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Design and Realization of a Sign Language Educational Humanoid Robot

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Abstract

This paper introduces a novel robotic platform, called *RASA* (Robot Assistant for Social Aims). This educational social robot is designed and constructed to facilitate teaching Persian Sign Language (PSL) to children with hearing disabilities. There are three predominant characteristics from which design guidelines of the robot are generated. First, the robot is designed as a fully functional interactive social robot with children as its social service recipients. Second, it comes with the ability to perform PSL, which demands a dexterous upper-body of 29 actuated degrees of freedom. Third, it has a relatively low development cost for a robot in its category. This funded project, addresses the challenges resulting from the at times divergent requirements of these characteristics. Accordingly, the hardware design of the robot is discussed, and an evaluation of its sign language realization performance has been carried out. The inspected recognition rates of certain signs of PSL, performed by *RASA*, have also been reported.

Keywords Social child-robot interaction · Hardware design · Sign language · Hearing impaired children

1 Introduction

Ever increasing research interest and deployment of robots in various areas of social robotics, including education, therapy, service, and entertainment, have nurtured the development of new commercial and academic robots with novel applications. A huge body of research is dedicated to applications in the field of Child-Robot interaction (cHRI). This is because of the well-established fact that children can form a special bond with a suitably designed social robot.

There is abundant literature on the positive impact of employing robots in children's education. In one of the earliest studies [1], the English language was taught to Japanese children with a Robovie robot [2]. In a similar study [3], English was taught employing a wheeled Tiro robot. In a more recent study [4], employing robots in second language teaching was investigated and the impact of the robot's embodiment on the teaching process was reported as significant. In a study conducted by Sugimoto [5], robots have been used in storytelling scenarios. Children were engaged in the story, while concurrently participated with their robots in storytelling. In recent research conducted in Iran [6], a Nao humanoid robot was used in teaching a second language to junior high school students. Results indicated significant improvement in vocabulary gain, retention, and speed of learning with the robot-assisted learning method.

An average of 15 children with detectable levels of hearing loss are born every day in Iran. Most of these children, who suffer from severe and profound impairments, are born to hearing parents and as a result will not naturally learn the language their parents speak. Although when used as an early intervention cochlear implants improve pre-lingual deaf and hard of hearing children's access to sound, it is not sufficient for most children to reach normal language competence. What's more, some parents are concerned that access to sign language might hamper efforts toward developing spoken language and thus deprive their children from acquiring any other types of communication

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tools than spoken language. As a result most of these children normally do not develop a natural language. From a developmental psychology point of view, this language deficit is known to affect cognitive functioning and social skills [7, 8]. Linguistic research confirms that sign language is a natural language with a structure similar to a spoken language, and fulfills the same role for hearing-impaired children as spoken language does for hearing children. In addition, studies have shown sign language competency has a positive relationship with reading skills and future academic success [9]. Therefore, many specialists strongly advocate deaf and hard of hearing children learn sign language in addition to other possible efforts to develop oral/aural communication skills to guarantee a functioning communication system and normal development [10, 11]. The authors based on their observation also believe that learning sign language for deaf and hard-of-hearing children, specifically needs more attention in Iran.

To date, Kose et al. have conducted the only research on the employment of robots as sign language tutors in a series of studies [12–14]. In these studies, they investigated the effect of using a social humanoid robot on learning enhancement of different groups of children with different levels of hearing impairment, and in general it was argued that robots facilitated the learning process. They investigated the role of the robots' embodiments and examined the difference between robot-based and video-based learning methods. They argued that using a social robot as a sign language tutor for children can be more effective than video-based learning methods, which is in line with other studies in child-robot interaction. This suggests that robot-based tutoring systems are often more effective than computer-based tutoring ones [15, 16]. The main limitation in their studies came from the kinematic capabilities of the Nao [17] and Robovie R3 robots employed in performing Turkish sign language, which significantly limited the number of signs they could realize.

Designing a social robot can be a challenging task when the robot functions have divergent requirements that need to be satisfied. Most of today's robots with dexterous hand-arm systems have not been primarily designed for social aims rather for research and applications in grasping and dexterous manipulation. These aims do not demand certain criteria that an interactive social robot requires concerning its morphological properties, e.g. its exterior appearance. Examples of state of the art humanoid robots with dexterous hand-arm systems include NASA's Robonaut II [18] featuring 11 DOF hands and 7 DOF arm, the iCub robot [19] featuring 9 DOF hands and 7 DOF arms, and the most dexterous humanoid robot the latest version of Honda's Asimo [20], which features 13 DOF hands and 7 DOF arms designed for humanoid robotics research.

- In this present endeavor we have addressed these challenges by designing a fully functioned social robotic platform capable of performing Persian sign language. *RASA* primarily is expected to be employed in teaching PSL to deaf and hard of hearing children. The current version of *RASA* possess a wheeled lower-body platform suitable for use in institutions and schools for hearing impaired children. Figure 1 displays the flow diagram for developing the *RASA* robot, which consists of the hardware development steps of the robot along with the final assessment of its performance in realizing the Persian Sign Language (PSL).

2 Key Concepts

This section covers key concepts prior to the design steps of *RASA*. These concepts specify the overall guidelines in the industrial design of the robot. There are three main characteristics which guide and govern the design process. The first is *RASA*'s ability to perform as a fully functioned social robot, enabling Child-Robot Interaction (cHRI). The second is *RASA*'s ability to perform Persian Sign Language (PSL) and the third is its low development cost. Needless to say, these characteristics include contradictory requirements in some areas which in turn demand reasonable tradeoffs in the design process. These characteristics are discussed in great detail in the following concepts.

2.1 Appearance

The appearance of a social robot plays a significant role in its acceptability as it makes the very first impression when interacting with a human child user. Two main issues must be addressed regarding the appearance of the robot. The first issue concerns the robot embodiment as an anthropomorphic, zoomorphic, or machine-like system,

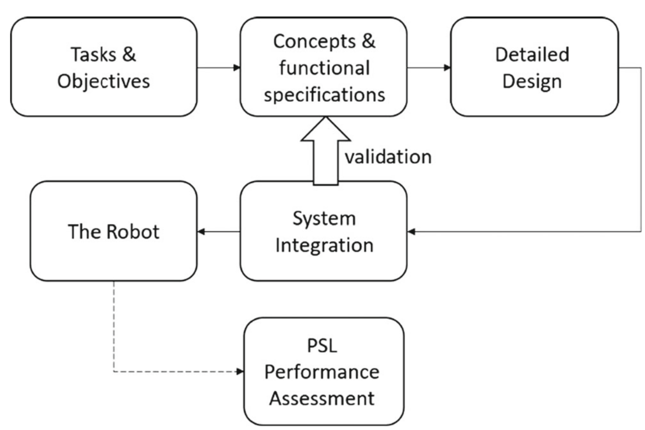


Fig. 1 Flow diagram for developing the *RASA* robot

and subsequently its other corresponding attributes (e.g. size and age in an anthropomorphic case). The second issue is finding a suitable appearance to optimize the robot's attractiveness and hence children's willingness to engage with it.

