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Research Paper

Robotic Information System (RIS): Design of Humanoid Robot's Head Based on Human Biomechanics

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Abstract: Robotic Information System (RIS) is a new information system architecture that provides data, information processing and services for users in a wide geographical space based on intelligent robots. The front end of the RIS is a humanoid robot head that interacts with users by different means to provide different services. Developing a robot which is similar to a human shape, function and socially accepted by human beings was and is still a challenging subject. Arslan is a new humanoid robot head that has been designed to be close to real human skeletal structure, where its physical structure is designed to be identical to the real human skull, jaw and the nick vertebrae. In order to develop a high-quality and low-cost system, Arslan has a smart mechanism that is controlled by 16 servo motors in order to control its nick, jaw, eyes and facial expression, which have been located according to analysis of human biomechanics. Arslan's nick mechanism allows one side axial rotation of 41° and flexion/extension of 45°, mandible rotation around the hinge axis of 6 degrees, its eyes can rotate around their axis of motion with Adduction 19°, Abduction 34°, Supraduction (elevation) 0° and Infraduction (depression) 20°. The distance between the upper and the lower eyelid of Arslan can range from 0 up to 17 mm to cover different expressions. Also, it is equipped with devices for motion, vision, audition, smelling, and speech. It also can recognize its head tilting and is capable of maintaining its eyes' direction constantly during head motion.

Keywords: Biomechanics, Facial Expressions, Humanoid Robot, RIS

1. Introduction

Humanoid robot design and development is considered one of the most attractive scientific fields because of the scope of their applications in the current time and in the future [1, 2]. Developing a machine which is similar to a human shape and function was and is still a challenging subject because of many integrated and interrelated aspects including vision, audition, motion … etc. Basically, human-to-human interaction is done mostly using the head organ's parts. This indicates that the most important part of Human-Robot-Interaction (HRI) is to develop a robot with capabilities similar to the ones of the human head. Developing such a thing depends on 2 main factors; the shape of the robot's head and the behavior of that head. Many studies [3 – 6] have been conducted to evaluate how far robots could be socially accepted by humans, and they concluded that the robot needs to have a humanlike head shape and features in addition to humanlike behavior. In general, most humanoid robots have vision abilities, audition abilities and nick mobility; however, some humanoid robots have extra abilities such as smelling and maintaining the direction of eyes constant during head motion, have facial expression capabilities such as happiness, surprised, etc. There exist many humanoid robots, where some of them don't have facial expressions [7–11] and others have [12–15]. However, robots such as: Being Sophia [16], Geminoid DK [17], Eva [18] and Ameca [19] are more socially acceptable because of their close appearance and behavior to human beings.

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The skeleton of physical structure of all existing humanoid robots, heads and nick which are socially acceptable (according to our best knowledge) were designed as an approximate shape of a human's head and nick. However, their nick motion results in a non-realistic head motion due to differences between the robot's nick structure and the human nick structure. Some issues can also be noticed with the operation of most existing humanoid robots with facial expressions: lips' motions are not realistic while speaking, eyelids are not entirely closing during blinking and eyebrows are not moving in a realistic way, and the relatively large cost of developing those systems. Solving those issues requires analyzing their anatomy and biomechanics side-by-side with the required motion to identify the minimum number of actuators and their locations for achieving the required functional motion.

The aim of this research is to develop a new Robotic Information System (RIS) from end-to-end at low-cost where a humanoid robot head is employed to interact with humans to perform different tasks that involve information processing, such as information desk applications. The new system architecture provides data and information processing for users in a wide geographical space using many languages to ensure real-time and efficient response. Having a front-end like a humanoid robot with realistic motion and facial expressions would make the system more socially acceptable. There are a variety of fields that have been addressed in this research including design and implementation of a realistic humanoid head with human, like biomechanics and facial expression, machine vision, machine audition, artificial intelligence, data integrity and security, networking, load balancing, and interfacing with external devices. This manuscript focuses on the first part, which is to develop a humanoid robot head with more advanced behavior and smart mechanical functions for facial expressions biomechanics, which makes it more socially acceptable to human beings.

2. Experimental Methods

2.1 Robotics Information System (RIS) Architecture

With an abstract view of the new RIS, there are 3 main blocks of concern (Figure1): a humanoid robot's head (to be called Arslan), data and information processing engine (The Oracle and database server(s). Each of those blocks has been developed with some improvements to existing methods which are usually used to guarantee real-time and efficient response. The main objective of this project is to develop a network of intelligent robot heads which are identical to human shape, behavior and capabilities, and capable of communicating in many languages to help people in different aspects of life that require information processing, such as providing directions to a specific place, booking tickets, booking hotels, proposing places to visit, restaurants, lost & found ……. etc., and keep track with a user requests anywhere in a large geographical space.

