Social Humanoid Robot SARA: Development and Dilemmas

Marko Penčić, *Member, IEEE*, Maja Čavić, Srđan Savić, *Member, IEEE*,
Milan Gnjatović, *Member, IEEE*, Branislav Borovac, *Member, IEEE*, and Zhenli Lu, *Member, IEEE*

***Abstract*—Paper presents the development of a humanoid robot Sara and dilemmas that have accompanied the development. Robot should represent anthropomorphic mobile platform for the research of social behavior of the robot in the immediate human environment. This implies several significant dilemmas – the need to enable verbal and nonverbal communication, cognitive system in all aspects of use, problem of motion and orientation of robots in unstructured environment, manipulation and handling objects, realization of complex sensor system and the need to enable energy autonomy of the robot. Sara will be able to communicate verbally and nonverbally. To express emotion by face, the robot will be able to move the eyes and eyelids. To extend the spectrum of nonverbal communication, the robot will be able to shrug when the question is confusing or when the robot does not know what to answer. In addition, Sara will have two anthropomorphic arms with a total of 14 DOFs, neck with 3 DOFs and lumbar spine with 7 DOFs in order to increase the mobility of the upper body without moving the lower.**

***Index Terms*—Social humanoid robot; verbal and nonverbal communication; facial expressions; mechanical design.**

I. INTRODUCTION

Sara is social humanoid robot for direct interaction with people in everyday human environment that is dynamic and unstructured. This implies several requirements and dilemmas. The most important are: (i) the necessity of verbal communication because it is the most natural form of communication between people and is also expected to be the case between humans and robots, (ii) the need to enable nonverbal communication and the ways for its realization, seeing that even 2/3 of communication between humans is based on the nonverbal communication, (iii) cognitive system which implies the inclusion and integration of the different aspects of cognitive functioning – from recognition of the objects in the living and working space of the humans to managing in environment in which it operates, (iv) problems of motion and orientation in space that is not predefined, (v) manipulation and handling of objects in the human environment, (vi) the sensor system and (vii) how to provide sufficient energy autonomy of the robot as well as independent energy recharging. All these aspects represent separate research areas, which, in case of realized unique device, need to be integrated and harmonized.

Basis of the control system represents is a cognitive system in which information of different nature are being collected and which need to be interpreted in different ways. Therefore, we will not specifically discuss the cognitive system, but only highlight where it must be included.

It is necessary to couple verbal communication and the cognitive system, because verbal communication represents the main source of information about the task that human asks robot to do. Cognitive aspects are extremely important, because they ensure the adequacy and logic of the robots operation. One aspect is to understand the speech of a human which is not subjected to all the rules of grammar. Other is learning that is based on the previous experience – the human assumes that the robot remembers or correctly understands the event that has happened in the past and that will accordingly act in the future.

Nonverbal communication is extremely important and should be realized the same way a human would and can understand – facial expressions and body language. Nonverbal messages are sending clear signals regardless to the meaning of the spoken word, which is why researchers are working intensively on improving the interactive elements of the robot. However, other ways of nonverbal communication can be explored that are not typical for a human, but that human can understand, such as the different types of luminous messages. For example, a man perfectly understands dog behavior although nonverbal communication of the dog – tail wagging, is not done by humans.

A special task is efficient motion and orientation of the robot in the space. When one says to the robot, for example, "Bring my glass from the kitchen!", besides that he needs to know what the glass is and to which glass the request relates, he needs to know how he can arrive to the kitchen from its current location. Solving this task has to rely on the cognitive system as well.

Manipulation and handling of the objects in the human environment implies several classes of tasks that are based on the technical and ergonomic requirements. Thus, opening/ closing doors is related to the handling of the knob, while switching on/off the light is performed by pressing the switch with a certain force. To activate the electrical device is necessary to insert the plug in the socket, where beside to the proper mutual orientation it is necessary to produce adequate force for the plug to be put in or pulled out of the socket. All this require that the robot must have a very sophisticated device for grasping and manipulating objects which performs very much like the human hand. This has not been fully realized, although there are several noticeable attempts. A particular problem is grasping and manipulation of the objects, because the same object can be taken in different ways depending on its use. This aspect is also inevitably linked to the cognitive

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Marko Penčić, Maja Čavić, Srđan Savić, Milan Gnjatović and Branislav Borovac are with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia (e-mail: {mpencic, scomaja, savics, milangnjatovic, borovac}@uns.ac.rs).

