

Eyes and Neck Kinematic Model Analysis with Limited Human Gestures

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Abstract— Human emotions such as happiness, sadness, despair, amazement among others are produced by the limbic system which causes the movement of the facial muscles as a result of those emotions. In the realization of Rudolf, the animatronic, was considered, the simulation, interpretation and imitation of human movements of eyes, neck and mouth, in order to respond immediately to the emotions of the human being. Each of these movements were analysed kinematically and dynamically by the Denavit-Hartenberg matrices. In order to imitate the facial gestures of a human, the dynamics of the eyes, their degrees of freedom (DOF), as well as the neck and lower jaw, were physically analysed in order to perfect the imitation of a human being. On the other hand, the neural system of real-time image storage, activation of actuators and facial recognition was made through programming in Python and decoding with the Raspberry Pi Hardware.

Keywords— Denavit-Hartenberg, kinematics, dynamics, DOF, neuronal system.

I. INTRODUCTION

The design and creation of humanoid robots is born mainly from the idea of improving existing methods for human-robot interaction (HRI); most robots that are seen today are used in industrial manufacturing and automation, however the idea of large companies is to start producing and distributing robots with interaction capacity (HRI).

When we talk about humanoid or social robots, we talk about robots that can mimic or make human movements, such as facial expressions, eye movements, neck movements, among others. The idea of these robots (HRI) is that they can interact and communicate as if they were human, this following a set of social rules that are previously established. Different studies have shown that making a mechanical design of a robot with social skills increases empathy and the level of acceptance of humans towards the robot [1][2]. To create a favourable design, a humanoid robot must have several aspects to consider in mechanics, but not only that should consider, but also emotional interaction, due to the high level of complexity to develop mechanisms and algorithms that allow interaction.

To develop this type of mechanisms it's necessary that the robot has a hardware connected to peripherals (sensors) where it can obtain information from the environment, a clear example is the movement of the eyes when recognizing facial faces. It is necessary to obtain the information of the aperture value in degrees of the eyes. To mechanically design the operation of the system, the data is acquired through a development card that in turn involves the rest of the facial mechanisms. To develop this type of mechanisms it's necessary the robot has a hardware connected to peripherals (sensors) where it can obtain information from the environment, a clear example is the

movement of the eyes when recognizing facial faces. It obtains the necessary information of the aperture value in degrees of the eyes. To mechanically design the operation of the system and the data is get through a development card that in turn involves the rest of the mechanisms. After developing the mechanisms, the following approach is done with the HRI, which consists an interactive system that helps improve the "affective" scenario with humans. The system can mimic gestures or some basic facial movements in order to increase empathy and acceptance with the human. There are two main contributions to this work. The first contribution is a new design for robotic humanoid head, this platform is equipped with actuators that allow movement and interaction with people in real situations. In addition, the humanoid head has an audio system that allows voice-to-voice communication between human and the robot. [3] As a second contribution, the robotic humanoid head is designed to a range of movements, where most of them are associated with the human's natural expressions.

The eye is the organ of the sight that enables visual perception of the environment. Eyes are provided over 80% of the environment perception. The main elements of the eye are the eyeballs, the optic nerve and sensory centers – Figure 1. The eyeball, due to its structure, dioptric system and neuroepithelial elements of the retina, enables receiving visual stimulus. Visual pathways connect the retina with visual centers in the brain. Thus visual stimulus created on the retina, is transmitted to the appropriate centers of the brain cortex where it is interpreted. [4]

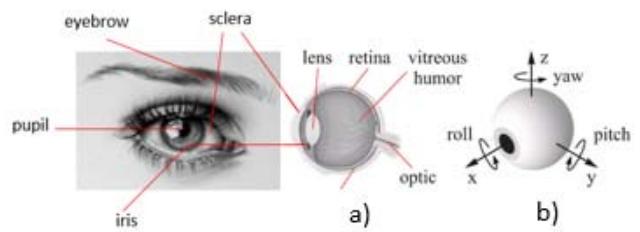


Fig. 1. The structure of the human eye (a) and eyeball movements (b).