Fig. 1. Robotic Information System (RIS) main blocks

This would be realized by many copies of Arslan humanoid robots, many processing engines (The-Oracle), and many database servers which are connected together using any existing network infrastructure (Figure 2).

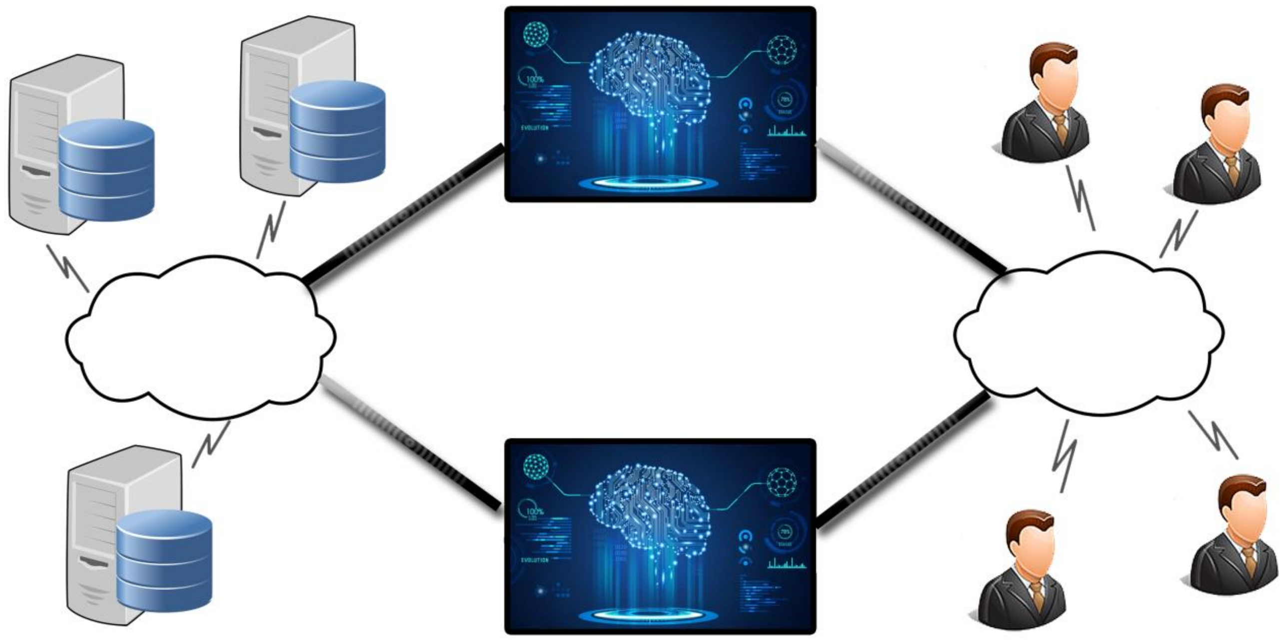

Fig. 2. RIS Network

RIS is designed to exchange data through the network at a high level of security and relatively very small in size (which will not affect the existing network performance) using optimized and abstract data processing and communication models. Many aspects such as reliability, usability, redundancy, availability … etc. (Figure 3), have been addressed in this research as well; however, this manuscript focuses on developing the front-end of the RIS which is a humanoid robot head that is socially acceptable by human beings and its biomechanics.

