Kinematic Optimization of the Robot Head Movements for the Evaluation of Human-Robot Interaction in Social Robotics

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Abstract. This paper presents the simplification of the head movements from the analysis of the biomechanical parameters of the head and neck at the mechanical and structural level through CAD modeling and construction with additive printing in ABS/PLA to implement non-verbal communication strategies and establish behavior patterns in the social interaction. This is using in the denominated MASHI (Multipurpose Assistant robot for Social Human-robot Interaction) experimental robotic telepresence platform, implemented by a display with a fish-eye camera along with the mechanical mechanism, which permits 4 degrees of freedom (DoF). In the development of mathematical-mechanical modeling for the kinematics codification that governs the robot and the autonomy of movement, we have the Pitch, Roll, and Yaw movements, and the combination of all of them to establish an active communication through telepresence. For the computational implementation, it will be show the rotational matrix to describe the movement.

Keywords: 3D additive printing · Biomechanics · Human robotic interaction · Lightweight mechanical design · Computing engineering

1 Introduction

The human head, as well as the hands, is one of the most complex systems in the body when it comes to developing or reproducing movements in order to express behaviors.

The movements of the head in social communication complement the answers to questions made to social robots in a Human-Robot Interaction (HRI) environment beginning to establish the understanding of feelings and emotions with people in a non-controlled environment by identified patterns in people around of the robot [1]. This approach has three main axes X, Y and Z for Roll, Pitch and Yaw respectively, for the general coordinate system, and next to three positions of local coordinate axes for the steering angle of rotation.

M. Di Nicolantonio et al. (Eds.): AHFE 2019, AISC 975, pp. 108–118, 2020.
https://doi.org/10.1007/978-3-030-20216-3_11

All servomotors are connecting by links that allow turns in the X, Y and Z coordinates axis to generate the rotation matrices that generate 4 Degree of Freedom (DoF).

The implementation of this kinematics allows to capture more details through the fish-eye camera. This optimization is strengthened with the autonomous navigation of the robot with 2 DoF more by a base wheeled system. This structure configuration allows kinematics of rotation of the head assumed from a base that represents the neck and that allows the gesticulation by means of a screen to represents human face features to experience the human-robot interaction.

With the variation of the distances to the coordinate axes, a second optimization phase have been developed with the static posture of natural rest that the head would have in a state of semi-consciousness or sleep state of the robot, simulating in this way the communication of the robot's sleep state to the actors of the human-robot interaction. The infrastructure of social robots in the area of telepresence is beginning from an assisted communication structure, which manipulates the activity of a mobile robot. This type of robot is designing with a transport module, a communication module and graphic, audio or text interface modules. These graphic or text interfaces are housing at the level of the thorax or head, taking as reference the morphological structure of the human [2].

On the other hand, in the next optimization, we have the variation of the gravity center of the head that allows improving the appearance of the robot when rounding all external parts, obtaining an anthropomorphic aspect more acceptable and evaluated together with the telepresence and images of human-robot interaction. An asynchronous motor is using for the system motors, helping to position and rotate each point of view and vision through the integrated camera. In this context, the communication established through the graphics and texts that the interlocutor can understand of the message transmitted by the robot. The gestural theme implemented by the RobotIcon library. It contains the graphic representation of various animated facial expressions to express emotions in the robot [3]. The effective and natural communication has a limitation. The channels through people can establish interaction with the robot are only by the read or pattern identification on a display. The proxemics is establishing in the interaction, improves with the perception and it can be achieved with the reinforcement of the message transmitted.

For the stimulation of the human-robot interaction in the social area, the gestural communication of the head is implementing with the affirmative, negative answers and even a response of possibility or doubt. For the implementation of this gestural movement, a lightweight structure is developing, based on the 3D printing of PLA/ABS plastic types, which supports a crank-crank structure together with a spatial kinematic chain. This structure also has a space to house a camera for the observation and feedback register of the Human-Robot interaction. In summary, the gestural communication achieved by the movements of the head and that are recognized and interpreted by the interlocutor, will contribute to improve the natural human-robot interaction.