Anthropomorphizing of a robot is generally done because certain human traits, e.g. intentions and emotions, need to be ascribed to the system to trigger a natural interaction between the child and robot [21, 22]. Hence the argument for choosing an anthropomorphic morphology for *RASA* robot is twofold; the robot is to play the role of a peer companion of children in learning sign language which requires the illusion of life and similar mental characteristics a human-like robot creates. This further suggests a child character for the robot, it also needs the ability to perform sign language which requires very specific physical human traits.

However, the second issue tries to increase the likelihood that children will like the human-like robot. The well-known uncanny valley hypothesis [23] advises against selecting an almost but not completely human-like appearance as it can cause adverse reactions due to unfulfilled expectations. Incorporating caricatured features in the human-like appearance of a social robot has been suggested to overcome this issue [24]. In a comprehensive survey, Woods et al. [25] investigated children's preferences toward 70 images of robot appearances. They confirmed the uncanny valley claim and suggested integrating cartoon-like features in the appearance of a social robot designed for children. Furthermore, it has been argued that the appearance and function must be consistent with each other to avoid any false expectations [21]. This segment concludes with the resulting key morphologic features of the *RASA* robot:

- The robot's appearance features both human-like and machine-like elements.
- The robot's appearance incorporates cartoon-like features.
- The robot's function and appearance are designed to in accordance with each other.

2.2 Kinematics of a SL Performing Social Robot

In order to realize the signs of a sign language it is deemed necessary to analyze its structures, mainly the phonological one. Phonology in SL refers to how a sign is formed and organized. Discussing the American sign language (ASL), C. Valli et al. [26] pointed out that each sign in ASL can be broken down into five components: handshape, movement of the handshape, location of the sign, palm orientation, and non-manual signals including head orientation, face expressions, etc. These components, which can also be applied to the signs in PSL, all together convey the meaning of a sign. PSL signs, like ASL, are derived much more from manual parameters rather than non-manual ones [27]. It should be mentioned that although lip-reading is not required to interpret the signs in PSL, PSL signers move their lips at the same time as signing and try to lip-read as they communicate with each other. This fact has made the signers somewhat dependent on lip-reading to quickly interpret the signs. PSL also contains multiple finger-spelling methods which include the spelling of written Persian words with the help of manual symbols of the Persian alphabet. Finger-spelled signs are used when a word cannot be represented with a specific sign. The most common finger-spelling method used in Iran is the "Baghcheban phonetic alphabet" which is somewhat similar to cued speech that utilizes lips and face movements in expressing the Persian alphabet [28].

There are three independent main kinematic chains that contribute to the construction of SL movements. The number of degrees-of-freedom, ranges of motions, relative length of each kinematic link and their position relative to the reference coordinate system are key kinematic parameters to produce these movements. Therefore, to generate the most accurate movements the robot must have kinematic chains' parameters as close as possible to those of a human. This cannot happen considering other design factors, specifically the low development cost criteria which acts as an important restricting factor. Consequently, regarding sign language realization, the goal was to design the robot's kinematic structure so that the PSL signs performed by the robot are as recognizable and distinguishable as possible to a user with previous knowledge of PSL, while still fulfilling other design considerations. A thorough investigation of individual PSL signs has been conducted in order to determine the optimal kinematics structure of the robot. In the following, characteristics of the upper-body kinematic layout are specified and the arguments for selecting each one are presented. It should be mentioned that the main focus is to investigate the minimum possible actuated DOF so to minimize the development cost of the robot.

- The kinematic characteristic for the flexion/extension of the hands' fingers excluding the thumbs are argued with the help of Fig. 2. After analyzing the signs of PSL, the first thing one realizes is that all four fingers of each hand need to move independently. This is not the case in many robotic dexterous hands designed primarily for grasping and manipulation tasks, where the ring and pinky fingers are actuated dependently and comprise a total of one DOF [29, 30]. Figure 2 shows four PSL signs with different finger flexion profiles which roughly present all possible fingers

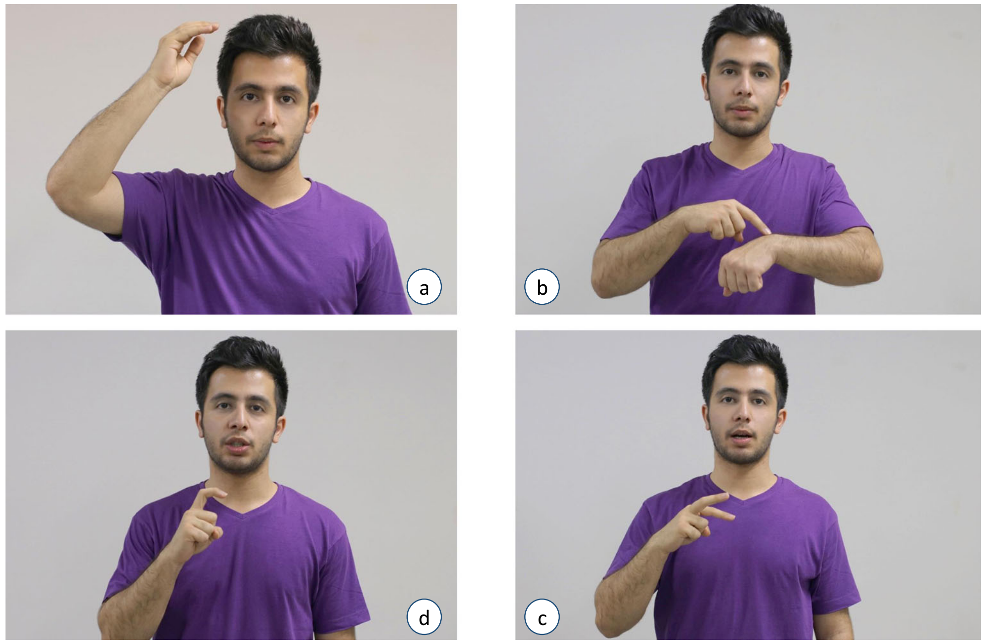


Fig. 2 Examples of finger profiles in some PSL signs

shapes in PSL signs. In most PSL signs' finger profiles, phalanges of the finger move in a relaxed movement in which the proximal phalange naturally sweeps a larger angle in the course of the flexion with respect to the intermediate phalange (examples are depicted in Fig. 2a, b). Of course there are many signs, such as the one depicted in Fig. 2d, in which one of the phalanges is fixed. However, it seems that with an optimized flexion/extension profile most of the signs can be realized with an acceptable recognition rate with only one DOF for each finger. This decision greatly reduces the development cost of the robot by reducing the number of actuators required.