Zhenli Lu is with the School of Electrical Engineering and Automation, Changshu Institute of Technology, Hushan Road 99, 215500 Changshu, China (e-mail: zhenlilu@cslg.cn).

system which presents a set of highly complex requirements.

Sensor system represents the basis of human interaction with the environment. Therefore, bearing in mind that the robot will operate in unstructured and dynamic environment, it is necessary that such a system exists in robots as well. Basic sensor that humans use is visual and although researches in this area are significant, there are still not good enough results. It is certain that the vision must be coupled with a cognitive system and that information obtained through vision – pictures, needs to be interpreted in different ways in order to fulfill different tasks. For example, from the image that robot got at the specified time, it is necessary, in one case, to extract information about a possible path so the robot can get to the desired location, while in the second case, it is necessary to see whether the glass that the robot is searching for, is on the table in front of him. In the third case, the robot should recognize where is he currently located and in which direction to go to reach the destination. The sense of hearing also represents a very important sensory system that should ensure quality reception of the audio signal from the interlocutor in real conditions where ambient noise is the basic problem. The sense of touch is also extremely important for contact detection of different parts of the body with the environment as well as for application in the realization of the functional requirements. Detection of the intensity and the position of the contact force are also necessary for the realization of walking and when grasping of the objects with the hand, but a method for interpretation of the information in these two cases is quite different.

It is extremely important to integrate all these aspects into a single device, because only then one can consider all the complexity and interdependence that arises here, therefore it is necessary to carry out research and applied to real systems.

II. State of the Arts

There are several robots that are able to demonstrate the solutions of some of the mentioned problems. A large research effort has been invested to enable nonverbal communication. Robotic heads for direct interaction with human – face to face, are Kismet [1], iCat [2], Flobi [3] etc. They are able to express different emotions like happiness, surprise, calmness, interest, sadness, anger, disgust. Facial expressions are created by moving the eyebrows, eyes, eyelids, ears, lips and jaw. Robots that can express nonverbal communications by using the face and body are iCub [4], BERT2 [5], KOBIAN [6] etc. Facial expressions are created by moving a particular part of the face or displaying it on the screen that represents a face with characteristic elements, or a combination of these two approach, while the gestures are usually realized by moving the head and the arm of the robot.

There are two basic groups of a robots that can move the eyeballs and/or the eyelids independently from the face. The first group of robots – Muecas [7], Probo [8], Twente Humanoid Head [9] etc., have eyeballs with 3 DOFs which move together about the pitch axis – elevation/depression movements and independently about the yaw axis – abduction/adduction movements. The second group of the robots – Robotinho [10], EveR-1 [11], KIBO [12] etc., have eyeballs with 4 DOFs which can move independently about the pitch and yaw axes. Upper eyelids can be actuated together with the eyeballs or independently – it is possible to move each eyelid individually or both together, while the lower eyelids are usually immovable. Power transmission and motion from the actuators to the eyeballs and eyelids is usually performed by belt mechanisms, lever mechanisms and low backlash gear mechanisms that provide high positioning accuracy and repeatability of movements.

There are two basic groups of robots that can move the head independently from the trunk by activating the cervical spine i.e. neck. The first group of robots has a neck with 2, 3 or 4 joints whereby each joint have 1 DOF – rigid structures, while the second group has a biologically inspired neck with a 3-7 joints – viscoelastic structures with 9-19 DOFs. The neck with 2 DOFs – movements about the pitch and yaw axes, is used in robots Pepper [13], NAO [14], MARKO [15] etc., the neck with 3 DOFs – movements about the yaw, roll and pitch axes, is used in robots Affetto [16], EveR-2 [17], HRP-4C [18] etc., while the neck with 4 DOFs – yaw, roll, upper and lower pitch movements, can be found in Romeo [19], SAYA [20], Flutis Robot WF-4RVI [21] etc. Neck structures of these robots usually consist of the rigid and low backlash mechanisms which are interconnected – harmonic drive, cable-driven mechanisms, spindle drive, low backlash gears etc. The advantage of these mechanisms is low backlash that provides high positioning accuracy that enables high accuracy and repeatability of movements, which is essential for motion control.