There are four basic types of simultaneous eye movements. The most common are saccades movements that enable rapid respectively ballistic movements of both eyes between fixation points – the angular velocity of these movements is $400 \div 800^{\circ}/s$.

Smooth pursuit movements are slow and gently eye movements for tracking objects in motion – the maximal angular velocity of these movements is $30^{\circ}/s$. Vergence movements enable the movement of both eyes in the opposite directions respectively focusing of the object – the interval of angular velocity is $30 \div 150^{\circ}/s$. Vestibule-ocular movements are reflex movements to stabilize the image

caused by sudden head movements – the maximum angular velocity of these movements reaches $800^{\circ}/\text{s}$ [8]. In addition, the average duration for a single blink of eye is $0.1 \div 0.4$ s. [9] [11]

II. MODEL AND DESIGN

A. Initial prototype

In the search for the perfect imitation of the gestures, each movement was verified through direct kinematics, this prevented the measured error percentages from being greater than those calculated. This first phase was carried out with the physical model of the head of a dummy to relate the scales of the part of the skull with respect to the eyes and the lower jaw with respect to the height of the neck showing in figure 2.



Fig. 2: (Right.) Isometric view of Rudolf. (Left) Left Side View of Rudolf. Made in Solid Word CAD simulation software.

B. Final prototype

Both the physical and neuronal structure (Software) were carried out considering the limitations of the opening and closing angles of the joints, the maximum speeds of the actuators according to the gesture type to be imitated and the maximal torsion forces for system actuators. The finally phase represents the animatronic it as machine capable of sharing dialogues with a human being showing in figure 3.



Fig. 3: (Right.) Front View of Rudolf. (Left) Isometric View of Rudolf. Made in Solid Word CAD simulation software.

III. SYSTEM CONTROL REPRESENTATION

The kinematic diagrams were made by means of the representation of ocular joints with cylindrical diagrams and central points of rotation and position. As the two eyes are linked by a single axis of movement, the study was conducted with the inflection angles of a single eye in order to reduce the kinematic equations and analyse their dynamic behaviour. [5] [6]

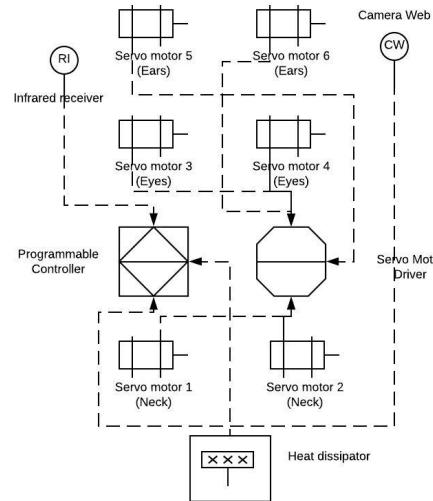


Fig. 4: Control diagram P&ID of the Rudolf project the animatronic.

Figure 4 shows the representation of the system by means of P&ID diagrams, in which the connection of each element to the peripherals of the development card is shown. The system consists of 6 servomotors, 1 infrared receiver, 1 development card (microcontroller) and 1 webcam. [7]

IV. KINEMATIC REPRESENTATION

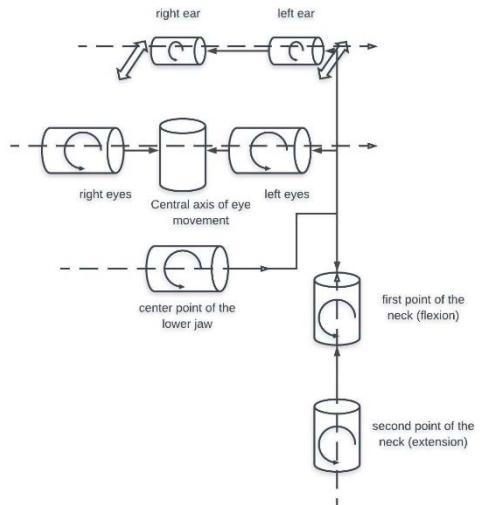


Fig. 5: Kinematic representation of each joint in Rudolf the animatronic. Joints represented cylindrically with each of its inflection points.