- Another necessary DOF of the hand can be identified in the pictures illustrated in Fig. 3. The signs depicted on the upper right and left side differ only in the lateral angles between the fingers. Yet these signs convey different meanings. Therefore, it was considered necessary for the robot to include the abduction/adduction DOF for the fingers.
- The last DOFs concerning the movement of the fingers in performing PSL is that of thumbs. Thumb dexterity plays a significant role in the realization of PSL signs. In Fig. 4 three movements of opposition, abduction, and flexion/extension of the thumb can be observed in the signs depicted. Including all the thumb's DOFs would increases the cost and complexity of the system. So two DOFs, the opposition and flexion/extension, were selected to achieve an acceptable rate of recognition while satisfying other design considerations.
- The next kinematic characteristic concerns the arms' movements. Referring to the aforementioned phonetics of PSL regarding the arms' kinematics, two elements of position of the palm and its orientation are of primary importance and require at least 6 DOFs integrated in each arm. It appears that the sideways movement of the wrist,[1] as the seventh redundant DOF of human arm, is the least significant DOF in realizing the signs. There are very few signs which require the sideways movement of the wrist. Those were argued to be able to be realized by other joint' motions with an acceptable recognition rate. Therefore, the seventh DOF was neglected. Special care must be taken in the proportionality of the links' lengths and the relative positioning of the three kinematic chains of the arms and the head to accommodate the wide workspace of the hands in PSL and achieve maximum possible ranges of motions of the joints.
- Finally, it should be mentioned that all 3 DOFs of rotation of the head with acceptable ranges of motion must be integrated in the kinematic layout of the robot.

Excluding the fingers' DOFs, the resulting kinematic layout of the 32 DOF *RASA* robot is depicted in Fig. 5. The lower-body DOFs of the robot will be discussed in later sections.

2.3 Expressive Face

There are two main arguments for selecting an expressive face for a SL performing social robot. Firstly, the quality of natural interaction of a social robot is greatly dependent

[1] Ulnar & radial deviations

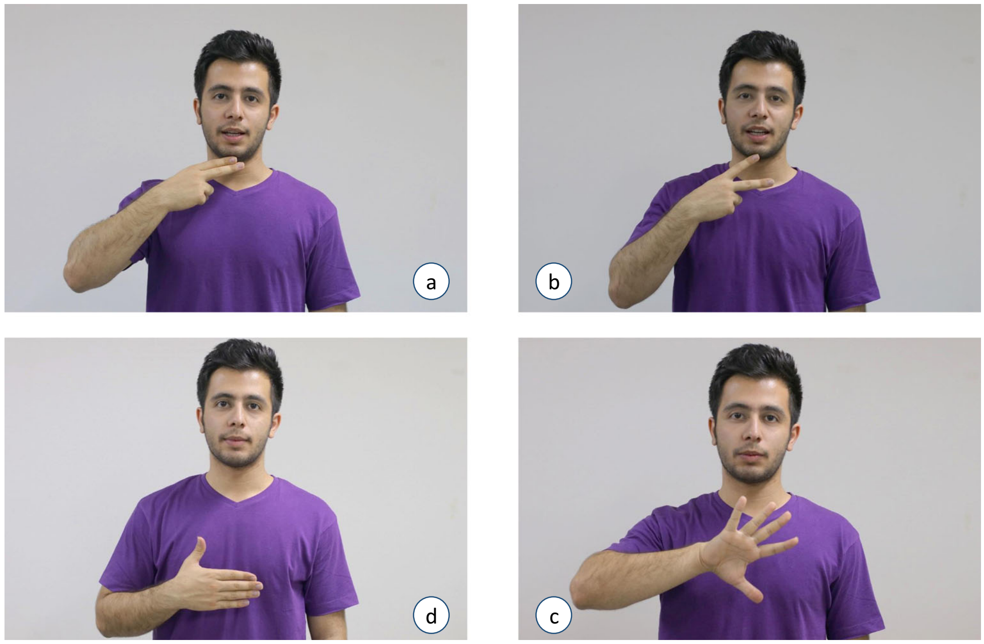


Fig. 3 Abduction/adduction movements of the fingers in some PSL signs

on its expressional and emotional capabilities of which an expressive face, in addition to body postures and gestures, is considered as its primary tool. Secondly, as was discussed in Section 2.2., the non-manual component of the SL signs is mainly realized by facial expressions. Although the number of signs with facial expressions is small relative to those without them, integrating an expressive face in the robot will enhance the SL-based communication.

Among possible alternatives, a graphical monitor-based face as opposed to a mechanical face can significantly reduce the development cost and design effort while at the same time yield complex interaction scenarios via facial expressions. The dynamic facial features must produce basic emotions and expressions. A very distinct advantage of a monitor-based face is the possibility to easily and quickly alter the appearance and facial emotional states of the robot.

2.4 Mobile Base

The current version of the robot is intended to be used in institutions and classrooms with flat floors making

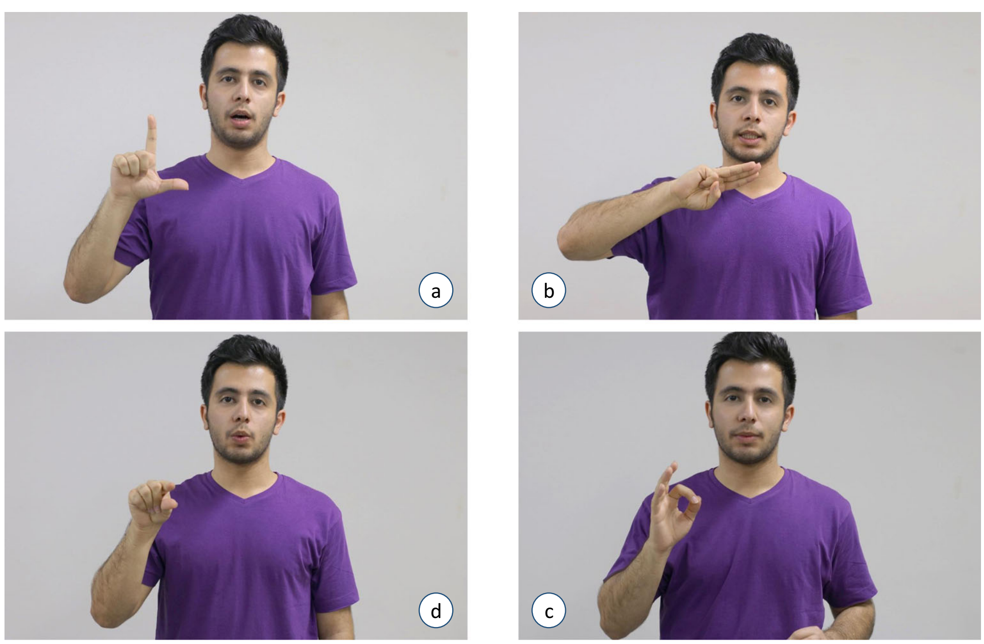


Fig. 4 Thumb movements in some PSL signs

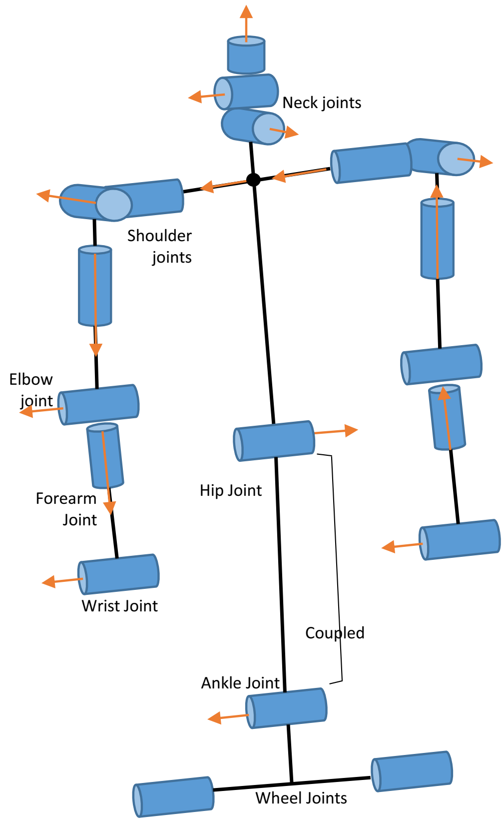


Fig. 5 Kinematic layout of the *RASA* robot, excluding the fingers' DOFs

wheeled mobile locomotion an ideal choice in the target environments. Full Autonomous navigation was not a priority for the robot nor was high maneuverability; therefore, a two-wheeled non-holonomic mechanism was selected. The system integrates multiple sonar sensors and an Inertial Measurement Unit (IMU) which are in charge of obstacle avoidance and localization tasks of the system.