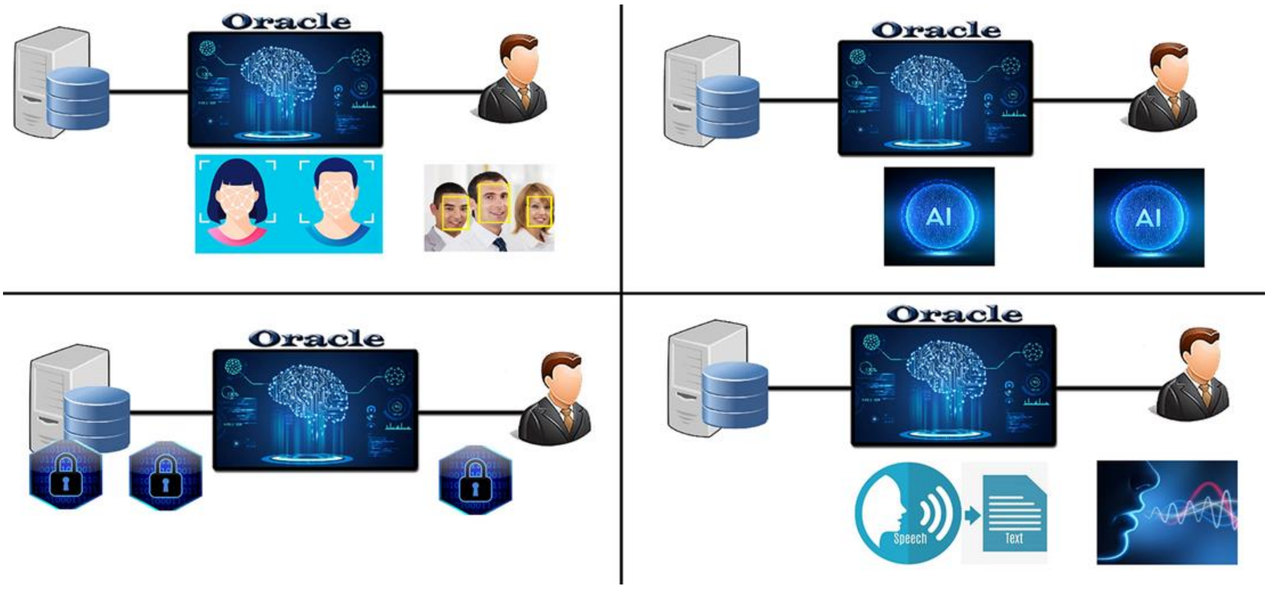

Fig. 3. The RIS Data Processing Modules (Vision, AI, Data Security and Audition)

Realistic shapes and motion of a humanoid robot depend mainly on how far its physical structure and mechanical operations are close to a human's structure and biomechanics. Arslan has been designed to be close to real human skeletal structure, where its physical structure is designed to be identical to the real human skull, jaw and the nick vertebrae. Arslan is equipped with a smart mechanism for nick motion and facial expressions which have been designed according to analysis of human biomechanics which make it close to human expressions.

A human's faces are controlled by a complex network of muscles which makes modeling of facial expressions usually done in a modular fashion obtained from image processing and/or bioelectrical signals where Arslan facial expression mechanisms have been designed in a modular fashion. In total, Arslan has 16 servo motors in order to control its nick, jaw, eyes and facial expression. Also, it is equipped with 2 cameras (one for each eye) for the binocular vision system, 3 microphones for the stereo audition system, smoke sensor, Inertia Measurement Unit (IMU), temperature sensor, and speakers. All those devices are integrated using a Raspberry Pi board for realizing vision, audition, motion, speech and artificial intelligence (Figure 4). Raspberry Pi (4 B) has already built-in communications sockets (LAN, Wi-Fi and Bluetooth) which can extend Arslan's functionality to interact with the different wired and wireless networks like other external devices such as users' smart phones.

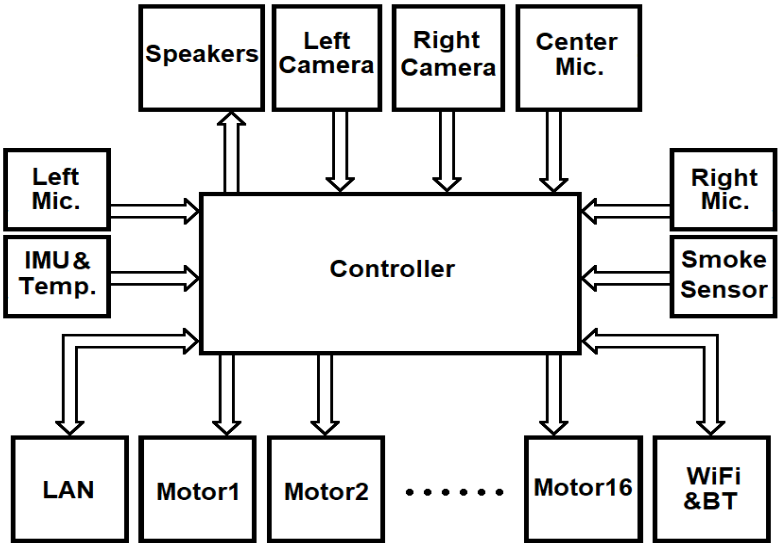

Fig. 4. Arslan's System Layout

2.2 Humanoid Robot Head's Layout

A 3D model of an anonymous human skull and jaw (mandible) [20] has been selected for constructing Arslan's skull. This skull is to be covered by a silicon mask of a real human face in order to make it more socially acceptable. Arslan's nick has been constructed using a 3D model of some vertebras of a real human spine column [21]. Those 3D models have been modified to include housings, pathways, hatches and groves in order to organize actuators, binders, speaker and sensors for Arslan's head and have been implemented using 3D printer.