2 The Robot Human Interaction

For the stimulation of the human-robot interaction in the social area, the gestural communication of the head is implementing with an affirmative or negative answer and even a response of possibility or doubt as well. For the implementation of this gestural movement, a lightweight structure is developing based on the 3D printing of PLA/ABS, which supports a slider-crank mechanism together with a spatial kinematic chain. This structure also has a space to house a camera for the observation and feedback record of the Human-Robot interaction. In summary, the gestural communication achieved by the movements of the head is recognizing and interpreted by the interlocutor. It will contribute to improve the natural human-robot interaction [4] (Fig. 1).

a) b) c)

Fig. 1. MASHI Robot: (a) MASHI Robot model with arms, (b) MASHI Robot smiling, (c) MASHI visiting the main Hall at La Bobila in L'Hospitalet

3 The Design Concept

For establishing the mechanical model and control implementation, the key parts are developing the kinematics of the head. The base of the neck has the concept according the biomechanical analysis of the cervical structure. The design is proposed with the 3 servomotors in each main axis Roll (X), Pitch (Y), and Yaw (Z) to develop the structure for the support of the kinematics components on the spatial chain, getting the gestural positions of the telepresence robot (Fig. 2).

3.1 Head Biomechanics

The head is moved by 7 cervical vertebrae [5], that are connected by cartilages. Those allow them to be flexible and move freely, developing a natural movement. The joints between the cervical vertebrae are summarizing in 3 degrees of freedom based on the

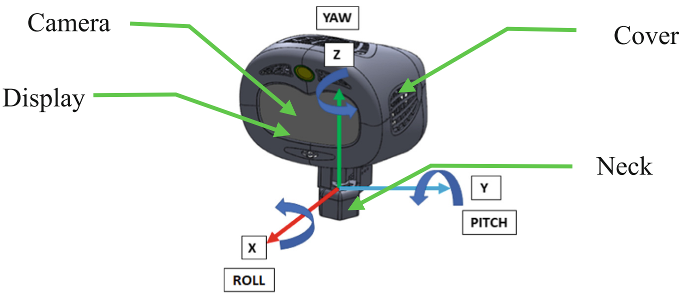

Fig. 2. 3D model of the robot head and angles roll-pitch-yaw

head. For determinate the movement limit of the head, according to the amplitudes of rotation and axis of the head movements, the positions have a gestural interpretation as the affirmation, negative and doubt or possibility answer (Fig. 3).

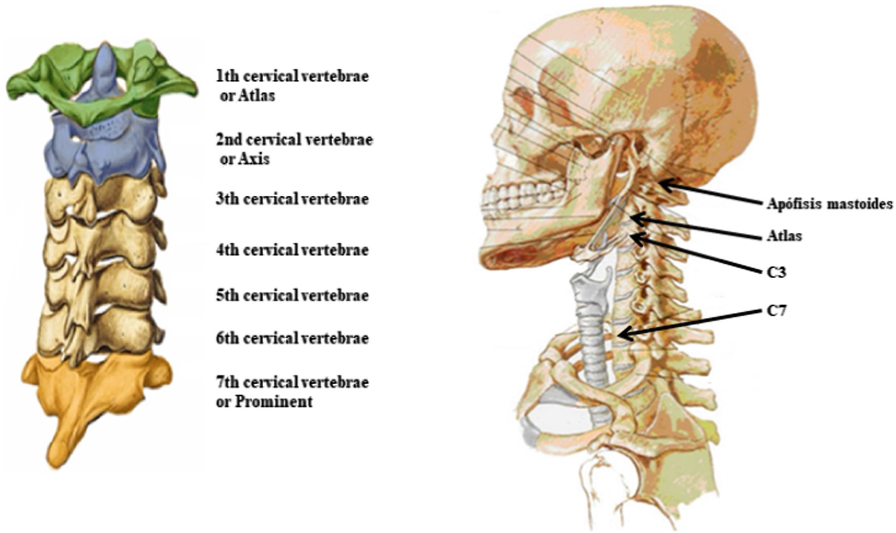

Fig. 3. Parts of the cervical vertebrae. Image modified from: https://prezi.com/-e2v7jftvwro/biomecanica-i-cabeza-cuello/

The height of the neck is approx. 120 mm and the circumference of the base is 340 mm [5] diameter, the references of the position of the head forward as a postural alteration affecting the position and amplitude of rotation in the 3 axes by the reduction of the angle of rotation that oscillates between 30–50º according to the ergonomic conditions. This postural position of the head is determined by the Vertebral Cranial Angle (CV) between the horizontal line passing through the spinous process C7 and the diagonal line that connects the spinous process C7 and the swallow of the ear [6] (Fig. 4).

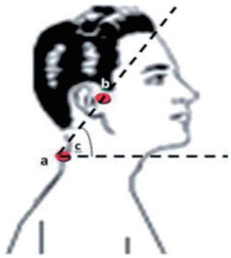

Fig. 4. Spinal Cranial Angle (CV) [6]

3.2 Design of the Neck-Head Mechanism

The kinematic of the head and neck is using on the reference of the Cranial Spinal vertebral rotation of the base of the neck and the inertial force that the center of gravity of the head makes [7]. For the simplification of the biomechanical system of rotation of the head, the distance of the turning point is short and a spatial link chain is using to develop the rotation of the head of the robot (Fig. 5).