2.5 Sensory System

As mentioned in previous sections, *RASA* is to be a fully functioned social robot. This means that the robot must possess stereo vision and stereo microphones along with stereo audios for intuitive interaction. This is especially important for future research concerning human-robot interaction, which is heavily dependent on *RASA*'s sensory system. In addition to interaction sensor modules, motion compensation and navigation constitute the other set of sensors required for the robot.

3 Mechanical Design

In this section the mechanical design of *RASA's* five main subsystems of 1) fingers, 2) forearm assemblies, 3) upper-arm assemblies, 4) head assembly, and 5) mobile base are discussed. The current weight of the robot is approximately 15 Kg and it stands 103 cm tall. Figure 6 shows the current version of the robot along with a picture of its 3D CAD model.

3.1 Manufacturing Processes and Material Properties

Materials used in the mechanical parts contribute significantly to the body mass of the system; therefore, minimizing the weight and moments of inertia of these parts permits the use of smaller actuators resulting in lower price and lower weight. Utilizing additive manufacturing processes can also greatly reduce the cost of the robot's development while allowing the production of rather complex optimized shapes without increasing production price (Fig. 7).

Most of the robot's parts are fabricated with PA2200 Polyamide.[2] Polyamides, while being lightweight, exhibit a combination of strength and flexibility which makes them suitable for robot structures exposed to external forces and possible impacts. Structural parts made of this thermoplastic are fabricated using the Selective Laser Sintering (SLS) method. VeroGray photopolymer,[3] another thermoplastic, is used to fabricate the robot's Finger phalanges. The PolyJet technology manufacturing process used to form these parts has a relatively higher resolution and precision with respect to the SLS process, making it suitable to fabricate highly detailed finger phalanges.

The highly stressed parts of the upper-body, e.g. joint shafts and gears, are manufactured from Al7075 aluminum alloy with an ultimate strength of 524 MPa. The bending mechanism described in Section 3.5 is also made of 6000 series aluminum alloy; and finally, stainless steel shafts, as the most stressed parts of the robot, have been used in the lower-body's joints and wheels' axes.

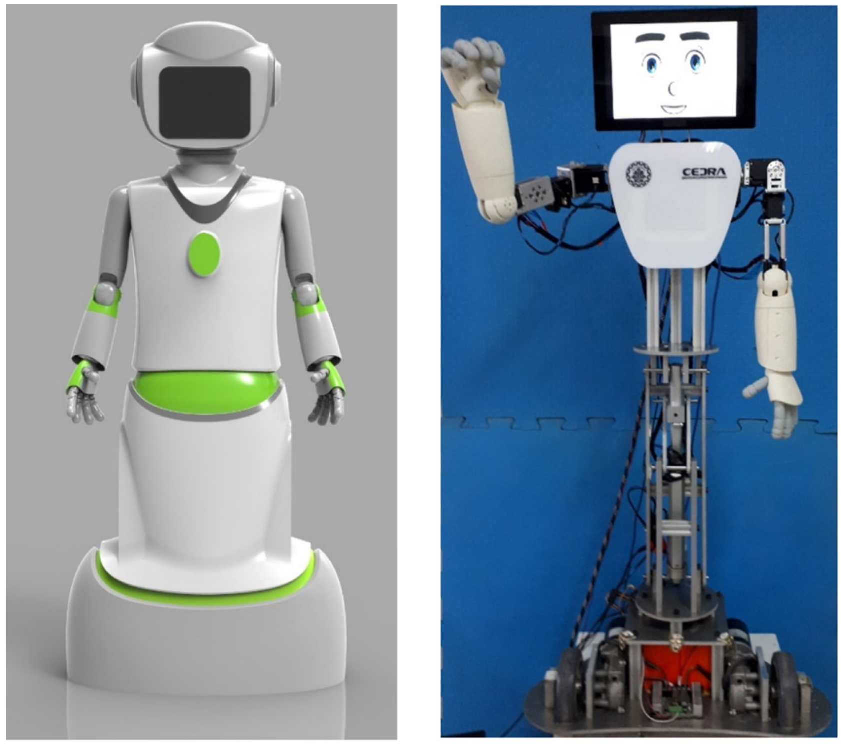
3.2 Fingers Design

Considering design guidelines established for a SL performing social robot, the cable driven, under-actuated mechanism proposed by Hirose [31] was selected for the fingers' flexion\extension movements. As illustrated in Fig. 8, the cable goes through 3 pulleys placed at the joints of the finger. There are three torsion springs placed at the joints ensuring the finger's extension as the motor unwinds the cable.

An under-actuated mechanism is suitable for multipurpose humanoid social robots due to its flexibility and its adaptability to the form of the object when grasping. It

[2]Datasheet available at: http://eos.materialdatacenter.com/eo/en

[3]Datasheet available at: http://www.stratasys.com/materials/material-safety-data-sheets/polyjet/rigid-opaquematerials



(a) (b)

Fig. 6 **a** Image of the 3D model of *RASA* robot and **b** The current version of the *RASA* robot

is also utilized in most commercial robots possessing fingers (e.g. the Nao robot [17]). On the other hand, a cable driven mechanism permits positioning of the fingers actuators away from the joints minimizing the inertial properties of the arms.

Hirose's mechanism, among under-actuated mechanisms, gives the ability to set the profile of each finger flexion\extension movement by adjusting the two main parameters of the pulleys' radii and the stiffness of each torsion spring placed at fingers' joints thereby satisfying the guideline set for the fingers in Section 2.2. Deriving the fingers' Equations of motion, the dynamic and static behavior of the fingers, i.e. flexion\extension movement and the fingers' vibration along it, are optimized. It is obvious that in a quasi-static flexion\extension movement, the relative rotation angle of finger phalanxes with regard to each are proportional to the diameter of the pulley and to the inverse of torsion spring's constant at the respective joints [32].

The first phalange of each thumb is actuated utilizing a closed-loop cable mechanism which in contrast to Hirose's mechanism moves the phalange in both directions. A torsion spring ensures the extension movement of the second phalange of the thumb. The abduction/adduction movement of the fingers also is realized by a closed loop cable mechanism. Steel Bowden cables, with a very low elasticity as compared to silk, have been selected for these closed-loop mechanisms in order to ensure the stiffness and constant presence of tension in the cables.