2.3 Nick's Biomechanics

The human head's motion is composed of one or more than one rotation action by the nick. Accompanying head rotations, there are some displacements occurring to the head location and this is due to the nick structure. Developing a robot head with realistic motion requires designing a nick that is similar to a human's nick structure, in order to obtain a realistic motion. This feature does not exist in other humanoid robots, as they have been developed to perform rotation motions regardless of the displacement action.

The spine column is a collection of vertebrae connected by ligaments, small muscles, vertebral joints, and intervertebral discs [22]. Its structure helps in supporting the body's weight, stability and motion, in addition to protection of the spinal cord [23, 24]. The human spinal column consists of 33 vertebrae organized into 5 regions [22]: Cervical (C1 – C7), Thoracic (T1 – T12), Lumbar (L1 – L5), Sacral

(S1 – S5) and Coccyx (Co1 – Co4). A typical vertebra consists of a body and a vertebral arch, and they are able to rotate with 3 degrees of freedom [22]. Nick's skeletal structure includes the Cervical joints (Table 1) where they contribute to the head's flexion\extension, lateral bending, and axial rotation [25].

Table 1. Representative values for the ranges of rotation of the Cervical joints [25]

Ranges of Rotations of the Cervical Joints type of motion (representative angle in degrees)			
cervical joint	combined flexion/extension	one side lateral bending	one side axial rotation
C0 – C1	25	5	5
C1 – C2	20	5	40
C2 – C3	10	10	3
C3 – C4	15	11	7
C4 – C5	20	11	7
C5 – C6	20	8	7
C6 – C7	17	7	6
C7 – T1	9	4	2

There is no intervertebral disc between C1 and C2 because they are very specialized [26]. This allows the head to move forward and backward and rotate around its axis by the use of a pivot joint. During head motion, muscles contribute to different forces on cervical joints. This motion is limited by cervical joints structures and affected by intervertebral discs.

Because lateral bending does not have a significant effect on Arslan's applications scope, it has been ignored and only flexion/extension and axial rotation have been allowed. Flexion and extension have been developed to be included in all levels from C2 to T1. However, for C1-C2 axial rotation is allowed because it has the greatest impact on axial rotation and also to eliminate the conflict between flexion/extension motion and axial rotation at that level.

Arslan's cervical joints have been linked together with some elastic bands and a spring, and two servo motors have been used to control Arslan's nick; one for axial rotation and the other for flexion/extension motion.

2.4 Mandible biomechanics

Mandibular (or jaw) movement results from a combination of rotations and translations around and along its horizontal axis, frontal axis, and sagittal axis [27, 28]. Usually, the main required function of mandible in humanoid robots is opening and closing during talking, which makes rotation of the mandible around the horizontal axis be the movement in concern. This movement is also called the hinge movement, while the axis is also called the hinge axis or the temporomandibular joint's horizontal axis [28]. This rotation is on average 12°, ranging between 10 and 13°, or between 18 and 25mm incisal opening. Arslan's mandible motion is realized using one servo motor at one temporomandibular joint's horizontal motion, and the other side is supported by a pin to rotate around the hinge axis.

2.5 Ocular biomechanics

In order to build a realistic model for eyes' movement, detailed study of the ocular biomechanical system has been conducted. The eye's muscles are driving the eye to move in 6 directions: Adduction / Abduction (left and right motion caused by rotation around vertical axis), Supraduction / Infraduction (up and down motion caused by rotation around horizontal axis) Intrusion / Extrusion (twist along vision axis) [29]. According to clinical trials on healthy subjects [30], the mean angles of maximum version were Adduction 47.4°, Abduction 46.4°, Supraduction (elevation) 31.8° and Infraduction (depression) 47.8°.

