A MOTORIZED GRAVITY COMPENSATION MECHANISM USED FOR THE NECK OF A SOCIAL ROBOT

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Abstract: *In this paper, the conceptual design and the mathematical model of a motorized gravity compensation mechanism used for the neck of a social robot is presented. Some characteristics of the new version of the social robot Probo are described in the first part. The second section starts with a brief description on the conceptual design of the neck. Then a mathematical model of the robot neck is presented, in terms of direct and inverse kinematics, static effects and gravity compensation. The last part highlights some numerical simulations for the second and the third joint, used in the estimation of the neck's motor torques, without/with gravitational compensation.*

Keywords: *gravity compensation, design, modeling, robotic neck, social robot.*

1. Introduction

The Robotics and MultiBody Mechanics Research Group, at Vrije Universiteit Brussel (VUB), developed a social robot, named Probo, which was developed to study child-robot interaction and investigate robot assisted therapy with e.g. autistic children [3].

An imperative demand in human-robot interaction (HRI) is to achieve the emotional behavior of the robot. In order to accomplish this requirement, the former version of Probo was equipped with 20 degrees of freedom (d.o.f.) [4]. Another aspect in the development process was to create a multi-disciplinary research community, hence it was investigated the possibility to reproduce the robotic platform in order to be used for Human-Robot Interaction (HRI) and Robot-Assisted Therapy (RAT) studies.

To reach the reproducible platform, it was necessary to adopt cheaper and simpler design solutions. So, a new "hobby" servo actuated version was conceived, maintaining in the same time the external mechanic aspect and compliant design of the robot. The new version has 21 degrees of freedom (d.o.f.), grouped in five subsystems, as follows: eye system (10 d.o.f.), ear system (2 d.o.f.), trunk system (3 d.o.f.), mouth system (3 d.o.f.) and neck system (3 d.o.f.). The CAD model and the real prototype of the robot are presented in Figure 1.

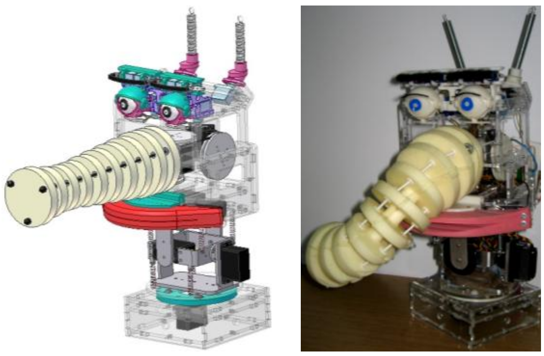


Figure 1: *New version of the robot Probo - CAD model and real prototype*

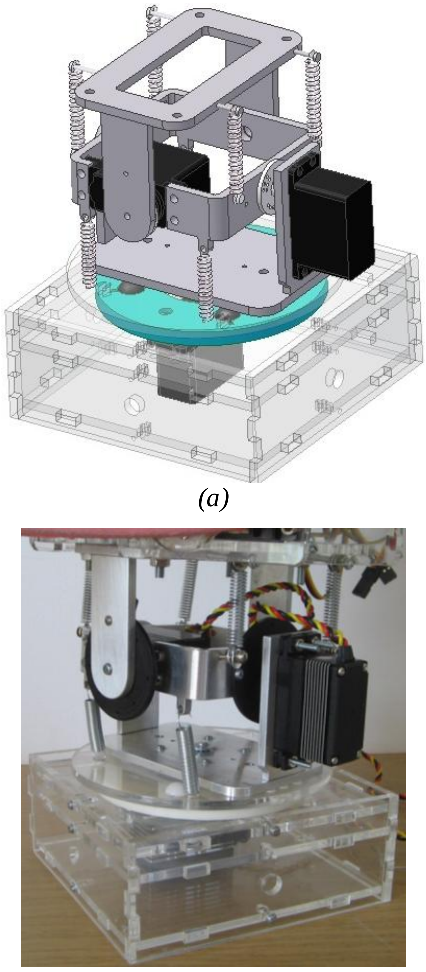
In the development process a major requirement was to choose the most suitable solution for the neck mechanism since the neck must support all the head components and must provide soft and natural movements of the robot head. Also, the neck must have 3 d.o.f., since these are the main motions of the human neck. But these motions require powerful actuators meaning high weights and large sizes. Hence, some estimation about the necessary motor torques and speeds had to be done. To provide this information, it was, also, necessary to estimate the robot dimensions, mass and materials used for the components. Other design specifications were chosen in terms of modularity, safety, low cost, compliance, robustness, "servo" actuation.