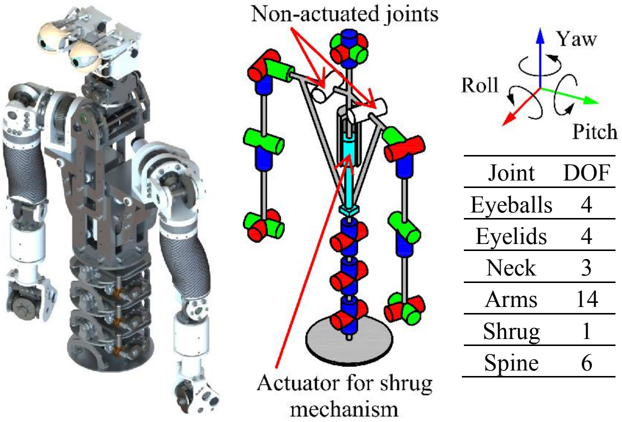
There are two basic groups of robots which can move the trunk independently of the pelvis. The first group has a so-called waist/torso joint with 1-3 DOFs – rigid structure, while the second group have a trunk which is based on the human spine with 3-5 lumbar vertebrae – viscoelastic structure with 9-15 DOFs. Robots Albert HUBO [22], BARTHOC [23], MARKO [24] etc. have waist/torso joint with 1 DOF – movements about the yaw or pitch axis, robots HRP-4 [25], WE-4RII [26], ARMAR-4 [27] etc. have waist/torso joint with 2 DOFs – movements about the yaw and pitch axes, while cCub [28], ROMAN [29], COMAN [30] etc. have waist/torso joint with 3 DOFs – movements about the yaw, roll and pitch axes. Waist/torso joint most commonly consists of rigid and low backlash mechanisms which are interconnected and whose rotation axes intersect in one point – harmonic drive, cable-driven mechanisms, low backlash gears etc.

Biologically inspired cervical/lumbar structures with 3-7 cervical respectively 3-5 lumbar vertebra and large number of DOFs – movements about the yaw, roll and pitch axes, are implemented in robots Kenzoh [31], Kenshiro [32], Kengoro [33] etc. Each vertebra has points for attaching tendons thus enabling independent motion of each joint. Between each two vertebrae there is viscoelastic element – disc of silicone rubber and tension springs – ligaments. The height of each rubber disc is slightly greater than the distance between adjacent vertebrae wherefore discs generate the pressure on the joints and ligaments tighten them. During spine bending, the elastic elements generate force that opposes gravity and thereby help actuators. The advantage of elastic elements is in achieving a significant force at the moment of releasing the accumulated energy.

Basic problem in hand realization is need for actuation of the large number of DOF, because of power transmission and motion as well as the placement of a large number of actuators in a small space. This task has not yet been satisfactorily resolved and presumably requires a new type of actuator which can generate significant forces without transforming rotary into linear motion. Hand actuation is usually performed with tendon-driven mechanisms, planar/spatial linkage mechanisms, low backlash gears, spindle drive and PAMs [34-37]. Although modern hydraulic systems – electro-hydrostatic actuators [38], provide new perspectives there are significant problems that yet have not been resolved.

III. MECHANICAL DESIGN

Sara will be able to communicate verbally and nonverbally. To express facial expressions, biologically inspired eyes and eyelids with 8 DOFs are being developed. In order to extend the spectrum of nonverbal communication, the robot will be able to shrug when the question is confusing or when the robot does not know what to answer. In addition, Sara will have two anthropomorphic arms with 14 DOFs, self-locking neck with 3 DOFs and self-locking multi-segment lumbar spine with 7 DOFs to increase the mobility of the upper body without moving the lower body. Fig. 1 shows the kinematic structure of the robot Sara.



Joint	DOF
Eyeballs	4
Eyelids	4
Neck	3
Arms	14
Shrug	1
Spine	6

Fig. 1. Social robot SARA – current prototype and its kinematic structure

A. Face and Eyes

The requirements concerning the look of the robots face are not entirely clear because of the inhomogeneous auditorium with which the robot should communicate, but it is commonly accepted that the robot should resemble the human. Differences must be obvious, because, in that case, imperfections will be not considered as defects. Fig. 2 shows the face of a robot Sara which is stiff and motionless, while the eyes are movable. Face has a feminine look with striking eyes. Eyelids are rotated in two planes – first about the z axis for the angle α, and then about the x axis for the angle β. The upper eyelid will have eyelashes. In addition, parts of the face will be able to change color depending on the situational context of the robot.