In Figure 5, each actuator is represented by a type of cylinder, as well as the eyes, neck and mouth as animatronic dynamic system. This diagram is made to facilitate the analysis of it.

A. Abbreviations and Acronyms

HRI, human-robot interaction
DOF, degrees of freedom
D-H, Denavit-Hartenberg

B. Units

In this article, the international system of units is used for mathematical calculation for D-H matrices.

C. Equations and analisys of dates

The figure 6 shows the kinematic scheme of the eyeball management system that was used, this is a plane and space mechanism, thanks to the structure of the links, the mechanisms can work independently. In this system, or it's used as the geometric center and the axes x_e, y_e, z_e .

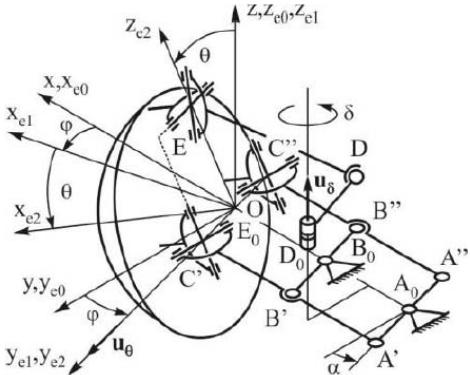


Fig. 6: Kinematic representation of each joint for a single eye. The reference is made that there are two equal eyes with the same study parameters.

Angle α is an input parameter and represents the rotation of lever $A'A''$ about the point A_0 . Four-bar linkages are of the parallelogram configurations, so $A_0A' = B'B_0$ and $A_0A'' = B''B_0$. In addition $A_0A' = A_0A'', B'B_0 = B''B_0$, $A'B' = A''B''$ and $C'B' = C''B''$. Spatial mechanism represents a four-bar linkage of RSCR configuration. The input link is a lever D_0D which is by a cylindrical joint connected to an immovable link in the point D_0 . Lever D_0D performs a rotation by angle δ about an axis whose unit vector is u_δ .

Although the eyeball movements are performed simultaneously, in order to form the kinematic equations, they are considered separately. Geometric and input kinematic parameters $\alpha(t), \dot{\alpha}(t), \ddot{\alpha}(t)$ and $\delta(t), \dot{\delta}(t), \ddot{\delta}(t)$ are known. First, the eyeball movements in the direction of adduction/ abduction are analyzed determining the output parameters $\varphi(t), \dot{\varphi}(t), \ddot{\varphi}(t)$. When lever $A'A''$ rotates about a point A_0 by angle α , then local coordinate system moves from the initial position $Ox_{e0}y_{e0}z_{e0}$ into the position $Ox_{e1}y_{e1}z_{e1}$. Thereby the position of point E does not change. The position of points C' and C'' is determined by the position of vectors c' i c'' , respectively:

$$c' = (-\overline{A'A_0} \sin \alpha, \overline{A'A_0} \cos \alpha, 0) \quad (1)$$

$$c'' = (-\overline{A''A_0} \sin \alpha, \overline{A''A_0} \cos \alpha, 0) \quad (2)$$

Given that $A_0A' = A_0A''$, eyeball performs a rotation about the z axis. Rotation angle of the eyeball φ is equal to the angle α , so that:

$$\varphi = \alpha, \dot{\varphi} = \dot{\alpha}, \ddot{\varphi} = \ddot{\alpha} \quad (3)$$

Now, the eyeball movements are observed in the direction of elevation/depression determining the output parameters $\theta(t), \dot{\theta}(t), \ddot{\theta}(t)$. Unit vector of the y_{e1} axis is u_θ . Position of the point D is defined by the vector:

$$d = [R_{\delta,u_\delta}](d_s - d_0) + d_0 \quad (4)$$

where:

d_0 = position vector of immovable point D_0 ,

d_s = position vector of point D in initial position ($\delta = 0$), and $[R_{\delta,u_\delta}]$ - axis rotation matrix, rotation δ about an axis $u_\delta = (u_{\delta x}, u_{\delta y}, u_{\delta z})$, see appendix.