Knowing that social robots need best lightweight motors, a gravity compensation based neck mechanism is designed. The advantages of using a balanced robot neck are that the stiffness in the last two joints is zero at any position and the static gravity forces are eliminated. Hence the neck offers no resistance when it is touched (safe design) and smaller motors can actuate the system since they have to overcome only the inertia (compactness and energy saving). The next paragraphs are focused on the conceptual design and the mathematical model of this neck mechanism used in a new version of the robot Probo.

2. Design of a balanced robot neck

Based on the imposed criteria, the Fitzpatrick's model [2] was chosen as the most appropriate solution for the neck system of the new version of the social robot (Figure 2). This mechanical solution is a serial mechanism, with three degrees of freedom, providing the three mentioned motions. This serial mechanism is equivalent to a spherical wrist. The ranges of motion are limited and smaller than the ranges of the human head motion, but satisfactory to potentiate the expressive behavior of the robot. They include rotation around vertical axis (±60°), inclination forward/backward around horizontal axis (±30°) and inclination left/right in frontal plane (±30°).

To compensate the gravity, and consequently to reduce the required motor torque for tilting or swinging the head, the neck was equipped with helical tension springs. An analogue principle is used in the neck and torso design of the robotic head ROMAN [1], which concluded that if the set of spring pairs are well dimensioned, the required motor torque is reduced to approximately the torque introduced by the inertia of the head.



(a)

(b)

Figure 2: *The neck: a) CAD model; b) real prototype*

2.1 Direct kinematics

First, if we apply standard Denavit - Hartenberg convention to the serial mechanism of the neck (Figure 3), we get the parameters presented in Table 1. Based on these, we can perform the direct kinematic analysis, writing the transition homogeneous transformation matrixes that express the position and orientation of the current frame with respect to the previous one. Multiplying all these matrixes we will get the total homogeneous transformation matrix (1) of the neck mechanism that expresses the position and orientation of the last frame with respect to the referential frame.

Tabel 1: *Standard Denavit-Hartenberg parameters*

Link No.	a_i	α_i	d_i	θ_i
1	0	$-\pi/2$	l_1	θ_1
2	0	$-\pi/2$	0	$-\pi/2+\theta_2$
3	l_3	0	0	θ_3