Servo control of each finger is realized by the use of custom-designed sensor modules placed at the first two joints of robot's index, middle, ring and little fingers, as well as two joints in each thumb. The last sensor module

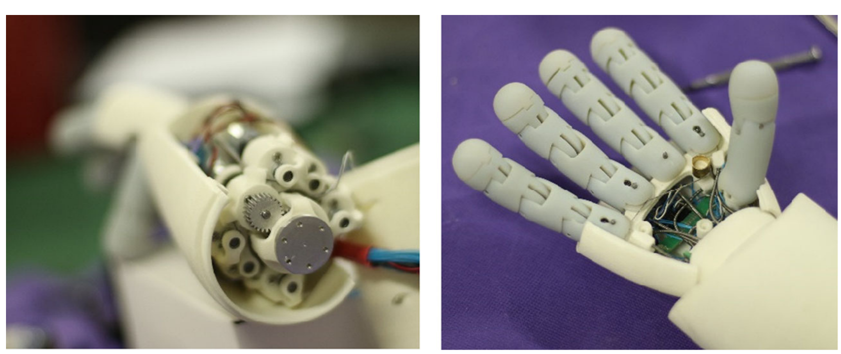


Fig. 7 The right hand and forearm assembly of the *RASA* robot fabricated by additive manufacturing processes

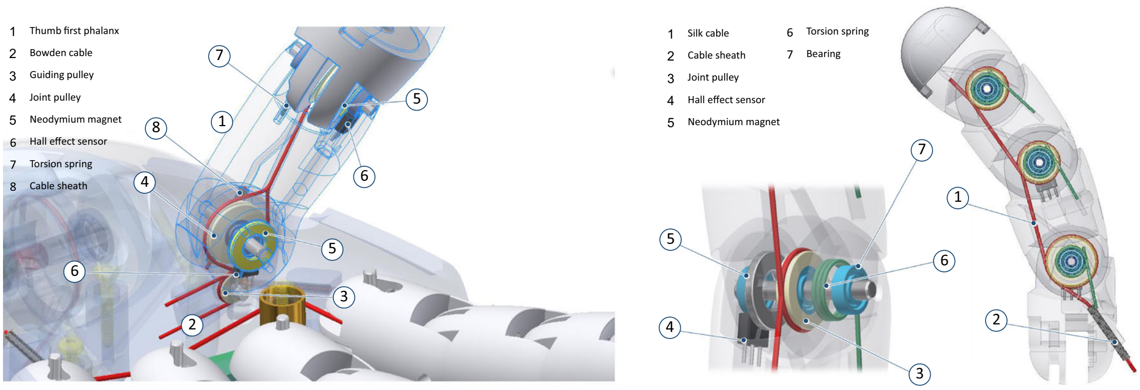


Fig. 8 Fingers actuation mechanisms where the right thumb is depicted on the right

in each hand, placed at the abduction/adduction joint of the pinky, obtains the rotating angle of the lateral movement of the fingers. It is worth mentioning that utilizing the PolyJet 3D printing method allowed us to employ Hall Effect based sensors in a very limited space, which in turn reduced the cost that would be imposed if other position sensing solutions were selected.

3.3 Forearm Assemblies

All the actuators of the hand movements along with those of the wrist and elbow DOFs are placed in the forearm in a highly compact configuration satisfying the size requirements of the robot. Moreover, achieving the desirable output power for hand actuators while minimizing their size and considering the minimum cost criteria left us with only a few actuator options. With that said, Nine 1.2 and 2.5 Watt Maxon brushed DC motors coupled with planetary gearheads, with reduction ratios, ranging from 1:67 to 1:131, were selected to drive the respective joints. Machined aluminum capstans attached to the output shaft of the gearheads wind and unwinding the cables driving the hand movements. SLS technology permitted the design of complex shaped mechanical parts, particularly in the forearm assembly, which allowed the minimization of the number of fasteners. This would not be possible if traditional manufacturing processes were used.

As suggested in the concept development phase of the design, one DOF for each wrist of *RASA* robot is adequate and satisfies the examined design guidelines. A cable drive transmission was selected for the wrist joint. Although this mechanism adds to the complexity of the assembly process, it is compatible with the size and space constraints of the forearms. Figure 9 shows the tendon mechanism of the wrist joint as well as cable routes. The motion is transmitted to the wrist joint through a series of idle pulleys. Two tensioners ensure sufficient tension in each steel Bowden cable. A magnetic position sensor is used in order to measure the rotation of the joint.

The elbow joint is the only joint in the hands and forearm subassemblies which employs a geared power transmission. 7075 T6 aluminum alloy gears ensure the desired joint stiffness. As depicted in Fig. 9, this joint also incorporates a magnetic position sensor to measure the rotation of the joint.

3.4 Upper-Arm Assemblies

The upper-arm of the robot constitutes a total of 4 degrees of freedom. These joints are actuated by MX64 and MX28 model Dynamixel commercial servo motors. As stated in Section 2.2, many PSL signs are dependent on the range of movements of these DOFs in human arms, which in effect expand the workspace of the hands. Great care has been taken in the mechanical design of the upper-arm to maximize the movement ranges while preserving the design guidelines. For instance, in a trade-off to achieve larger motion ranges, the three shoulder joints axes do not intersect at a single point; consequently, an analytical solution can no longer be found for the inverse kinematics of the arms.

3.5 Head Assembly

The role of the head movement has been analyzed in Section 2.2, where it was argued that a robot capable of performing PSL must incorporate the 3 DOFs of a human neck. Facial expressions are generated on the tablet screen for both better communications via sign language and expressing the robot's emotions.*RASA's* human-like emotions and expressions comes from four major facial features including eyebrows, eyes, eyelids, and lips. Figure 10 shows *RASA*'s head assembly. The three DOFs in the neck are realized using three MX28 Dynamixel servo motors in a serial pitch, roll, and yaw configuration. A pair of microphones, the tablet face and its driver board,