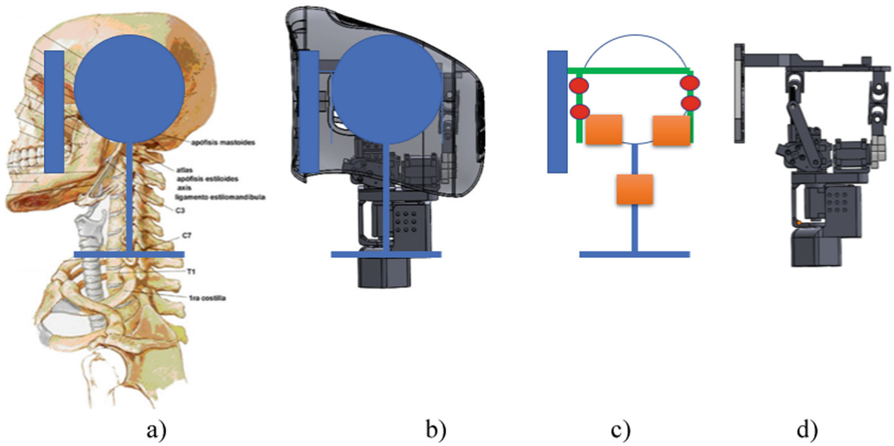

Fig. 5. Design of the mechanical mechanism: (a) Geometry definition, (b) Robot head structure (with cover), (c) structure concept of the links, nodes, servomotors and kinematics spatial chain, and (d) lateral view of the mechanisms implemented with servomotors (without cover).

The kinematics is implementing with 3 servomotors simplifying the mechanism of the spatial chain consisting of 10 links (2 virtual anchors), 5 universal nodes, 2 prismatic nodes and 2 cylindrical nodes. In accordance to the formulation of Grüber spatial you have 4 degree of freedom of positioning of the head in the main axes Roll (X), Pitch (Y), and Yaw (Z). The fourth degree of freedom allows positioning the screen on the top of the head, thus focusing the interlocutor with the robot. The responses that can be interpreted in the human robot interaction in the telepresence approach are affirmative, and denial in most cases, but the possibility response to a question is open to a position in which the movements of the 4 degrees of freedom. When this position is achieving, the universal links balance the head of the robot, resulting in the gesture of possibility as response. This classification of responses in the interaction opens a spectrum of analysis to complement the digital gesture of the face and reinforce the message sent [3, 8].

3.3 Additive 3D Printing

The characterization for the selection of the mass and density play an important role for the definition of the printing model [9]. The components of the neck and head were developing with PLA (density approx. 1.25 g/cm^3) in contrast to Aluminum (density approximately 2.7 g/cm^3). For a better stability, the printing parts and components were did with a minimum thickness of 5 mm and the rounded contours for the admission of loads of up to 1 kg. The geometry was formally developing to avoid the summation of internal tensions that could fracture the material deposited in 3D printing.

The stratification of the PLA in some parts of combined forces was strangeness with a composite based on sodium bicarbonate and an instant liquid adhesive. This combination is crystallized, strong and easy to polish with a dremel. Within the geometry, stability patterns are implementing for the mass overload to the model [10, 11] (Fig. 6).

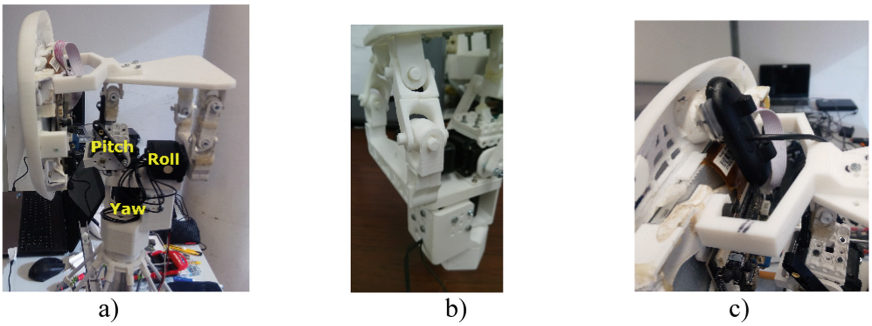

Fig. 6. 3D printing: (a) Base of the head structure (without cover) and servomotor assembly with the spatial chain, (b) Joins of the spatial chain, (c) Camera assembly [12]

The print of the parts, must be controlled by the temperature of the line deposition en each part.