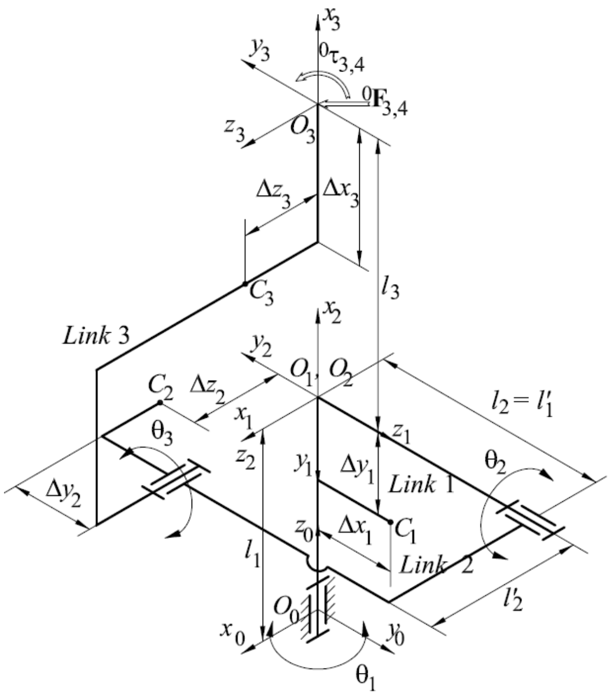


Figure 3: *Kinematics of the neck mechanism*

$$^0_3T = {}^0_1T \cdot {}^1_2T \cdot {}^2_3T =$$

$$= \begin{bmatrix} s_1 \cdot s_2 \cdot c_3 - -c_1 \cdot s_3 & -s_1 \cdot s_2 \cdot s_3 - -c_1 \cdot c_3 & s_1 \cdot c_2 & l_3 \cdot \left(s_1 \cdot s_2 \cdot c_3 - -c_1 \cdot s_3 \right) \\ -c_1 \cdot s_2 \cdot c_3 - -s_1 \cdot s_3 & c_1 \cdot c_2 \cdot s_3 - -s_1 \cdot c_3 & -c_1 \cdot c_2 & l_3 \cdot \left(-c_1 \cdot s_2 \cdot c_3 - -s_1 \cdot s_3 \right) \\ c_2 \cdot c_3 & -c_2 \cdot s_3 & -s_2 & l_3 \cdot \left(-c_2 \cdot c_3 \right) + +l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$= \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix}$$

where: $s_i = \sin\theta_i$, $c_i = \cos\theta_i$, for $i = 1...3$, and r_{jk} (for $j = 1...4$ and $k = 1...4$) are supposed to be known at any moment. It means that we may know, at any moment, the position and orientation of each current frame with respect to the previous one and, also, the position and orientation of the final frame with respect to the referential frame.

2.2 Inverse kinematics

Based on (1), we may proceed in solving the inverse kinematics in order to get the joints variables. We need these variables for the next step, when we will try to get the joints torques, first without gravity compensation and then using elastic springs for gravity compensation.

$$\theta_1 = A\tan 2\,(r_{13}, -r_{23}) \quad (2)$$

$$\theta_2 = A\tan 2\,(-r_{33}, \sqrt{r_{13}^2 + r_{23}^2}) \quad (3)$$

$$\theta_3 = A\tan 2\,(-r_{32}, r_{31}) \quad (4)$$

2.3 Statics

At this stage, dynamics effects will be neglected and we will try to solve the joint torques that must be acting to keep the system in static equilibrium. Because the proposed neck mechanism is a serial chain, the forces and torques applied to the end of the last link propagate from one link to the next, through to the base. In this calculus, we are interested in joint torques required to balance the externally applied forces but also the links masses (robot head mass). The external forces can be reaction forces resulting from the head collisions with objects from its workspace or they may be forces exercised by some persons around the robot head. These forces change from task to task, where the mass of the neck links are constant. The forces and torques required to balance the mass of the links vary with the configuration of the manipulator, and the forces and torques required to balance the external forces and torques due to interaction with the environment vary with the task.

Due to the fact that the external forces could be applied on any part of the robot head, the torques estimation is a very complex process. This is why the external forces will be considered nulls for numerical simulation. The only forces that will act on the links will be their gravity forces.

We wish to solve the set of joint torques needed to support static load acting on the robot head. The procedure of solving the joint torques, needed to keep the neck mechanism in equilibrium, will require writing down the force and torque equations for each link. For a serial mechanism, this leads to consider how forces and moments "propagate" from one link to the next, starting from the last one through to the base:

$$^{0}\mathbf{F}_{i-1,i} = {}^{0}\mathbf{F}_{i,i+1} - m_i \cdot {}^{0}\mathbf{g} \qquad (5)$$

$$\begin{aligned} {}^{0}\boldsymbol{\tau}_{i-1,i} = {}^{0}\boldsymbol{\tau}_{i,i+1} + {}^{0}\mathbf{p}_{i-1,i} \times {}^{0}\mathbf{F}_{i-1,i} - \\ - {}^{0}\mathbf{p}_{i,C_i} \times \left(m_i \cdot {}^{0}\mathbf{g}\right) \end{aligned} \qquad (6)$$

where: $i = 0 \ldots 3$ denotes the link number; ${}^{0}\mathbf{F}_{i-1,i}$ is the force applied to link i by link $i-1$; m_i is the mass of link i; ${}^{0}\mathbf{g}$ denotes the gravitational acceleration with respect to the referential frame, ${}^{0}\mathbf{g}^T = [0 \quad 0 \quad -g]$; ${}^{0}\boldsymbol{\tau}_{i-1,i}$ is the torque applied to link i by link $i-1$; ${}^{0}\mathbf{p}_{i-1,i}$ denotes the position vector from the origin of frame $i-1$ to the origin of frame i; ${}^{0}\mathbf{p}_{i,C_i}$ is the position vector from the origin of frame i centre of gravity of link i.