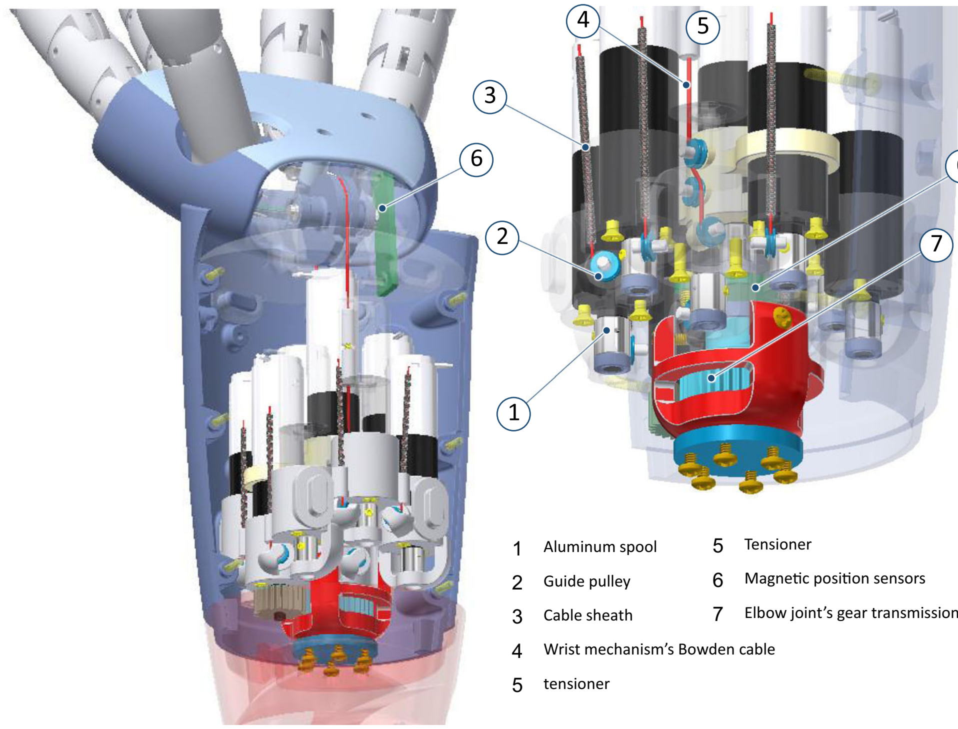


Fig. 9 Details of the forearm assembly

and a pair of speakers providing stereo audio for verbal communication are also integrated in the head assembly.

3.6 Mobile Base

Figure 11 shows the current RASA robot's mobile platform. A non-holonomic wheeled base has been selected to enable the robot to move in its intended environments. A pair of actuated wheels along with caster wheels constitute the support polygon of the robot.

The mobile platform also encompasses a bending mechanism which enables the robot to bend up to 60 degrees from the hip, in the sagittal plane of the body, without losing stability. There are several legged and wheeled robots which integrate this motion; these robots either include one DOF in which only one hip joint is actuated with very limited bending angle, or two DOFs in which two hip and ankle/knee joints are independently actuated in the bending action to achieve a larger bending angle without losing stability [33–35]. Needless to say, in the latter case the need for two actuators increases both the development cost and power consumption of the system. The present 6-bar linkage mechanism performs the bending action with a single non-backdrivable linear actuator. In the CAD model picture of the mobile base presented in Fig. 11, the linkages of this mechanism are shown in different colors to be easily distinguishable. As the actuator's rod retracts, the torso rotates forward from the hip joint while the leg rotates

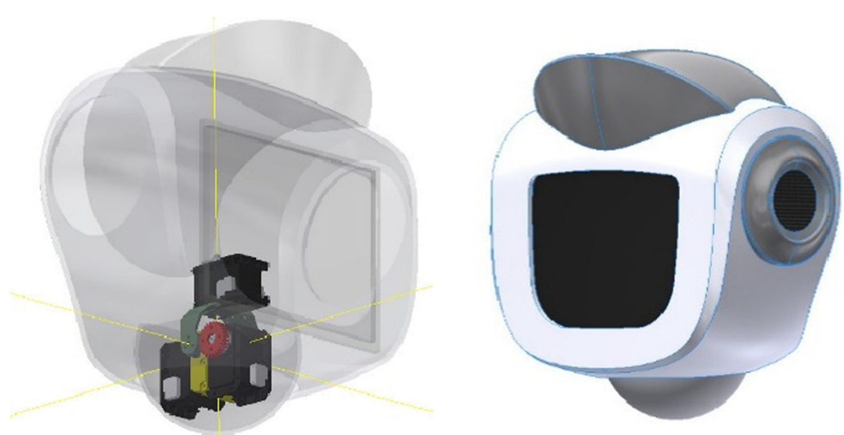


Fig. 10 The robot's head assembly

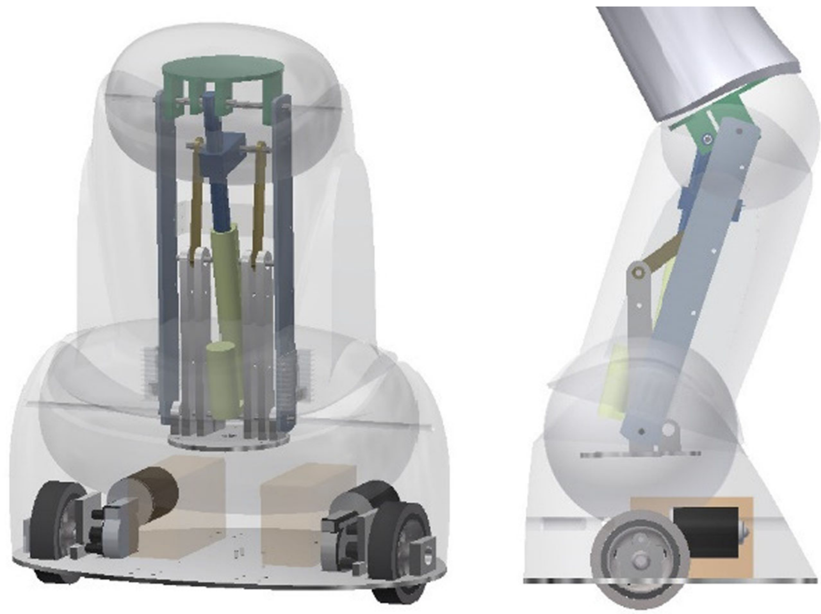


Fig. 11 The robot's mobile base including the bending mechanism

backward from the ankle joint maintaining the robot's center of gravity roughly in the same vertical line which ensures the stability of the system during the bending action.

4 Sensors and Electronics

4.1 Position Sensors

As previously indicated in Section 3.3, 22 Hall Effect sensor modules have been custom designed to acquire position feedback of the finger joints of the hands. Figure 8 shows a finger joint incorporating a sensor module. This module is based on the varying output voltage of a linear Hall Effect sensor, in front of a rotating diametrically magnetized neodymium magnet. The present configuration has been inspired by works such as [30]; however, multiple other configurations for the hall sensor and the magnet can be found in the literature. This particular configuration was selected in consideration of the joints' limited space. The positioning and distances of the sensor module elements are optimized to achieve a more semi-linear voltage response. The output voltage of the sensors ranges between 1.2 to 4 V as the magnet rotates in front of it. Although this sensor module design adds to the complexity of the assembly, it reduces the development cost of the robot and helps with a more compact design of the forearms, which is a necessity considering the size constraints of the robot.

It should be mentioned that the hands' sensor modules are designed with the described characteristics (e.g. Output voltage Semi-linearity) to measure rotations less than 80 degrees. As a result, the wrist and elbow joints rotation servo control is done by employing 12 bit magnetic AS5162 sensors from Austria Microsystems with programmable output ranges. The position sensor boards are depicted in Fig. 12.

In order to minimize the noise effects on the Hall Effect chips readings, two custom designed boards embedded within the hands are in charge of digitizing the analog output voltage of 13 position sensors of the hand-forearm systems. The boards utilize a highly compact design in order to fit into the palms.