Rotation angle θ of eyeball is determined according to:

$$\theta = 2 \arctan \left(\frac{-b + \sqrt{a^2 + b^2 - c^2}}{c - a} \right) \quad (5)$$

Where:

$$a = (d - e_0)^T [I - Q_{u\theta}](e_s - e_0) \quad (6)$$

$$b = (d - e_0)^T [P_{u\theta}](e_s - e_0) \quad (7)$$

$$c = (d - e_0)^T [Q_{u\theta}](e_s - e_0) \dots$$

$$\dots + \frac{1}{2}(d_s - e_s)^T (d_s - e_s) \dots$$

$$\dots - \frac{1}{2}(d - e_0)^T (d - e_0) \dots$$

$$-\frac{1}{2}(e_s - e_0)^T (e_s - e_0). \quad (8)$$

where:

e_0 = position vector of immovable point E_0 ,

e_s = position vector of point E in initial position ($\delta=0$),

I = unit matrix 3x3, and $[Q_{u\theta}]$ and $[P_{u\theta}]$ - corresponding matrixes, see appendix. Position vector of point E is determined according to:

$$e = [R_{\theta,u_\theta}](e_s - e_0) + e_0 \quad (9)$$

where:

$[R_{\theta,u_\theta}]$ = axis rotation matrix, rotation θ about an axis $u_\theta = (u_{\theta x}, u_{\theta y}, u_{\theta z})$. Velocity of point D on the input link DD_0 is:

$$\dot{d} = \dot{\delta}[P_{u\delta}](d - d_0) \quad (10)$$

where:

$\dot{\delta}$ = angular velocity of the input link DD_0 , and $P_{u\delta}$ corresponding matrix, see appendix.

Angular velocity of the output link EE_0 is:

$$\dot{\theta} = \frac{(d)^T(d - e)}{(d - e)^T [P_{u\theta}] (e - e_0)} \quad (11)$$

Velocity of point E on the output link EE_0 is:

$$\dot{e} = \theta [P_{u\theta}](e - e_0). \quad (12)$$

Acceleration of point D on the input link DD_0 is:

$$\ddot{d} = \{\ddot{\delta}[P_{u\delta}] + \dot{\delta}^2[P_{u\delta}][P_{u\delta}]\}(d - d_0) \quad (13)$$

where:

$\ddot{\delta}$ = angular acceleration of the input link DD_0 . Angular acceleration of the output link EE_0 is:

$$\begin{aligned} \ddot{\theta} &= \frac{(d - e)^T \{\ddot{d} - \dot{\delta}^2[P_{u\theta}][P_{u\theta}](e - e_0)\}}{(d - e)^T[P_{u\theta}](e - e_0)} \\ &\dots + \frac{(d - e)^T(\dot{d} - \dot{\epsilon})}{(d - e)^T[P_{u\theta}](e - e_0)} \end{aligned} \quad (14)$$

V. ANALYSIS OF RESULTS

A. Analysis of equations

Figure 7: showing the free body diagram and representation of the movement vectors of the neck and eyes. The ocular drive system was analysed with 7 DOF. This system consists of: 2 driving eyeballs, as well as for the ears with 2 DOF. [12] The control system consists of two flat mechanisms identical to the independent movements of the eyeballs on the axis. In accordance with the kinematic parameters of the robot's eyes, neck and ears drive systems (positions, speeds and accelerations are present), the use or installation of a camera on the top of the head is given as a solution. The camera has the function of manufacturing an artificial vision of the robot. The eyes in conjunction with the robot's ears are of paramount importance for the imitation of facial gestures with humans, therefore, the DH kinematic matrices resulted in the upper actuator (servo motor) of the eyes (up-down).) must have a maximum opening degree of 30 degrees, in the same way that the lateral actuator (servo motor) (right - left) has a maximum opening degree of 40 degrees. With respect to the neck joint, to flex and extend the head, these maximum opening degrees did not exceed 130 degrees for flexion and 140 degrees for extension.