If we consider the external forces, ${}^{0}\mathbf{F}^T_{3,4} = [F_x \quad F_y \quad F_z]$ and ${}^{0}\boldsymbol{\tau}^T_{3,4} = [\tau_x \quad \tau_y \quad \tau_z]$, and we will proceed for the neck mechanism as mentioned above, we will find out ${}^{0}\boldsymbol{\tau}_{2,3}$, ${}^{0}\boldsymbol{\tau}_{1,2}$, ${}^{0}\boldsymbol{\tau}_{0,1}$.

Finally, we want to know what torques are needed at the joints in order to balance the reaction forces and moments acting on the links and, also, to balance the gravity forces acting on each link. All components of the force and moment vectors are resisted by the structure of the mechanism itself, except for the torque about the joint axis. Therefore, to find the torque required to maintain the static equilibrium, the dot product of the joint-axis vector with the moment vector acting on the link is computed:

$$\tau_i = {}^{0}\mathbf{z}^T_{i-1} \cdot {}^{0}\boldsymbol{\tau}_{i-1,i} \qquad (7)$$

where ${}^{0}\mathbf{z}_{i-1}$ is an unity vector, which denotes the axis of joint i with respect to the referential frame: ${}^{0}\mathbf{z}^T_0 = [0 \quad 0 \quad 1]$; ${}^{0}\mathbf{z}^T_1 = [0 \quad 1 \quad 0]$; ${}^{0}\mathbf{z}^T_2 = [1 \quad 0 \quad 0]$.

It means, the joint torques are as follow,

$$\begin{aligned} \tau_1 &= {}^{0}\mathbf{z}^T_0 \cdot {}^{0}\boldsymbol{\tau}_{0,1} = {}^{0}\tau_{0,1z} = \\ &= \tau_z + l_3 \begin{bmatrix} F_y\left(c_1 s_2 c_3 + s_1 s_3\right) - \\ -F_x\left(s_1 s_2 c_3 - c_1 s_3\right) \end{bmatrix} \end{aligned} \qquad (8)$$

$$\begin{aligned} \tau_2 &= {}^{0}\mathbf{z}^T_1 \cdot {}^{0}\boldsymbol{\tau}_{1,2} = {}^{0}\tau_{1,2y} = \tau_y - \\ &-l_3 \begin{bmatrix} \left(F_z + m_3 g\right) \cdot \\ \cdot\left(c_1 s_2 c_3 + s_1 s_3\right) - \\ -F_x c_2 c_3 \end{bmatrix} + \\ &+m_3 g \begin{bmatrix} \Delta x_3\left(c_1 s_2 c_3 + s_1 s_3\right) - \\ -\Delta z_3 c_1 c_2 \end{bmatrix} - \\ &-m_2 g\left(\Delta y_2 s_1 + \Delta z_2 c_1 c_2\right) \end{aligned} \qquad (9)$$

$$\begin{aligned} \tau_3 &= {}^{0}\mathbf{z}^T_2 \cdot {}^{0}\boldsymbol{\tau}_{2,3} = {}^{0}\tau_{2,3x} = \tau_x + \\ &+l_3 \begin{bmatrix} \left(F_z + m_3 g\right)\left(s_1 s_2 c_3 - c_1 s_3\right) - \\ -F_y c_2 c_3 \end{bmatrix} - \\ &-m_3 g \begin{bmatrix} \Delta x_3\left(s_1 s_2 c_3 - c_1 s_3\right) - \\ -\Delta z_3 s_1 c_2 \end{bmatrix} \end{aligned} \qquad (10)$$

2.4 Gravity compensation

To compensate the gravity, and consequently to reduce the required motor torque for tilting or swinging the head, the neck is equipped with helical tension springs. An analogue principle is used in the neck and torso design of the robotic head ROMAN [1].

The working principle is presented in Figure 4, based on equations (11)-(25) for the second joint (θ_2), respectively in Figure 5, based on equations (26)-(40) for the third joint (θ_3).

$$L_1(\theta_2)=\sqrt{\left[c\cdot(1-\cos\theta_2)\right]^2+(a+c\cdot\sin\theta_2)^2} \quad (11)$$

where: $L_1(\theta_2)$ is the length of the right spring in Figure 4; a is the length of the springs in equilibrium position (for $\theta_2=\pi/2$); c is the distance between θ_2 joint axis and the right spring fixing point.