4.2 DC Motor Controllers

A pair of custom-designed boards handle the control tasks of 9 DC motors placed in each forearm and have been designed as compactly as possible to fit in the forearm. The first board acting as the control unit is based on two 32 bit Atmel's SAMD21 microprocessors which offer 256KByte Program flash and 32KByte SRAM with a running frequency of 48 MHz. The second board is in charge of delivering power to the actuators consisting of nine DRV8871 H-bridge drivers equipped with voltage, current, and temperature safety features as well as current

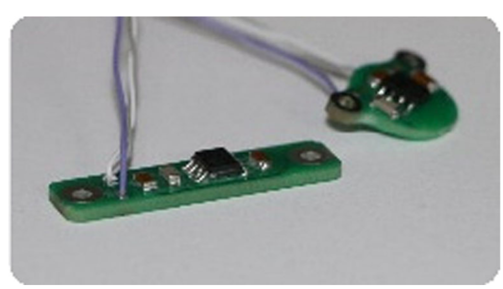


Fig. 12 Wrist and elbow joints angular position sensor boards

regulation circuitry which makes possible an even more compact design of the power board. The board can provide power up to 4 A at 12 V. The motor controller board receives the position sensors' data via a SPI bus with a frequency rate of 12 MHz and communicates with the CPU via serial communications with a baud rate of 115200 bps.

4.3 Central Processing Unit

A pair of custom-designed boards handle the control tasks of 9 DC motors placed in each forearm and have been designed as compactly as possible to fit in the forearm. The first board acts as the control unit and is based on two 32 bit Atmel XMega64 microprocessors which offer 64KByte Program flash and 4KByte SRAM with a running frequency of 72 MHz. The second board is in charge of delivering power to the actuators consisting of nine DRV8871 H-bridge drivers equipped with voltage, current, and temperature safety features as well as current regulation circuitry which makes possible an even more compact design of the power board. The board can provide power up to 4 A at 12 V. The motor controller board receives the position sensors' data via a SPI bus with a frequency rate of 12 MHz and communicates with the CPU via serial communications with a baud rate of 115200 bps.

5 PSL Performance Evaluation

As stated, the established goal regarding the robot's PSL performance is for users with PSL knowledge to be able to distinguish the signs correctly. This evaluation can be performed in a user study, by measuring the recognition rate of human subjects for a number of selected PSL signs realized by the robot. As mentioned in Section 2.2, many PSL signs share the same phonological elements from which the signs are created (e.g. handshape), and consequently share the same kinematic attributes. Therefore, a limited number of signs with diverse kinematic characteristics were selected such that a relatively thorough presentation of PSL signs was achieved.

Accordingly, the participants in this experiment were presented with 70 standard PSL signs which consisted of signs for 60 Persian words and 10 signs of the Baghcheban alphabet. It is important to note that many deaf people in Iran, especially the uneducated, use what is called "natural" PSL (informal PSL). Therefore, the requirement that participants in this study had to possess sufficient proficiency in standard PSL restricted the number of participants to 15, including 11 female and 4 male PSL translators/instructors. The average age of the group was 36 years and the participants ranged in age from 26 to 51.

In this online survey the subjects were presented with video clips or images of the selected signs in two separate steps. First, they were required to try to recognize the signs solely based on the robots performance. Second, they were asked to modify their first recognition to a second guess based on 5 choices presented for each PSL sign and 3 choices presented with each Baghcheban alphabet sign. In the selection of these multiple choices an attempt was made so that at least one of them shared one or more similar structural elements (e.g. handshape, etc.) with the respective sign. Considering the fact that the Baghcheban phonetic hand alphabet makes use of lips movements as well as hand gestures to represent letters of Persian alphabet and since the robot currently doesn't feature dynamic mouth and lip movements, the Baghcheban alphabet signs were presented separately from the 60 other signs to narrow down the possible choices the participant might have had for each of these signs. The video of RASA performing these 70 signs is available online.[4] This user study can be structurally compared to the ones conducted in [32–34, 36] which evaluate the recognition of different robotic face expressions.

To avoid questionnaire fatigue, but still achieve the survey goals, the questionnaire was designed as short and simple as possible. Each sign came with two boxes for the respondent's guesses in the two steps of the survey. Upon completion of the survey they were asked to generally state the reasons for possible mismatch of their first and second attempts at recognition of the signs. Fleiss' Kappa value was calculated in the experiment to assess the agreement between the participant's recognition of the signs.

Table 1 shows some of the signs with their received average recognition scores. The overall average recognition score in the first step of the experiment was 77 percent with the standard deviation of 23 (M = 77%, SD = 23%). These values for the 60 signs of Persian words and 10 signs of Persian alphabet was (M = 74%, SD = 23%) and (M = 92%, SD = 18%), respectively. The first 60 signs are related to the Persian words and the next 10 are the Baghcheban alphabet. the Fleiss' kappa value in the first step was 0.236 ($p = 0.000$), which according to [35] indicates a fair agreement between the subjects' recognition of the signs. Therefore, although undesirable, one can conclude that the robot's performance in realizing the signs cannot be considered as the only factor involved in the recognition scores. This result can be deduced when we look at the recognition rate received by some of the selected signs.

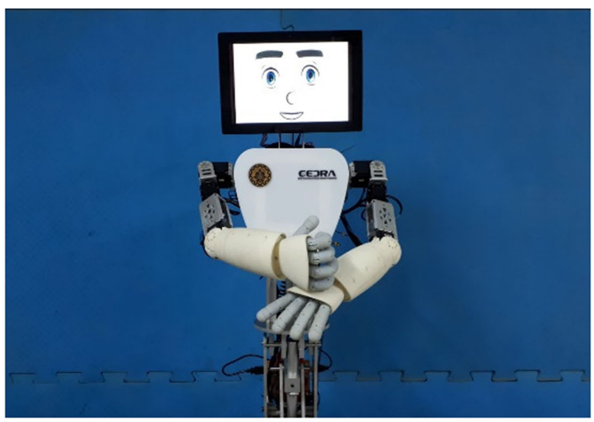
For example, the respective sign for the word "president" (sign #59), depicted in Fig. 13, had an average recognition

[4] https://drive.google.com/file/d/1fmxcShvR0DXEdRbnZLID3KZGeQiCaIvH/view

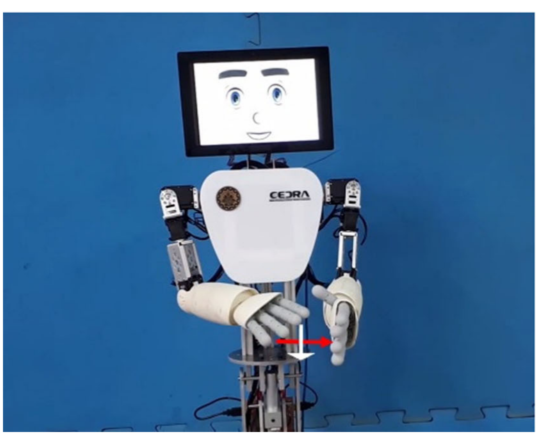
Table 1 The average received recognition rate of the selected signs

Number of sign	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
First step score %	100	80	73	87	40	100	47	67	93	93	73	33	60	53	80	33	67	93
Second step score %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Number of sign	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
First step score %	93	100	93	87	40	40	100	80	87	93	87	47	100	40	100	53	87	73
Second step score %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Number of sign	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
First step score %	93	93	73	93	27	53	100	87	67	100	40	80	47	100	47	80	87	100
Second step score %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Number of sign	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70		
First step score %	73	73	100	60	33	87	100	100	73	100	100	100	100	100	47	100		
Second step score %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	93	100		