B. Movement of the neck

Without a doubt, the degrees of movement of the neck imitate almost perfectly the human neck. The speeds of displacement as well as the angular velocities of the eyes, neck, ears and mouth are adjusted automatically by means of the entrance of the cinematic equations to the Programming Software (Python - Matlab). The animatronic is facial recognition was performed through interpretations of skin tightening patterns and volume change of the face. The mouth is next improvement for the easy handling of speech with respect to the lips.

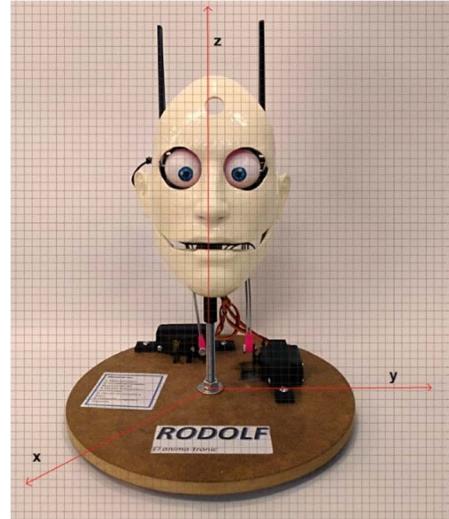


Fig. 7: Animatronic workspace. Free body diagram and representation of the movement vectors of the neck and eyes.

Eye movements should be as natural as possible, and it is therefore accepted that their duration should not be longer than 0.2 s. Considering the fact that eye movements are a fast and reversible action. [10]

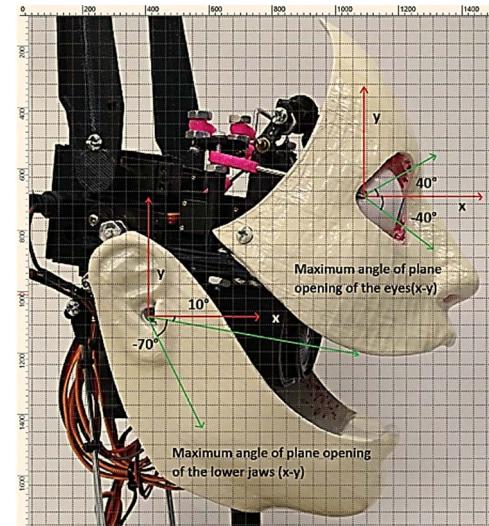


Fig. 8: Maximum and minimum angles of the movement of the eyes on the X-Y plane and representation of the movement of the neck (flexion and extension). Measurement values in 1:1 scale.

Figure 8 shows the maximum and minimum values for the movement of the eyes on the side view of the face. The practical study resulted in a lower inclination to simulated values in the CAD. The degrees of the eyeballs on the horizontal axis was 40 degrees of elevation and depression represented in figure 9.

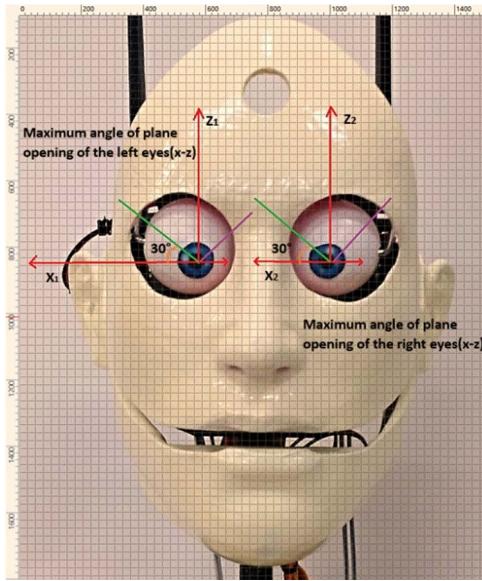


Fig. 9: Maximum and minimum angles of the movement of the eyes on the X-Z and Y-Z planes. Measurement values in 1:1 scale.

This trajectory allows the simulation of a mechanical system without the appearance of a shunt in the neutral. Table 1 shows the input kinematic parameters of the left and right eye. Based on the kinematic analysis [1] [8] and all the input parameters, the motion simulation of the eyeball management system is performed using the MATLAB and Excel software.

