Design and Simulation of a Human-like Robot Neck Mechanism

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***Abstract-* A vast range of human-friendly interactive robotic heads is being developed by researchers. However these robot heads require improvements in construction and behavior to achieve more human-like performance. Therefore this paper proposes a design of a robotic head with human-like movements. The details of the kinematic analysis, particulars on mechanical design of the neck, the electrical and control system of the robotic neck are discussed. The design parameters have been identified by analyzing the bio-mechanical information related to basic head movements of the humans. This paper includes a way to imitate human neck movements of flexion and lateral flexion. Design of this robotic neck platform is done in such a way that it can be used as a platform for facilitating further developments in integrating more additive features to a robotic neck, which are to be incorporated as per needed by any developer.**

Keywords—robot neck mechanism; human biomechanics; robot kinematics; mechanical design

I. INTRODUCTION

Developing robots which can interact with humans with a close resemblance to human to human interactions has been an area of major interest for quite some time [1-7]. Through excessive research and analysis, many robotic heads have been developed around the world, each of which possesses human like interactive features to some degree [8-10]. Despite the developments in features associated with robot heads, human-like performance of developed robot necks still remains a challenge.

In early stages of robot head development, robotic designers mainly focused on modelling the human neck as a joint with three degrees of freedom. This eventually resulted in artificial movements when compared with human head. Other than to that, the stability of head was compromised when making all three movements using rotational movement actuators. Control mechanism mainly took the form of controlling three separate motors associated with three rotational movements. Therefore the controlling of overall movement was a simultaneous movement of three rotations.

Fig.1 shows a common arrangement found among robot head developers when it comes to neck design.

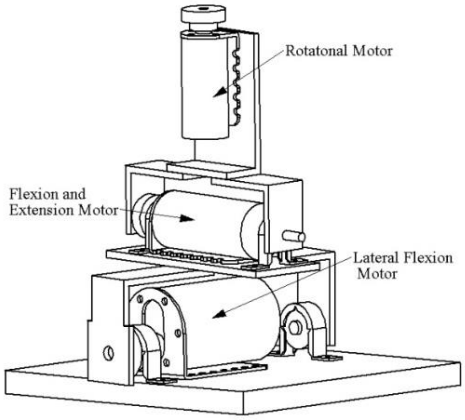

Fig.1. Modeling human neck with three motors [8].

This paper suggests a way of developing a robot neck with minimal control effort. That is to use two linear actuators or a built linear actuating mechanism which uses screws and stepper motors to overcome the complexity, stability and most importantly the closeness of neck movements to that of a human.

Following sections of this paper will discuss in detail regarding biomechanics of a human head, mapping of the modelled movement space with that of a natural head, suggested solution, control mechanism and evaluation of the design.

II. BIOMECHANICS OF HUMAN NECK

The human neck consists of seven vertebrae and it is a complex mechanical system from a kinematic point of view. The vertebrae are capable of providing flexion/extension movements, lateral flexion movement and rotational movement. Human cervical vertebrate system has been studied to identify and gather information on the natural neck motions in order to design a mechanism that is capable of appropriately reproducing movements in the neck of attentive robot head [8].

Table I indicates the extent to which, each part of the vertebrate in a human neck are utilized for different motions [11]. Here C0 is the skull and C1….C7 are the disks of cervical vertebrae. The configuration of cervical vertebrae is shown in Fig.2 [12]. Table II provides statistical data on the ranges of motion of human neck [13].

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Fig.2. Configuration of cervical vertebrae.

Usually a grown human being has a cervical vertebrae of a length around 12cm. Seven disks named above are spanned over this length. Along with the muscles neck has an average circumference of 34cm. Naturally the arrangement of cervical vertebrae enables a human head to move beyond the basic three movements by relative movements between two disks. From point of view of a mechanical designer, it should also be noted that three basic movements have their own axes and origin points on neck structure.

Lateral flexion has the point of origin at the start of the neck while flexion and rotation usually initiates at a plane below the ear of human head. However the lateral flexion naturally results from more than a single origin point. It associates a proportional angular movement from top of the neck. Therefore these things should be taken into account when designing an optimum design to model human neck.