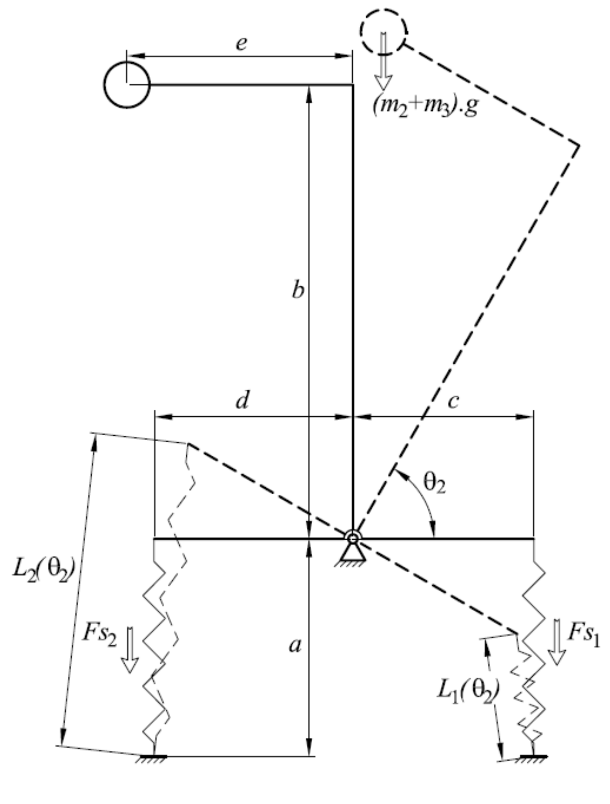


Figure 4: *Gravity compensation working principle for joint θ_2*

$$\theta_2\in\left[\theta_{2_{\min}},\theta_{2_{\max}}\right];\ \theta_{2_{\min}}=\frac{\pi}{3};\quad \theta_{2_{\max}}=\frac{2\pi}{3} \quad (12)$$

$$\Delta x_1(\theta_2)=L_1(\theta_2)-L_{1_0}=L_1(\theta_2)-L_1\left(\theta_{2_{\min}}\right) \quad (13)$$

where: $\Delta x_1(\theta_2)$ is the deformation of the right spring in Figure 4; $L_{1_0}=L_{1_{\min}}$ is the length of the right spring for $\theta_{2_{\min}}=\pi/3$.

$$\Delta x_{1_{\max}}=L_{1_{\max}}-L_{1_0}=L_1\left(\theta_{2_{\max}}\right)-L_1\left(\theta_{2_{\min}}\right) \quad (14)$$

$$k_1=\frac{\tau_G\left(\theta_{2_{\max}}\right)}{2\cdot\Delta x_{1_{\max}}\cdot c}=\frac{(m_2+m_3)\cdot g\cdot\left|b\cdot\cos\theta_{2_{\max}}-e\cdot\sin\theta_{2_{\max}}\right|}{2\cdot\Delta x_{1_{\max}}\cdot c} \quad (15)$$

where: k_1 is the elastic constant of the right spring in Figure 4; $\tau_G\left(\theta_{2_{\max}}\right)$ is the gravity torque for $\theta_{2_{\max}}=2\pi/3$; m_2 is the mass of the link 2 in Figure 3; m_3 is the mass of the link 3 in Figure 3; b is the distance between θ_2 joint axis and the robot head center of mass, on vertical direction; e is the distance between θ_2 joint axis and the robot head center of mass, on horizontal direction.

$$F_{s_1}(\theta_2)=2\cdot k_1\cdot\Delta x_1(\theta_2) \quad (16)$$

where F_{s_1} is the elastic force of the right spring in Figure 4.

$$\tau_{s_1}(\theta_2)=F_{s_1}(\theta_2)\cdot c \quad (17)$$

where τ_{s_1} is the elastic force of the right spring in Figure 4.