Figure 10, for the total movement of the eyeball in the direction of elevation / depression, which equals 70° , the maximum angular velocity is $140 \text{ }^\circ/\text{s}$.

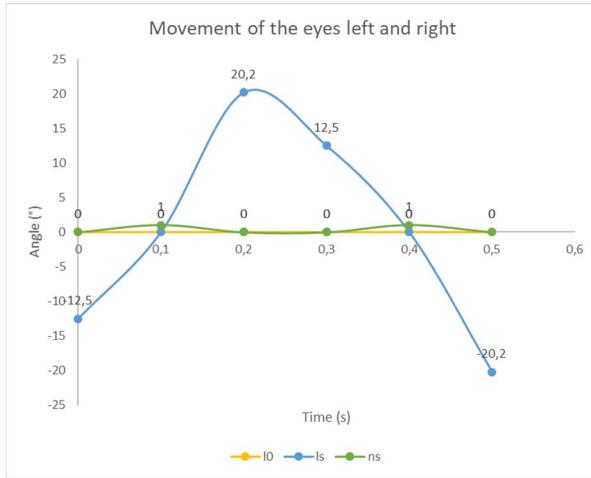


Fig. 10: Input kinematic parameters of the left and right eye. Notation: k0 – position vector point K0, ks – position vector of point K in initial position ($\lambda = 0$) and nλ – unit vector of axis λ.

Figure 11, in the initial position, the eyeball rotates -50° around the Y axis - angle ξ . For the total movement of the eyeball in the direction of abduction / adduction, it is 30° , the maximum angular velocity is $145 \text{ }^\circ/\text{s}$.

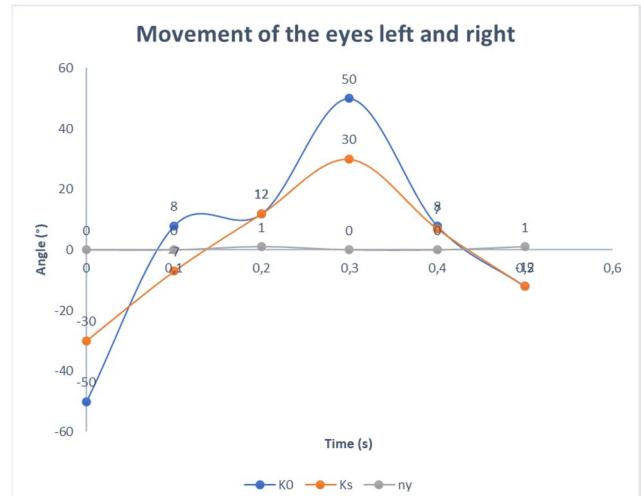


Fig. 11: Input kinematic parameters of the left and right eye. Notation: k0 – position vector point K0, ks – position vector of point K in initial position ($\lambda = 0$) and nλ – unit vector of axis λ.

Figure 12, the initial position of the jaw opens 70° around the Y axis - angle ξ . For the total movement of the jaw in the opening and closing direction is 40° , the maximum angular speed is $105 \text{ }^\circ/\text{s}$.

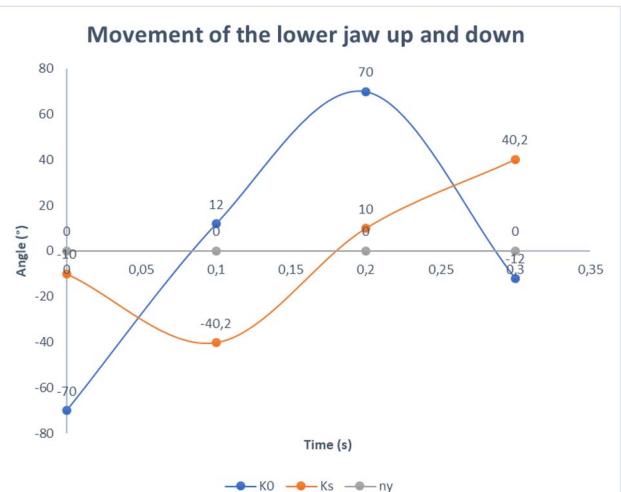


Fig. 12: Input kinematic parameters of the left and right eye. Notation: k0 – position vector point K0, ks – position vector of point K in initial position ($\lambda = 0$) and nλ – unit vector of axis λ.