TABLE I. DEGREES OF NECK MOVEMENTS WHICH OCCURRED IN THE CERVICAL VERTEBRATE OF THE NECK [8]

Segment	Lateral Flexion	Flexion/Extension	Rotation
C0/C1	30º	10º	1.0º
C1/C2	30º		40.5º
C2/C3	12º	70º	3.0º
C3/C4	18º		6.5º
C4/C5	20º		6.8º
C5/C6	20º		6.9º
C6/C7	15º		5.4º

TABLE II. RANGES OF MOTION OF HUMAN NECK [8]

Movement		Male		Female	
		5th percentile	95th percentile	5th percentile	95th percentile
Rotation	Right	73.3º	99.6º	74.6º	108.8º
	Left	74.3º	99.1º	72.2º	109.0º
Flexion		34.5º	71.0º	46.0º	84.4º
Extension		65.4º	103º	64.9º	103º
Lateral flexion	Right	34.9º	63.5º	37.0º	63.2º
	Left	35.5º	63.5º	29.1º	77.2º

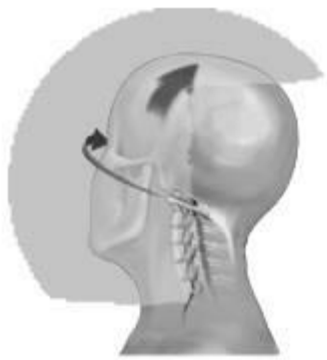

Fig.3. Movement space of a natural human neck.

III. DESIGN OF NECK MECHANISM

Natural human head is a joint of 3 degrees of freedom subjected to above limitations in movements when it comes to each individual movement.

Movement space of a natural human neck is shown in Fig.3. It is observable that the Movement space is a result derived from limitations associated with each movement. Mechanical design of robot neck should be able to cover the Movement space of a natural human neck. Therefore before going deep into the design aspects and controlling mechanism of designed robot neck, its Movement space is mapped using MATLAB as given in Fig.4.

According to the two movement space mappings shown in Fig. 4, mechanical design was made to cover almost every possible movement space point inside the natural human neck movement space.

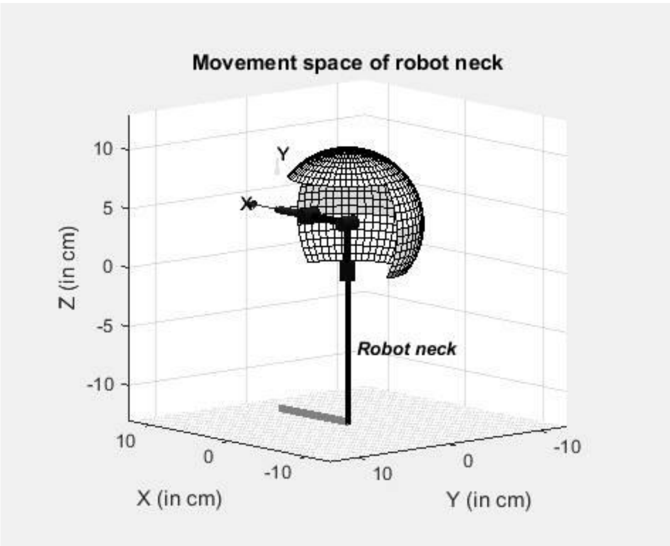

Fig.4. Movement space of designed mechanism.

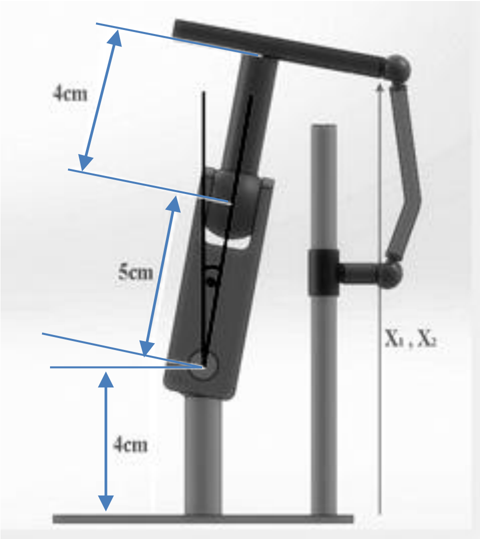

Fig.5. Design of neck mechanism.