$$L_2(\theta_2)=\sqrt{\left[d\cdot(1-\cos\theta_2)\right]^2+(a-d\cdot\sin\theta_2)^2} \quad (18)$$

$$\Delta x_2(\theta_2)=L_2(\theta_2)-L_{2_0}=L_2(\theta_2)-L_1\left(\theta_{2_{\max}}\right) \quad (19)$$

$$\Delta x_{2_{max}} = L_{2_{max}} - L_{2_0} = = L_2\left(\theta_{2_{min}}\right) - L_2\left(\theta_{2_{max}}\right) \tag{20}$$

$$k_2 = \frac{\tau_G\left(\theta_{2_{min}}\right)}{2\cdot\Delta x_{2_{max}}\cdot d} = \frac{\left(m_2+m_3\right)\cdot g\cdot\left|b\cdot\cos\theta_{2_{min}} - e\cdot\sin\theta_{2_{min}}\right|}{2\cdot\Delta x_{2_{max}}\cdot d} \tag{21}$$

$$F_{s_2}\left(\theta_2\right) = 2\cdot k_2\cdot\Delta x_2\left(\theta_2\right) \tag{22}$$

$$\tau_{s_2}\left(\theta_2\right) = F_{s_2}\left(\theta_2\right)\cdot d \tag{23}$$

$$\tau_s\left(\theta_2\right) = \tau_{s_2}\left(\theta_2\right) - \tau_{s_1}\left(\theta_2\right) \tag{24}$$

All the notations in equations (18-24), for the left spring in Figure 4, are similar to those mentioned for equations (11-17).

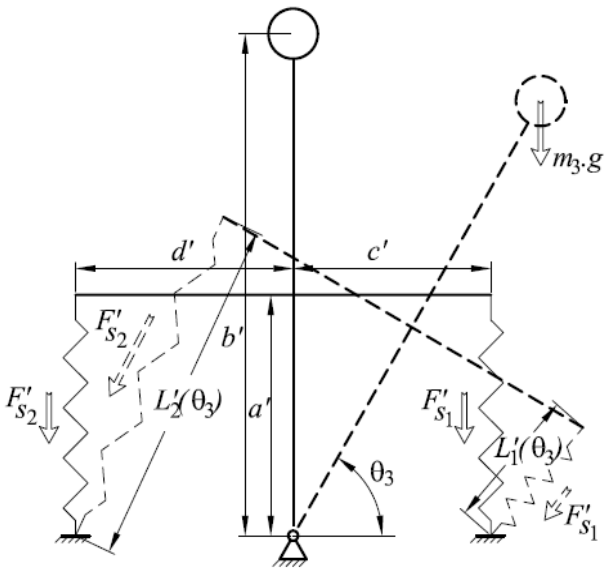


Figure 5: *Gravity compensation working principle for joint θ_3*

The resultant torque of the θ_2 joint will be:

$$\tau_{rez}\left(\theta_2\right) = \tau_G\left(\theta_2\right) + \tau_s\left(\theta_2\right) \tag{25}$$

$$L'_1\left(\theta_3\right) = \sqrt{\left[a'\cdot\cos\theta_3 + c'\cdot\left(\sin\theta_3 - 1\right)\right]^2 + \left(a'\cdot\sin\theta_3 - c'\cdot\cos\theta_3\right)^2} \tag{26}$$

$$\theta_3 \in \left[\theta_{3_{min}}, \theta_{3_{max}}\right];\ \theta_{3_{min}} = \frac{\pi}{3};\ \theta_{3_{max}} = \frac{2\pi}{3} \tag{27}$$

$$\Delta x'_1\left(\theta_3\right) = L'_1\left(\theta_3\right) - L'_{1_0} = = L'_1\left(\theta_3\right) - L'_1\left(\theta_{3_{min}}\right) \tag{28}$$

$$\Delta x'_{1_{max}} = L'_{1_{max}} - L'_{1_0} = = L'_1\left(\theta_{3_{max}}\right) - L'_1\left(\theta_{3_{min}}\right) \tag{29}$$

$$k'_1 = \frac{\tau'_G\left(\theta_{3_{max}}\right)}{2\cdot\Delta x'_{1_{max}}\cdot c'} = \frac{m_3\cdot g\cdot b'\cdot\left|\cos\theta_{3_{max}}\right|}{2\cdot\Delta x'_{1_{max}}\cdot c'} \tag{30}$$

$$F'_{s_1}\left(\theta_3\right) = 2\cdot k'_1\cdot\Delta x'_1\left(\theta_3\right) \tag{31}$$

