&\qquad \boldsymbol{\tau}_{i,j}(\mathbf{P}, \boldsymbol{\theta}, \mathbf{f}) + \boldsymbol{\tau}_{g_{i,j}}(\boldsymbol{\theta}) < threshold \\
&\qquad \mathbf{f} > 0
\end{aligned}$$

After getting the insertion points that minimize muscle length, it is necessary to know the maximum force exerted by each muscle, to conceptualize the kind of motor to use and the type of spring to integrate in the cables.

The solver provides the insertion points that it's evaluating to a second minimization function which uses them to compute the force at the designated static orientation (given by the rotations provided in the beginning).With the points it is possible to compute the force direction and the second solver computes then the necessary force magnitude distributed across all muscles to counter the torque caused by gravity.

$$\begin{aligned}
&\underset{\mathbf{f}}{\text{minimize}}\ f(\mathbf{f}) = \|\mathbf{f}_i\|^2 \\
&\textbf{subject to} \\
&\qquad \boldsymbol{\tau}_{total} = \boldsymbol{\tau}_{gh} + \boldsymbol{\tau}_{gn} = 0
\end{aligned}$$

where $\boldsymbol{\tau}_{gh}$ is the gravity torque produced by the head and $\boldsymbol{\tau}_{gn}$ is the same, but produced by the neck. Consider a generic gravity torque $\boldsymbol{\tau}_g$. This variable may be computed as

$$\boldsymbol{\tau}_g = c_m \times f_g$$

where $c_m$ is the center of mass of a generic body and $f_g$ is its gravity force. The centers of mass are rotated according to the rotation of the neck.

# 5 Simulator

The simulator was made using Robot Operating System's functionalities, namely Gazebo. A URDF file was created and developed in which the specifics of the robot were defined: The number of links, their properties and the joints connecting said links. However, since Gazebo is not capable of reading sphere joints yet, these had to be simulated by three mutually orthogonal revolute joints (each one responsible for the rotations around one axis). One sphere joint is located at the bottom of the neck and one at the center of the head, responsible for eye rotation. There is also a revolute joint below the head's center of mass that allows the head to rotate vertically. The meshes were exported from SolidWorks, resorting to SW2URDF add-in. Each body part (torso, neck,head and eye) was meshed and exported individually. Since is not very reliable to simulate the cables (muscles) in Gazebo, they are emulated through stronger motors that actuate on the joints.

## 5.1 Controllers

The controllers chosen were effort controllers. Inside this type of controllers there are several sub-types, namely effort, velocity and position. The first allows to apply the desired torque directly to a joint. The second has velocity as input that goes through a PID controller and outputs torque to the joint. The last one is the same as velocity but its the pose of the body that serves as input.

For this model, position controllers were chosen for each of the joints, since it is aimed that the optimal control outputs the ideal trajectory for each of the links, for any rotation, and then this trajectory is passed to the simulator to observe the dynamic properties: velocity profiles, Listing's law and the main sequence.

$$\begin{aligned}
&\underset{\mathbf{P}_i,\mathbf{f}_i}{\arg\min}\ \boldsymbol{\lambda}_1 \left\| \mathbf{J}^T\mathbf{f} + \boldsymbol{\tau}_g \right\|^2 + \lambda_2 \left\| \mathbf{f}_i \right\|^2 \\
&\textbf{subject to} \\
&\qquad \boldsymbol{\tau}_{total} = 0 \\
&\qquad \mathbf{f}_i \geq 0
\end{aligned}$$

$$\boldsymbol{\tau} = \mathbf{J}^T\mathbf{f} \tag{5}$$

$$\mathbf{J}^T = \begin{bmatrix} l_2 & 0 & 0 \\ 0 & -l_1 \sin\theta_2 & l_1 \cos\theta_2 - l_2 \\ l_2 \cos\theta_2 - l_1 & 0 & 0 \\ -l_2 \cos\theta_3 \sin\theta_2 & -l_1 \sin\theta_3 \sin\theta_2 & l_1 \sin\theta_3 \cos\theta_2 - l_2 \sin\theta_3 \end{bmatrix} \tag{6}$$

$$^{w}T_{ny} = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & 0 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$^{n_y}T_{nr} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_3 & -\cos\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$^{n_r}T_{nt} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ -\cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$^{n_t}T_{h} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & -l \\ \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

## 5.2 New accuracy cost

$$J_a = \sum_{i=0}^{T} (x_i - x_d)^2 \tag{11}$$

$$x^p = A^p x_0 + \sum A^{p-1:0} B u^{p-1} \tag{12}$$

$$x^{p+1} = A\left(\sum A^{p-1:0} B u^{p-1}\right) + B \delta u^p \tag{13}$$

# References

[1] Shyh-Chour Huang. Numerical simulations of human head-neck dynamics. *Bio-medical materials and engineering*, 9(1):61–71, 1999.

[2] Anita N Vasavada, Siping Li, and Scott L Delp. Influence of muscle morphometry and moment arms on the moment-generating capacity of human neck muscles. *Spine*, 23(4):412–422, 1998.

[3] Lin Bo, Rami Seliktar, Alberto Esquenazi, and Carol A Oatis. A hybrid biomechanical model of the human neck. *IFAC Proceedings Volumes*, 27(1):471–473, 1994.

[4] M De Jager, AAHJ Sauren, J Thunnissen, and JSHM Wismans. A three-dimensional head-neck model: Validation for frontal and lateral impacts. *SAE transactions*, pages 1660–1676, 1994.

[5] Dannis Michel Brouwer, Jan Bennik, Jam Leideman, Herman MJR Soemers, and Stefano Stramigioli. Mechatronic design of a fast and long range 4 degrees of freedom humanoid neck. In *2009 IEEE International Conference on Robotics and Automation*, pages 574–579. IEEE, 2009.