IV. Solution and Control Mechanism

The side view of the newly designed neck is shown in the Fig.5. Lengths as shown in the Fig.5 have been selected after studying the natural human neck and its movements as discussed previously. The new design was required as the initial neck had some drawbacks such as failure of moving the head in all degree of freedom simultaneously as the head was unable to doing both flexion and lateral flexion simultaneously. As in the previous design shown in Fig.1, there were two separate motors to implement flexion and lateral flexion and those two motors were unable to control simultaneously, the neck was unable to perform those two mentioned movements simultaneously. As a result, movements of the robot head were not humanlike as some movements that human neck performs are combination of those two movements. Another drawback was that its movements were not smooth as the smallest movement that motors implement flexion and lateral flexion can perform typically falls into range of 3°.

The concept behind new neck design that could give a solution to the above mentioned drawbacks is to use a “Neck joint”, a dual pivoted joint that has two degrees of freedom. The neck joint is shown in the Fig.7. A 3D view of implemented neck mechanism is shown in Fig.6.

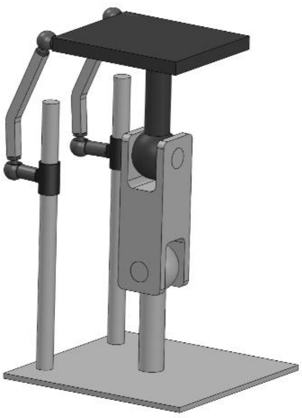

Fig.6. Neck Mechanism.

Fig.7. Neck joint.

The movements of the “Neck joint” can be perform by using two leadscrews and two stepper motors (with low step angle) for the operations of movements in roll and pitch of the head. The use of two screws and two stepper motors can also be replaced by two linear actuators.

When using leadscrews and stepper motors method,neck movements can be achieved with reduced play as it consist of screws. This enables the arms to give a higher holding torque. When both the stepper motors rotating in same speed and same direction the neck can perform flexion. And when motors rotating in opposite direction in the same speed it can achieve movement of lateral flexion. Therefore it can be used to easily achieve the required simultaneous movement by combining the above mentioned main two movements. Fig.8 shows a simulation window when the designed neck mechanism perform a flexion.

Play of the robot head can be easily taken to a minimum with the linear actuators. The Flexion only can be achieved when both the actuators move upwards or downwards with same speed. And when both actuators move with same speed in opposite direction, lateral flexion can be achieved. By combining the movements of above mentioned main two movements, the simultaneous movement can be achieved and hence neck can performs its movements more humanlike. Fig.9 shows a window of simulation where the designed neck mechanism performs lateral flexion.

Fig.8. Performing Flexion.

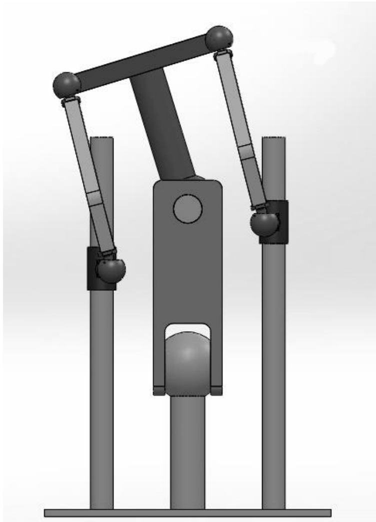

Fig.9. Performing Lateral Flexion.

Therefore the use of above two approaches can answer the drawbacks of most of the previous designs. Forth mentioning design is associated with the two screws and two stepper motors method as stepper motor has a holding torque which was not there in the linear actuators. Holding torque is a much necessary factor as the robot head may move under the gravity and it may give non-humanlike appearance to the robot. Another obvious reasons to go with the stepper motor method were that linear actuators being more expensive and stepper motors having a greater controllability. Suggested method of controlling through leadscrews and a stepper motor is shown in Fig.10.

The design was modeled in 'Solidworks 2014' and the Fig.11 shows the serious of snapshots taken when the flexion is performed by the model.