To maintain the direction of eyes constant during head motion is termed as vestibulo-ocular reflex (VOR) [31]. It depends on rotations around the eyes' horizontal axis and vertical axis. Intrusion / Extrusion motion is mainly used for realignment of eye view when the head is subjected to lateral bending; however, this can be resolved in humanoid robots by using tilt sensor and matrix rotation. In binocular vision system, the depth of an object affects the vision axis as the eyes tends to converge more when the object is getting closer to them [32]. This requires making the eyes capable of rotating around their vertical axis separately. It was reported in the literature [33, 34] that the eyeball's diameter is around 24 mm (The size of a human adult eye is approximately 24.2 mm (transverse) × 23.7 mm (sagittal) × 22.0-24.8 mm (axial)) and average distance between them (Pupillary Distance) is 63 mm (majority between 58 – 70 mm).

A simple mechanism for rotating Arslan's eyes has been developed using 3 servo motors, where 2 of them are for each eye's vertical axis rotation and one motor for both eyes' horizontal axis rotation. Each eye is equipped with a camera in order to provide Arslan with binocular vision ability.

2.6 Eyebrows biomechanics

Eyebrow motion is mainly (not only) controlled by the Occipitofrontalis muscles [35] which are also causing the shrinking of the forehead. The main goal is to find the suitable location of one servo motor for each brow that allows Arslan to express some facial expressions and move its forehead realistically without complicated mechanisms. Four facial expressions (without over reacting) have been included to model Arslan's eyebrow motion, namely: normal, joy, surprise, and anger. Data of human (this manuscript author) facial expressions is used for that job, where 11 marking points which surround an eyebrow have been identified and traced for each expression. The reference point has been chosen to be the intersection between the eyes' center axis and the face's center axis in normal face expression. Nose holes have been taken as a common reference base for all images (Figure 5).

By tracing the profiles of markers, it is concluded that each one follows a semicircular path with a center point located in the upper right corner and shifts with respect to the upper profile are almost constant for each group (Figure 5).

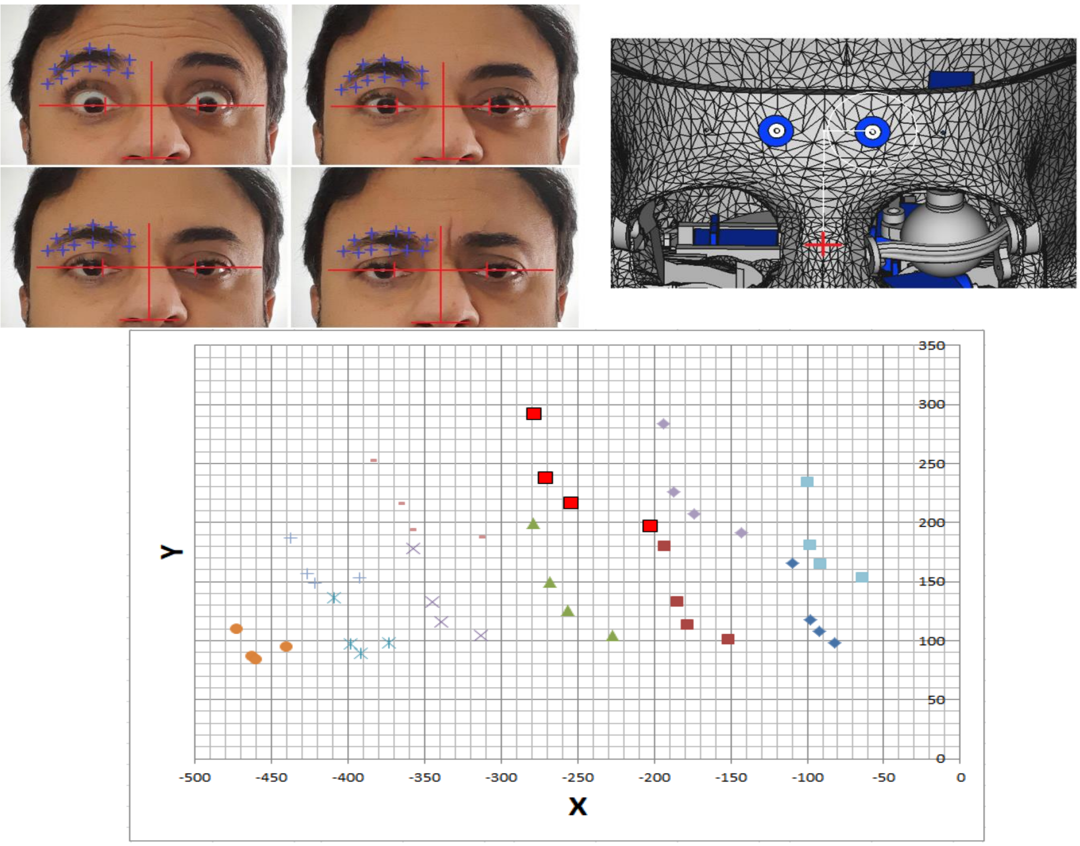

Fig. 5. Eyebrow markers tracing for some human's expressions

To find the location of the servo motor axis, a circular regression method has been applied to the upper marker [36] where, for the vector P of the upper markers, N points are used to calculate the following state matrices such that:

$$A = \begin{bmatrix} \sum P_x & \sum P_y & N \\ \sum P_x P_y & \sum P_y^2 & \sum P_y \\ \sum P_x^2 & \sum P_x P_y & \sum P_x \end{bmatrix} \tag{1}$$

$$B = \begin{bmatrix} \sum(P_x^2 + P_y^2) \\ \sum(P_x^2 P_y + P_y^3) \\ \sum(P_x^3 + P_y^2 P_x) \end{bmatrix} \tag{2}$$

$$a = A \backslash B \tag{3}$$

$$Xc = -\frac{a_x}{2} \tag{4}$$

$$Yc = -\frac{a_y}{2} \tag{5}$$

$$R = \sqrt{({a_x}^2 + {a_y}^2)/4 - a_z} \tag{6}$$

Where Xc and Yc are the regression circle center point and R is that circle's radius.

2.7 Eyelid biomechanics

One of the most action that any human does continuously is blinking, which makes humanoid robots with that ability more socially acceptable than others. Blinking is done by the motion of the upper and the lower eyelids, where the first has the significant impact in that process [37].

According to literature [38], the normal distance between the upper and the lower eyelids varies according to human race. The distance between the upper and the lower eyelid margin in the mid-pupillary plane can range from 8 mm to 11 mm. Furthermore, eyelid motions also occur during talking and other facial expressions, which make it an important feature that exists in more socially acceptable robots. The eyelids mechanism has been developed for Arslan as 2 arcs with angular movements. One servo motor is used to control each arc angle asynchronously.

2.8 Lips biomechanics

Facial expressions and speech are usually accompanied by the mouth's motion. Mouth motions reflect mainly a combination of lips' motions, jaw motions and face muscle motions. Concerning lips [39], they are controlled by a complex network of muscles, where the Orbicularis Oris (OO) muscle encircles the mouth and contributes to speech and impressions movements. OO can be divided into two parts: the Marginal Orbicularis Oris (OOM), which is closest to the lip opening, and the Peripheral Orbicularis Oris (OOP), which is farther from the lip opening. OOM and OOP can also be divided into superior (OOMs; OOPs) and inferior (OOMi; OOPi) portions, which run above and below the lip opening, respectively, and can function independently. Regarding speech, the majority of languages utilize at least 3 places of articulation for stops, namely: bilabial consonants (made with lips), dental or alveolar consonants (made with jaw) and velar consonants (made with tongue) [40]. Modeling of lips motion for speech is usually done in a modular fashion, such as electromyography (EMG) [41] and image processing [42]. Four lip layouts have been included to model Arslan's lips' motion, namely: Joy, Normal, Sad and shrink lips. Data from a human subject (this manuscript author) has been used for that job, where 11 marking points which surround half of both upper and lower lips have been identified and traced in each picture. The reference point has been chosen to be the lower center point of the nose (Figure 6).