3.4 Mathematic Model and Control Mechanism

For the developing of the movement of the space chain that contains the housing is subject to a servomotor that acts as a neck (axis Z0') and has a link that contains the spatial kinematic chain. The space kinematic chain contains two motors that move the universal connectors and the links. At the front, to assimilate the turn is a crank-crank system on the front. This system also helps as a pivot point between the rear motor anchor and the weight of the screen (Fig. 7).

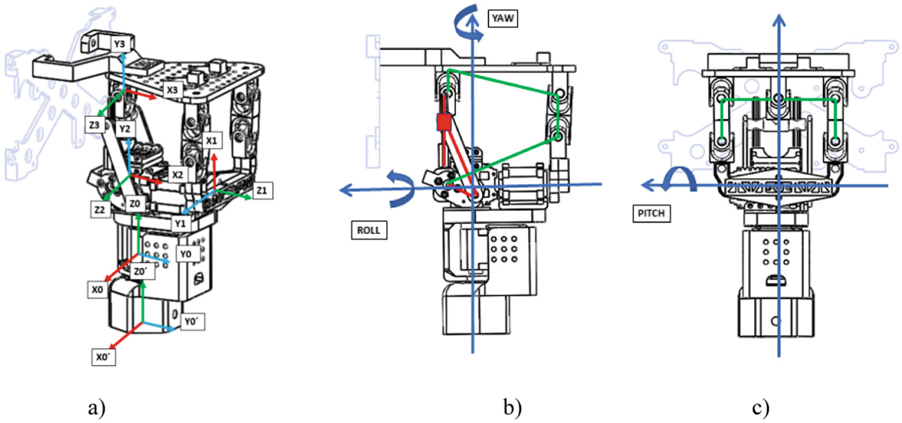

Fig. 7. 3D Model: (a) Coordinate axis, (b) & (c) Slider-crank mechanism and spatial chain wit the angles roll-pitch-yaw.

According to the rotation model of the roll-pitch-yaw angles, it describe from one rotation to another. Figure 8 gives the configuration frame of the rotation matrix (R = I), where an angle ϒ is first rotated around the X axis in the fixed frame, then the angle β is rotated around the Y axis of the frame fixed and the angle α around the Z axis.

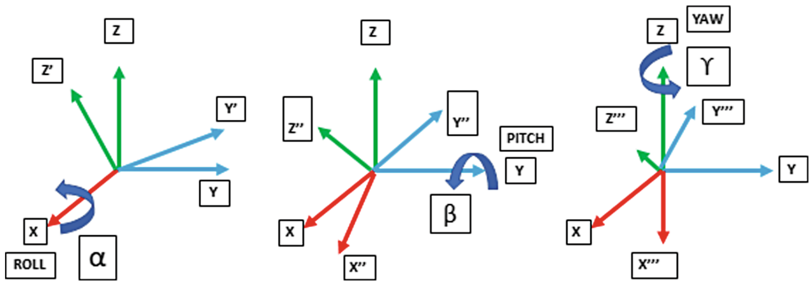

Fig. 8. XYZ roll-pitch-yaw angles.

The explicit form of a vector $\boldsymbol{v} \in R^3$ (expressed as a column vector using fixed frame coordinates) rotate about the fixed frame X-axis by an angle ϒ. The rotated vector, denoted $\boldsymbol{v}'$, is:

$$v' = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix} v \quad (1)$$

If $\boldsymbol{v'}$ is now rotated about the fixed frame Y-axis by an angle β, then the rotated vector $\boldsymbol{v''}$ can be expressed in fixed frame coordinates as

$$v'' = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} v' \quad (2)$$

Finally, rotating $\boldsymbol{v''}$ about the fixed frame Z-axis by an angle α yields the vector

$$v''' = \begin{bmatrix} \cos\propto & -\sin\propto & 0 \\ \sin\propto & \cos\propto & 0 \\ 0 & 0 & 1 \end{bmatrix} v'' \quad (3)$$