Another main concern regarding controlling the robot neck was to develop a control algorithm for this neck. Controlling is taken as seen from the point of view of "Robot head plate".

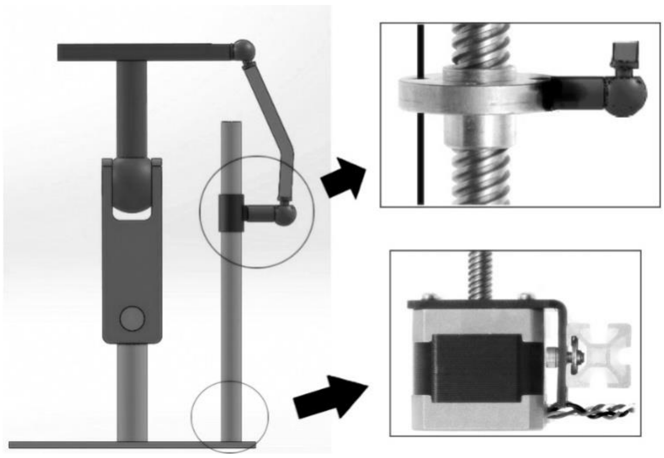

Fig.10. Use of leadscrews and stepper motor.

Fig.11.Solidworks model performing flexion.

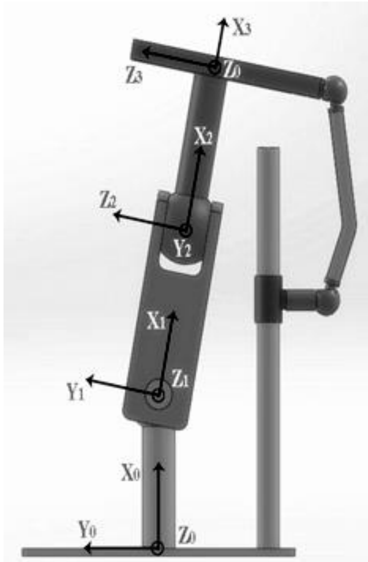

Fig.12. Coordinates systems along 'neck joint'.

Coordinate frames were named according to the diagram and top center position of head plate is taken as coordinate frame number 3. Fig.12 shows the defined axes for purpose of analyzing mechanical model. In order to have control, the location of the center of robot head plate should be known with respect to the base frame (i.e frame number 0) and its final position with the angles θ_1 and θ_2. Here θ_1 is taken as the rotation angle of the frame 1 and θ_2 is taken as the rotation angle of the frame 2.

Therefore the easiest method to find its position is deriving parameters through "D-H Parameters method". In the D-H Parameters method, the transition matrix from (i-1)th frame to ith frame is as follows,

$^{(i-1)}T_i$ =

$$\begin{bmatrix} \cos\theta i & -\sin\theta i & 0 & \alpha(i-1) \\ \sin\theta i \text{ x } \cos\alpha(i-1) & \cos\theta i \text{ x } \cos\alpha(i-1) & -\sin\alpha(i-1) & -\sin\alpha(i-1)\text{x di} \\ \sin\theta i \text{ x } \sin\alpha(i-1) & \cos\theta i \text{ x } \sin\alpha(i-1) & cos\alpha(i-1) & cos\alpha(i-1)\text{xdi} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where,

- α_{i-1} is the angle from z_{i-1} to z_i around x_{i-1}
- a_{i-1} is the distance from z_{i-1} to z_i along x_{i-1}
- d_i is the distance from x_{i-1} to x_i along z_i
- $\theta_i$is the angle from x_{i-1} to x_i around z_i

When the D-H parameter method is applied for this robot manipulator, following D-H Table III was arrived at.