Figure 13, the initial position of the jaw closes at 15.7° around the Y axis - angle ξ . For the total movement of the jaw in the opening and closing direction is 40° , the maximum angular speed is $105 \text{ }^\circ/\text{s}$.

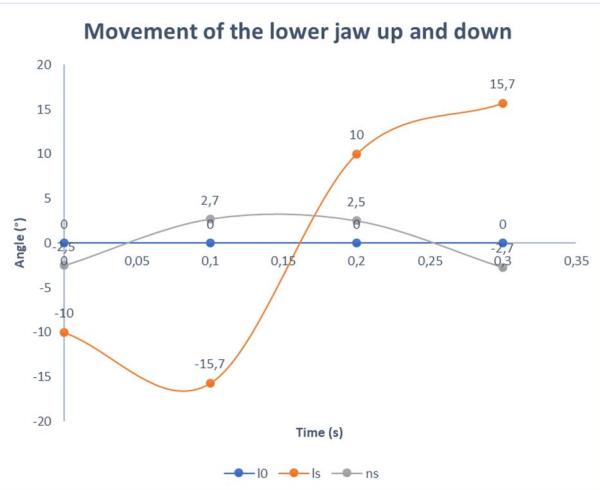


Fig. 13. Input kinematic parameters of the lower jaw up and down.
Notation: k₀ – position vector point K₀, k_s – position vector of point K in initial position ($\lambda = 0$) and n λ – unit vector of axis λ .

Table 1 is made with kinematic values for the left and right eyeball.

Vector	Eyeball left			Eyeball right		
	Coordinates [mm]			Coordinates [mm]		
	x	y	z	x	y	z
K ₀	-50	8	12	50	8	-12
K _s	-30	-7	12	30	7	-12
n _y	0	0	1	0	0	1
I ₀	0	0	0	0	0	0
I _s	-12,5	0	20,2	12,5	0	-20,2
n _s	0	1	0	0	1	0

Table 1 showing input kinematic parameters of the left and right eye. Notation: k₀ – position vector point K₀, k_s – position vector of point K in initial position ($\lambda = 0$) and n λ – unit vector of axis λ .

Where:

- K₀ is the position vector point K₀,
- K_s –vector position of point K in initial position ($\lambda = 0$) and n λ unit vector of axis λ .

Table 2 is made with kinematic values for the movement of the jaw in opening and closing.

Vector	Lower jaw up		Lower jaw down		
	Coordinates [mm]		Vector	Coordinates [mm]	
	x	z			
K ₀	-70	12	K ₀	-70	12
K _s	-10	-40,2	K _s	-10	-40,2
n _y	0	0	n _y	0	0
I ₀	0	0	I ₀	0	0
I _s	-10	-15,7	I _s	-10	-15,7
n _s	-2,5	2,7	n _s	-2,5	2,7

Table 2 showing input kinematic parameters of the left and right eye. Notation: k₀ – position vector point K₀, k_s – position vector of point K in initial position ($\lambda = 0$) and n λ – unit vector of axis λ .

CONCLUSION

In this work the functional and structural design of the eyes, neck and mouth of a robotic head with characteristics similar to the human being was presented. The kinematics analysis was carried out by means of Denavit-Hartenberg matrices, based on this, the types of movements and ranges of the input parameters were defined with pattern recognition. In this work, an eye, neck and mouth management system with a total of 6 DOF is proposed. The eyeball displacement system has 3 DOF, which allows the rotation of both eyeballs together around the tilt axis and around the orientation axis. The proposed solution allows the installation of a camera on the front of the head. According to the requirements, a simulation of the movement of the eyeball is performed. For the range of motion corresponding to the human eye, the angular velocities of the eyeball reach and exceed the kinematic parameters of the human eye for the animatronic.

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