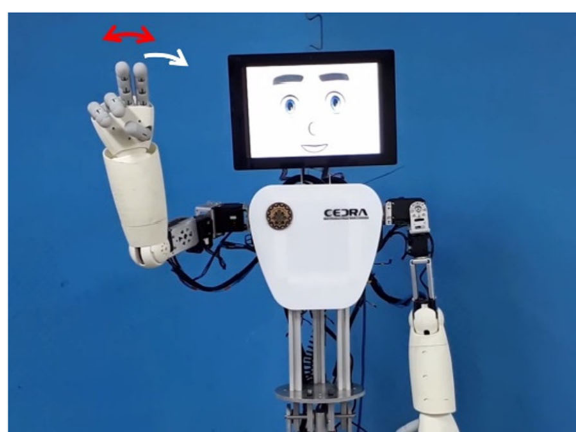
rate of 33 percent in the first step of the experiment. Sixty-seven percent of the subjects deciphered it as the word “chairman” whose sign is identical to that of “president” with the only difference of the left hand making a fist. In other examples, the signs for the words “Monday” (sign #5) and “river” (sign #52), also depicted in Fig. 13, was



(a) PSL sign for the word "president".



(b) PSL signs for the words "river" and "dam". Movements depicted by the white and red arrows, respectively.



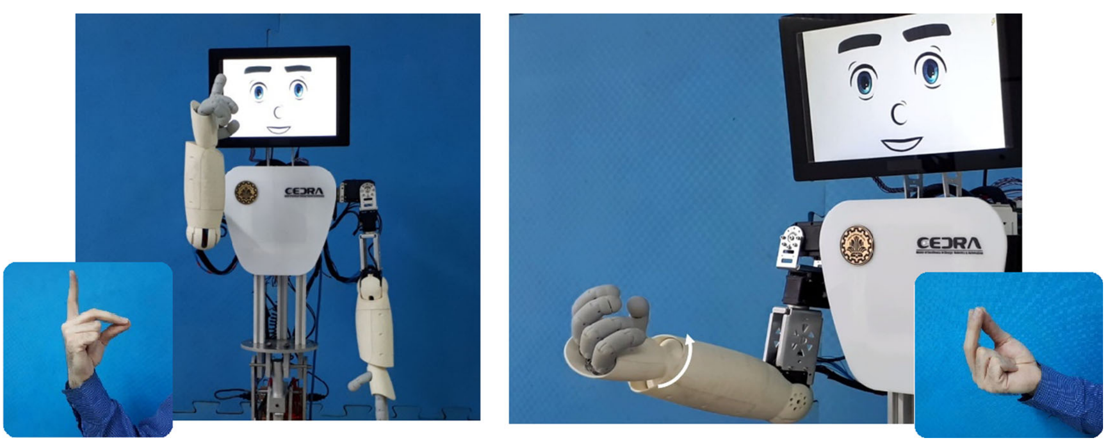
(c) PSL signs for the words "Monday" and "twenty". Movements depicted by the white and red arrows, respectively.

Fig. 13 Examples of some misinterpreted signs understood by some participants as the words “twenty” and “dam”, respectively. These pairs of words share the same hand gestures but have a slight difference in the movement of the hand. As the participants themselves pointed out, the main reason for the mismatch between the first and second guesses is mainly the fact that all Iranian PSL signers are heavily dependent on lip-reading when interpreting signs. Therefore, when the lips movements is eliminated they try to connect the sign realized by the robot to the first word that comes to mind. On the same basis, instead of giving a wrong answer some participants did not make any guesses for some of the signs (e.g. sign number 32 for the Persian word “wheel”).

As expected, the hardware limitation of the system can be considered another significant factor in the low recognition scores of some of the signs in the first step of the experiment. Most notably in signs number 41 and 69 of the word “alive” and the letter “ط” of Persian alphabet, depicted in Fig. 14, which had recognition scores of 27 and 47 percent, respectively. These scores illustrate the robot’s hand gestures did not accurately reflect the intended forms. A more accurate realization of these forms of hand gestures, shared in many PSL signs, can be achieved by either adding to the dexterity of the thumb or/and the dexterity of index and middle fingers. This can be a design consideration in possible future versions of the *RASA* robot. Since there are multiple structural elements which constitute a sign, multiple factors are necessary to distinguish one sign from another. All of the signs almost uniformly received higher recognition scores in the second step of the experiment, even those receiving the lowest scores in the first round of the experiment. The overall ranges of movements and proportionality of the length of the kinematic chains’ links were deemed acceptable for these 70 realized signs. Furthermore, the shape of the head and neck and their relative positions to other kinematic chains, as well as the facial elements and their positioning were observed to be essential in a more accurate realization and a higher recognition rate of many of the PSL signs. These points must be considered in the final stage of the construction of the remaining physical structures and exterior of the robot. As it has already been pointed out, a dynamic graphical mouth capable of expressing phonemes of Persian language can significantly make the robot’s signing more understandable and greatly enhance the quality of PSL-based communication of the robot. The feasibility of adding this feature must be examined in the future steps of the project.

6 Conclusion and Future Works

We have presented *RASA*, a novel social robotic platform, employed to facilitate teaching Persian sign language to deaf and hard of hearing Iranian children. The hardware design of the robot was discussed based on guidelines stemming from three key characteristics: first, *RASA* features a favorable exterior appearance with a cartoon-like face, and visionary and auditory interaction modules which are designed based on the requirements imposed by child-robot interaction guidelines. Second, *RASA* features an upper-body kinematic structure consisting of 29 degrees of freedom as well as expression capabilities which enable it to effectively perform PSL. And third, utilizing high quality rapid prototyping methods and an economic selection of sensor modules and actuators, with a trade-off between other requirements, the robot’s development cost was less than $10K. Lastly, in a survey with 15 participants, an



(a) PSL sign for the Persian letter "ط". The intended hanshape depicted at the right corner.

(b) PSL sign for the word "alive". Movement of the hand depicted by the white arrow. The intended hanshape depicted at the right corner.

Fig. 14 Examples of some misinterpreted signs assessment of *RASA's* PSL performance was carried out and the results of the experiment were discussed.

The future steps in enhancing *RASA*'s appearance and capabilities include development of the robot's perceptive and cognitive abilities to empower an efficient long-term child-robot interaction. The ability to learn PSL signs through imitation, constructing PSL sentences, and the ability to establish a PSL-based communication with children, are some of *RASA's* future pioneering capabilities. These features with various technical challenges along with enhancing its mobility for other possible applications are currently under study and development [37–39].

Consequently, in future studies other development design decisions will be tested by measuring the children's acceptance of the robot. Most importantly, suitable interaction and teaching scenarios based on the perceived cognitive abilities of the robot must be devised before the robot can be employed as a PSL teaching assistant. In addition, the effectiveness of employing the robot on learning enhancement and engagement of the children needs to be compared and reported with other available teaching methods, e.g. virtual or traditional human-instructor methods. In addition, we plan to report the project's possible influence on motivating parents, deaf communities and institutions.

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