TABLE III. DH PARAMETERS ON FRAMES OF 'NECK JOINT'

	α_{i-1}	a_{i-1}	d_i	θ_i
$^0T_1$	**0**	**L_1(4cm)**	**0**	θ_1
$^1T_2$	**-90**	**L_2(5cm)**	**0**	θ_2
$^2T_3$	**0**	**L_3(4cm)**	**0**	**0**

By using the Table III, following transition matrixes can be derived.

$$^{0}T_{1} = \begin{bmatrix} cos\theta 1 & -sin\theta 1 & 0 & l1 \\ sin\theta 1 & cos\theta 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}T_{2} = \begin{bmatrix} cos\theta 2 & -sin\theta 2 & 0 & l2 \\ 0 & 0 & 1 & 0 \\ -sin\theta 2 & -cos\theta 2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{2}T_{3} = \begin{bmatrix} 1 & 0 & 0 & l3 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Following calculation, position of robot head plate with respect to the base is given by,

$$^{0}T_{3} = {}^{0}T_{1} \text{ x } {}^{1}T_{2} \text{ x } {}^{2}T_{3}$$

$$^{0}T_{3} = \begin{bmatrix} c1 \times c2 & -s1 \times s2 & -s1 & 4 + 5c1 + 4c1 \times c2 \\ s1 \times s2 & -s1 \times s2 & C1 & 5s1 + 4s1 \times c2 \\ -s2 & -c2 & 0 & -4s1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where $C_{1=} \cos\theta_1$and$S_{1=}\sin\theta_1$

Finally this result is used to determine the respective positions of the linear actuating mechanism along the two poles. Those two positions are the input parameters needed to determine actuation requirements to take neck to a given position.

V. Evaluation of Design - Comparison with Human Neck

All possible movements of the neck can made to be imitated more human like with this design. In this design, the head plate is moved either by linear actuators or using leadscrew mechanism. The head plate is the platform on which the robotic head is fixed with the head rotation movement. The neck joint enables the lateral flexion and flexion movements of the robotic head. Fig.13 shows sub sections of this design.

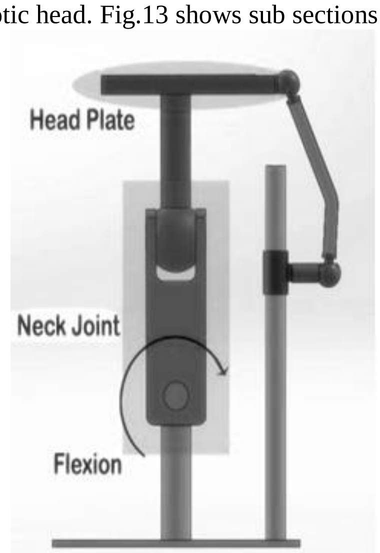

Fig.13. Final design – side view.

Attaining the actual dimensions of the human neck was a challenging task in early stages of robotic neck development. In most of the current designs, the circumference is larger than the average circumference of a natural human neck. The average actual circumference of a human neck is around 34cm. Linearactuators or stepper motors with leadscrews are used to make angular movements of the neck plate in the discussed design. Therefore in addition to the neck joint, only two leadscrews or outputs rods of the two linear actuators are placed inside the neck and hence the neck of the robot can be designed as per the actual dimensions (circumference of 34cm) of an average human neck.

As shown in Table II, 70^0 of flexion movement of the neck is achieved by the lower part of the cervical vertebrae and upper segments of the cervical vertebrae part(C0/C1/C3 discs Fig.1)carries the major influence of the lateral flexion movements. Therefore the neck joint is designed with two joints which are perpendicular to each other. Considering the configuration of the human neck, the distance between two joints was obtained to be around 5cm. The lower joint of the neck joint is used to attain flexion movement of the robotic neck while lateral flexion movement of the robotic neck is achieved by the upper joint of the neck joint.

VI. Conclusion

In this paper, the design and simulation of a human like robot neck for the purpose of smooth, simultaneous and more human like movements has been presented. This provides a natural look to the neck whilemaking it in scale with human head unlike other existing designs.

The movement space of the robot neck is resembled to the movement space of a real human neck. That is done using selecting appropriate values for the lengths of 'neck joint' discussed in the paper. In terms of control, this model has enabled the designers to control the whole neck using two linear movements which also increases the controllability and stability of design.

As a model, this provides an advanced method of building a robot neck which eliminates most of the common errors associated with existing designs. The implemented design is expected to be useful for designers of robots seeking a way to accurately and naturally display the features of a human head.

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