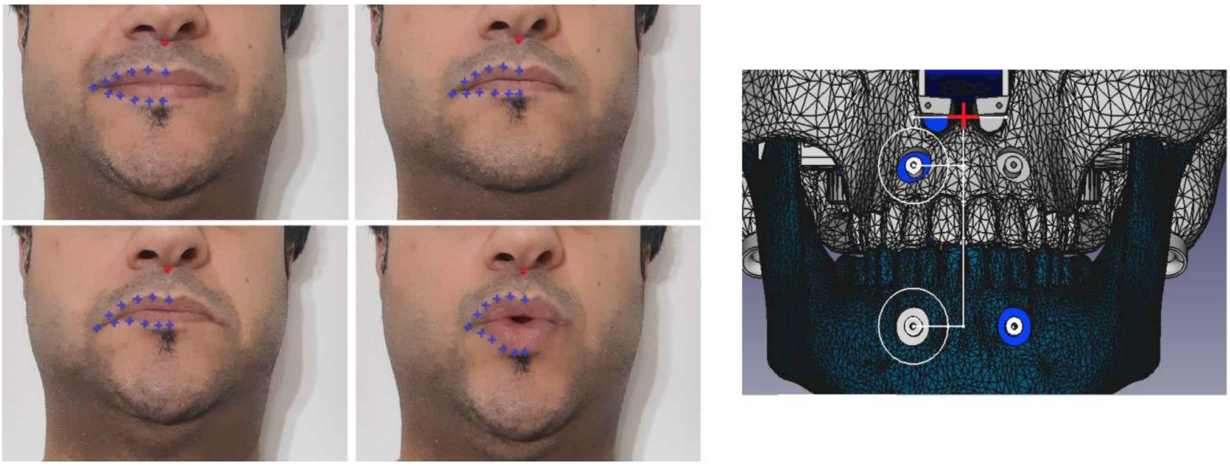

Fig. 6. Lips tracing

Once again, by tracing the profiles of markers, applying a circular regression algorithm, and applying suitable mapping between the used face and Arslan's skull, 4 motor locations have been selected on Arslan's skull and mandible.

3 Results and Discussion

3.1. Results

The RIS has been implemented from end-to-end where Arslan humanoid robot, which represents the system's front-end, is connected to other parts of the system (Figure 7).

Fig. 7. The RIS Full System Implementation

Arslan humanoid robot has been implemented using a 3D printer as separate modules and it has been assembled using suitable parts. Among the 3 popular 3D printing materials, namely PLA, ABS and PETG, PLA material has been selected as it has a high tensile strength, high resistance to fracture, and suitable elasticity. It was not necessary for Arslan's design to reach maximum ratings for each motion because humans do not do that most of the time. Arslan's nick mechanism allows one side axial rotation of 41° and flexion/extension of 45° which allows it to have an acceptable range of motion and, because of the nick's realistic structure, the head has been shifted during flexion/extension exactly like a human (Figure 8).

Fig. 8. Arslan's Physical Structure and Nick Rotations

Arslan's mandible can rotate around the hinge axis at 6 degrees, which allows it to perform sufficient actions during speaking (Figure 9).

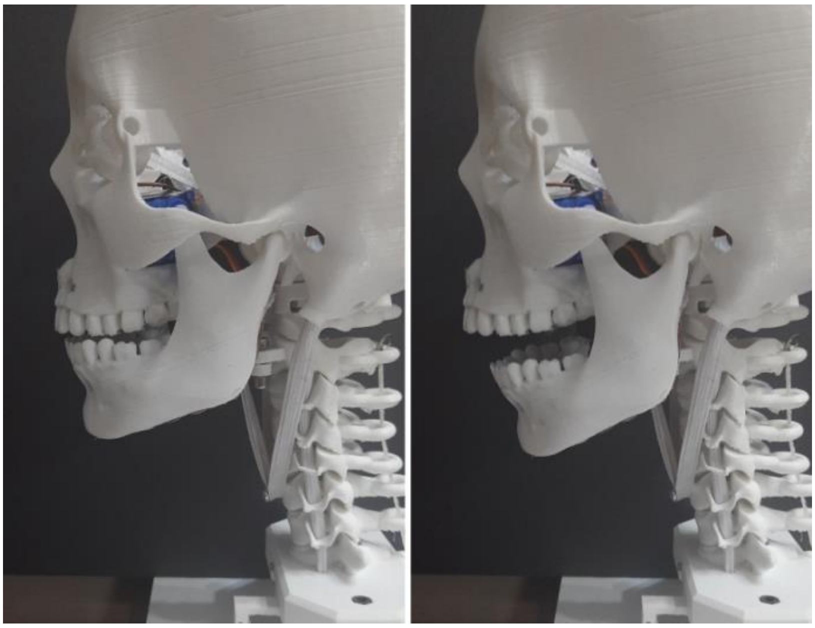

Fig. 9. Mandible Motion

Arslan's eyes can rotate around their axis of motion as the following: Adduction 19°, Abduction 34°, Supraduction (elevation) 0° and Infraduction (depression) 20° which allows a suitable range for VOR (Figure 10).