$$\tau'_{s_1}\left(\theta_3\right) = F'_{s_1}\left(\theta_3\right)\cdot c' \tag{32}$$

$$L'_2\left(\theta_3\right) = \sqrt{\left[-a'\cdot\cos\theta_3 + d'\cdot\left(\sin\theta_3 - 1\right)\right]^2 + \left(a'\cdot\sin\theta_3 + d\cdot\cos\theta_3\right)^2} \tag{33}$$

$$\Delta x'_2\left(\theta_3\right) = L'_2\left(\theta_3\right) - L'_{2_0} = = L_2\left(\theta_3\right) - L'_1\left(\theta_{3_{max}}\right) \tag{34}$$

$$\Delta x'_{2_{max}} = L'_{2_{max}} - L'_{2_0} = = L'_2\left(\theta_{3_{min}}\right) - L'_2\left(\theta_{3_{max}}\right) \tag{35}$$

$$k'_2 = \frac{\tau'_G\left(\theta_{3_{min}}\right)}{2\cdot\Delta x'_{2_{max}}\cdot d'} = \frac{m_3\cdot g\cdot b'\cdot\left|\cos\theta_{3_{min}}\right|}{2\cdot\Delta x'_{2_{max}}\cdot d'} \tag{36}$$

$$F'_{s_2}\left(\theta_3\right) = 2\cdot k'_2\cdot\Delta x'_2\left(\theta_3\right) \tag{37}$$

$$\tau'_{s_2}\left(\theta_3\right) = F'_{s_2}\left(\theta_3\right)\cdot d' \tag{38}$$

$$\tau'_s\left(\theta_3\right) = \tau'_{s_2}\left(\theta_3\right) - \tau'_{s_1}\left(\theta_3\right) \tag{39}$$

$$\tau'_{rez}\left(\theta_3\right) = \tau'_G\left(\theta_3\right) + \tau'_s\left(\theta_3\right) \tag{40}$$

All the notations in equations (26-40), for the springs of θ_3 joint in Figure 5, are similar to those mentioned for the springs of θ_2 joint in Figure 4.

2.5 Numerical simulation

To obtain numerical simulation for the second joint (Figure 6), the following parameters have been used: the mass of the robot head $m_2 + m_3$ was estimated to 1.595 kg; the center of mass is at a distance $b = 0.12$ m with respect to joint axis; the spring constants are $k_1 = 577$, and $k_2 = 105$ N/m, respectively; the initial lengths of the springs are $L_{1_0} = 0.028$ and $L_{2_0} = 0.028$ m; the current length of the springs, $L_1(\theta_2)$ and $L_2(\theta_2)$ are computed with the help of geometry.

In a similar way, to realize the numerical simulation for the third joint (θ_3) (Figure 7), were used the following parameters: the mass of the robot head m_3 was estimated to 1.5 kg; the center of mass is at a distance $b' = 0.12$ m with respect to joint axis; the spring constants are $k_1' = 270$, and $k_2' = 223$ N/m, respectively; the initial lengths of the springs are $L'_{1_0} = 0.028$ and $L'_{2_0} = 0.026$ m; the current length of the springs, $L'_1(\theta_3)$ and $L'_2(\theta_3)$ are also computed with the help of geometry. For simulation, external forces are neglected and $\theta_1 = \theta_3 = 0$ in (12), $\theta_1 = \theta_2 = 0$ in (13); the torque produced by the gravitational force applied on the second link is $\tau_G(\theta_2) = \tau_2$, in (28) and on the third link is $\tau'_G(\theta_3) = \tau_3$, in (43).

In our system, for each joint, two identical springs are mounted on each side. For a first estimation of the torques, only in the third joint, and considering small angles ($\theta_3 = -30°...30°$), it can be considered that the springs axes remain always parallel to the link axis. If the set of spring pairs are well dimensioned, the required torque around the motor shaft is reduced to approximately the torque introduced by the inertia of the head. Figures 6-7 shows the external and resulting torque on each joint, as well as the spring-generated torque, dependent on the angle θ_2 or θ_3. We have to mention that all these simulations have been done for ideal conditions: no friction in the joints; the initial (minimum) length of each spring is computed in such way that this spring is not tensed when the head is oriented (in the extreme position) to it; the elastic constant is computed from the equilibrium of the gravity and spring torques - it means, from $\tau_{rez} = 0$ condition, for the head extreme positions. In a future work, these diagrams will be determined starting from the real values of the springs parameters.