If we now take v to successively be the three unit axes of the reference frame in the identity orientation R = I, then after applying the above sequence of rotations to the three axes of the reference frame, its final orientation will be

$$R(\alpha, \beta, \Upsilon) = Rot(X, \alpha) \cdot Rot(Y, \beta) \cdot Rot(Z, \gamma) \cdot I$$

$$= \begin{bmatrix} C_\propto & -S_\propto & 0 \\ S_\propto & C_\propto & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_\beta & 0 & S_\beta \\ 0 & 1 & 0 \\ -S_\beta & 0 & C_\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_\gamma & -S_\gamma \\ 0 & S_\gamma & C_\gamma \end{bmatrix} \cdot I$$

$$= \begin{bmatrix} C_\propto C_\beta & C_\propto S_\beta S_\gamma - S_\propto C_\gamma & = C_\propto S_\beta C_\gamma + S_\propto S_\gamma \\ S_\propto C_\beta & S_\propto S_\beta S_\gamma + C_\propto C_\gamma & S_\propto S_\beta C_\gamma - C_\propto S_\gamma \\ -S_\beta & C_\beta S_\gamma & C_\beta C_\gamma \end{bmatrix} \quad (4)$$

Where the S_α shorthand for sin α, etc., and the angles α, γ ∈ [0, 2π) and β ∈ [− π/2, π/2).

To find the limits of each angle in the algorithm for computing the ZYX Angles, it must be implemented with the spatial limits of the geometry in step of 1º according the model geometry limits.

4 Evaluation of the Design: Comparison with the Human Neck

The head needs different movements possibilities to adopt the usually position to get human interaction with the interlocutor, in this way the head movement is reinforced the communication in a natural interaction [1]. The structure of the head is optimal with the spatial chain and the lightweight structure through the 3D printing. The head of the human has more degrees of freedom to coordinate the movements. In that way, the spinal cranial configuration is optimal designed with a simplification of the open chain and a spatial chain. The implementation of the servomotors gives the facilities for the integration with other systems, providing the connection possibilities and the coding with IoT elements.

5 Results

The results of the limits for the natural movements according the implementation of the start angle, was programing in steps of the servomotors code. The steps corresponding to the angle of each motor as follow (Table 1):

Table 1. Limits of the head movement for natural human robot interaction

Angle	Angle (º)
Roll	±15
Pitch	±15
Yaw	±50

For data analysis, only it took into account the recordings of six days of the zenital camera, with a total of about 480 min of recording. A single coder made the analyses of the episodes. In the results of the application of the library RobotIcon, the movements were evaluating with the following results (Table 2):

Table 2. Group characterization and spatial relationships [13]

Dimensions	Variables	Categories
Group characterization	Size	Single
		Couple
		Triple
		Larger
	Composition	Children
		Young
		Adults
		Mixed
Spatial relationships	F-formations	'Via-a-vis' (dyadic)
		'L-shape' (dyadic)
		'Circular form'
		'Horseshoe shape'
		'Side-by-side'
		'Performer-audience shape'
	Proxemic behavior	Intimate
		Personal
		Social

6 Discussion

The head has movements with translation possibilities to achieve the human-robot interaction in the space and proximity of the interlocutor, but the movement of the head without rotation, only translation has a limit in Y and Z-axis. The optional assembly of more parts will be change the inertial center, so will be change the structure and the computational implementation. Where is the limit? There is other option of head structure with translational mechanism of the neck, with more coding implementing the H-D method, but the specification needs materials with densities over 2.7 g/cm^3 [5]. The appearance of the robot is also other question about the acceptance of the group characterization. The geometry of the proxemics has different configuration of formations as well as the composition of the size of people evaluated.

7 Conclusions

In the implementation of the model, a lightweight mechanism was developing for the mechanical structure, that allow the motor and kinematics of the human head, starting with the neck characterization which in a natural way improves communication in human-robot interaction. A model based on easily acquired engines for coding and computational implementation was established. For the optimization of the model, a mechanism of four and five bars was used to assimilate the deformations of the structure, by the degrees of freedom of the spatial kinematic chain. On the other hand, there is space in one link of the kinematic spatial chain for future implementation with control circuit's elements of the robot face. Those allow us to evaluate the response to certain visual stimuli through the display of senses such as vision through the sensors as eyes. In this context, the rules of coexistence with collaborative robots are accepting in the industry and the acceptance of social robots. When they are adopting with identity? On the other hand, telepresence allows them to have an identity to the user, what is the identity of the user and robot as a unit and what kind of implications does this relationship have?

Acknowledgements. The authors would like to express their very great appreciation to L'Hospitalet City Hall and the BarcelonaTech in Barcelona, Spain for providing the research facilities used in this study. We are particularly grateful for the encouraging support of Mr. Ricardo Castro at La Bóbila Cultural Center. Assistance provided by Mr. Carlos Gómez and Ms. Rosa Almachi are also greatly appreciated.

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