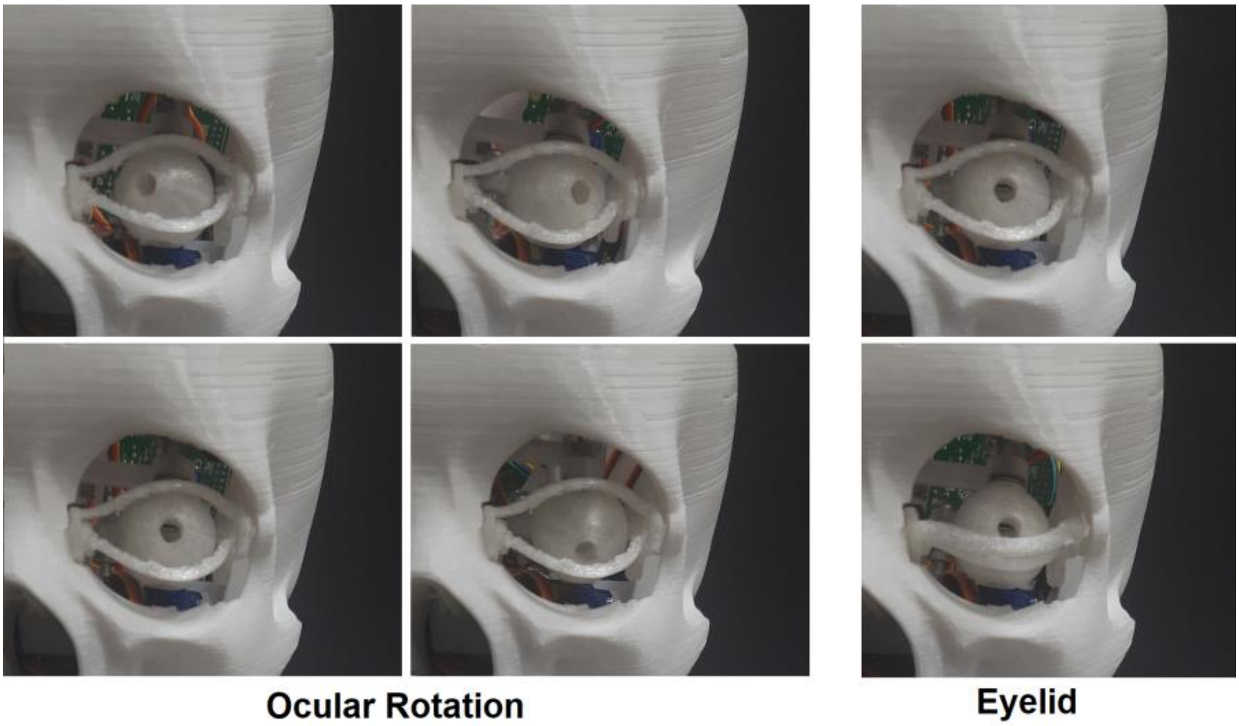

Fig. 10. Eyes Rotation And Eyelid Motion

The distance between the upper and the lower eyelid of Arslan can range from 0 up to 17 mm, where this covers more than the normal opening range and surprise emotion (Figure 9). After applying suitable mapping between the used face and Arslan's skull, motor locations of eyebrows and lips have been chosen according to the following table (Table 2) referring to selected reference points (Figure 5, Figure 6).

Table 2. Motors' locations of Arslan's eyebrows and lips referring to selected reference points.

	X	Y	Radius
Eyebrows	±13.2 mm	34.9mm	12mm
Upper lip	±13.6mm	18.5mm	8.8mm
Lower lip	±12.7mm	40mm	8.5mm

3.2. Discussion

It was not necessary for Arslan to reach the maximum rate for each motion as humans do not do that most of the time. Obtained ranges for each moving part is subjected to some physical constraints because of the skull. However, those ranges could be enlarged (again, which is not necessary) by stepping on more parts of the skull.

4 Conclusions

Robotic Information System (RIS) is a new information system architecture that provides data, information processing and services for users in a wide geographical space based on intelligent robots. The front end of the RIS is a humanoid robot head that interacts with users by different means to provide different services. The RIS has 3 main blocks: a humanoid robot's head (Arslan), a data and information processing engine "The Oracle" and a database server(s). Arslan humanoid robot, which is the front-end of the RIS, has been designed to be close to a real human's head skeletal structure, where its physical structure is designed to be identical to a real human skull, jaw and the nick vertebrae. Arslan is equipped with a smart mechanism for nick motion and facial expressions which have been designed according to analysis of human biomechanics which make it close to human behavior as well. Also, it is equipped with many sensors that allow it to see, hear, smell, sense head rotation and speak.

Authors' Contributions

The full project and the entire manuscript.

Competing Interests

The authors declare that they have no competing interests.

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