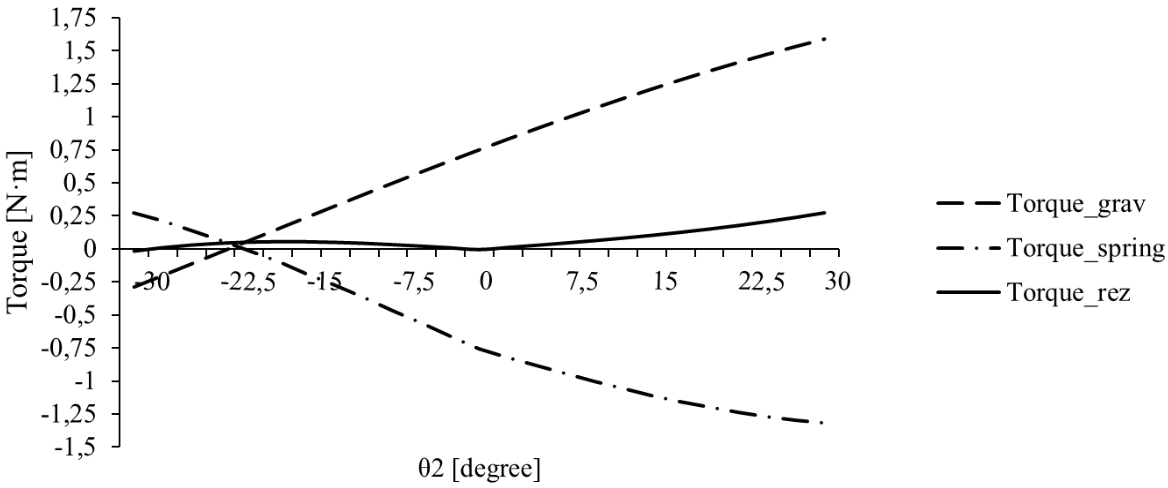


Figure 6: *Torques diagrams for joint θ2*

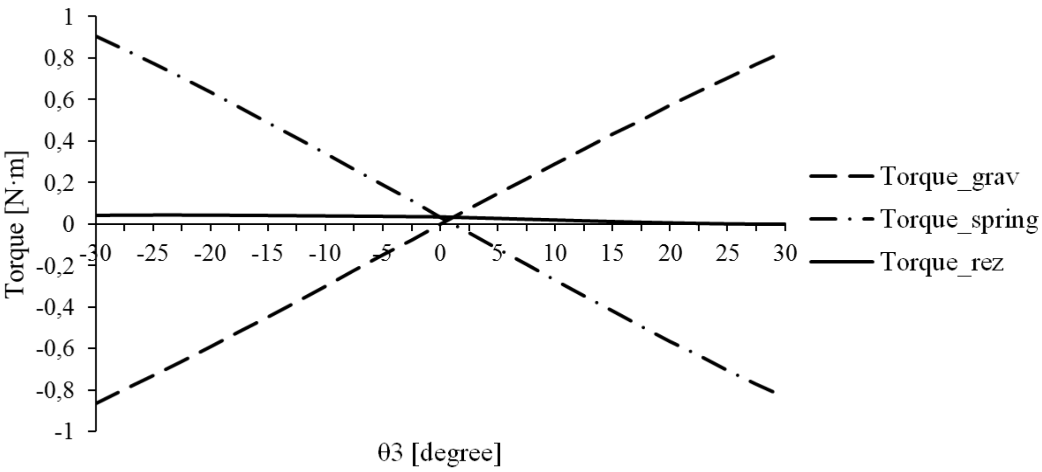


Figure 7: *Torques diagrams for joint θ3*

Summary

In this paper, the conceptual design and the mathematical model, in terms of direct and inverse kinematics and static effects, of the mechanism used for the neck of a social robot is presented. To apply the static balancing of mechanisms (gravity compensation), the neck was equipped with helical tension springs. If the set of spring pairs are well dimensioned, the required torque around the motor shaft is reduced to approximately the torque introduced by the inertia of the head. To outline this idea, numerical simulations for the second and the third joint were realized, without/with gravitational compensation, useful also in the estimation of the neck's motor torques.

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