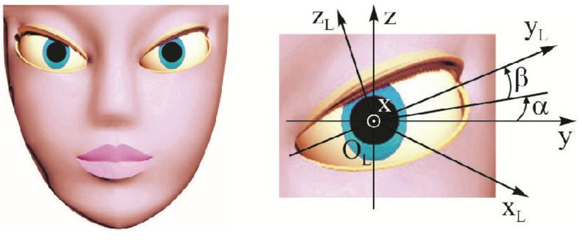


Fig. 2. Face of the robot Sara and eye with eyelids rotated in two planes

The eyes are the most expressive part of the face and represent an important aspect of social interaction. If a robot were to look at the face of the person in front of it, an impression of attention and focus would be given – blinking gives the impression of naturalness. In addition, the intensity of openness and position of the eyelids enables expression of different emotions such as surprise, fatigue, sorrow etc. All of the above, further gains in importance if the rest of the face is stiff and immovable, as is the case with most robots. Therefore, special attention should be given to the design and realization of the eyes.

In Fig. 3 robotic eyes with 8 DOFs are presented. They consist of two drive systems – eyeballs and eyelids drive systems. The eyeballs drive system has 4 DOFs and consists of two symmetrical planar mechanisms that enable independent motion of the eyeballs about the yaw axis – abduction/adduction movements and two identical spatial mechanisms that enable independent motion of the eyeballs about the pitch axis – elevation/depression movements. The eyelids drive system has 4 DOFs and consists of four structurally equal spatial mechanisms that enable independent motion of each eyelid – the mechanisms for driving the upper and lower eyelids are symmetrical, respectively. Based on the kinematic analysis [39] a motion simulation of eyeball and upper/lower eyelid is performed [40]. Velocities of eyeball/eyelids correspond to the parameters of the human eye. In addition, the proposed solution enables the installation of cameras in the eyeball thus realizing the function of artificial vision of the robot.

Fig. 3. Eyeballs and eyelids with 8 DOFs

B. Neck and Lumbar Spine

The human body is musculoskeletal and viscoelastic structure that has variable flexibility and about 350 DOFs. However, almost all humanoids that have been developed have rigid bodies and their mobility is therefore limited and unnatural. Spine enables the upper body movements without moving the lower, so the higher assortment of movements is achieved and the range of the robot arms reach is increased. In addition, humanoids that have 1 DOF in the torso area, when walking require 26.5% less energy compared to humanoids with rigid torso [41].

Based on reviewed literature, it is determined that there are two basic ways for the realization of the robot spine. The first is based on a low backlash mechanism that have a high stiffness, and the second on biologically inspired viscoelastic elements having variable elasticity. We propose a low backlash gear mechanisms that require small actuators.

In Fig. 4 neck mechanism with 3 DOFs is presented. It enables movements in the direction of flexion/extension, lateral flexion and rotation. The movements of flexion/extension are enabled by a worm mechanism that is self-locking – lead angle is greater than the friction angle, and has low backlash – a few teeth of a worm gear are always in mash with the worm shaft. The movements of the lateral flexion and rotation are enabled by differential mechanism with three bevel gears – two gears are driving and are identical, and the third one which is driven gear to which the robot head is attached. If driving gears have the same circumferential velocities and the same direction of rotation, then the lateral flexion movements are performed, and in the case of the opposite direction of rotation, torsion movements are performed. If the circumferential velocities of driving gears are different, a combination of these two movements is achieved.

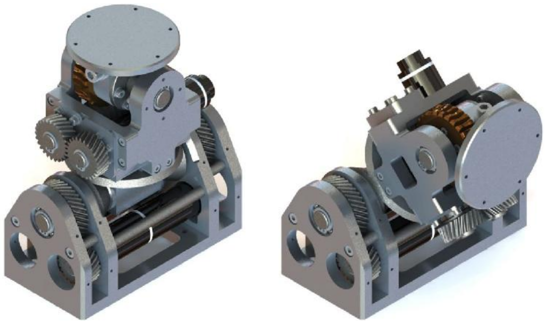


Fig. 4. The self-locking and low backlash neck mechanism with 3 DOFs: (left) upright posture and (right) flexion + left lateral flexion + left rotation

Fig. 5 presents the multi-segment lumbar structure with 6 DOFs that enables movements of lateral flexion and rotation, as well as the combination of these two movements [42]. It consists of three identical segments which are interconnected whereby each segment has 2 DOFs. The movements of lateral flexion are enabled by worm mechanism with reduced dimensions – because of the small range of rotation only a few teeth are in use, so worm gear body is realized as a circular segment. The worm mechanism is self-locking and has low backlash. The movements of rotation are realized by spindle drive mechanism with trapezoidal thread which is also self-locking and has low backlash.

Further work on the development of the lumbar structure, in addition to already realized movement of lateral flexion and rotation, predicts and embedding of additional joint in the pelvis area for movements of flexion/extension. This will, expand the spectrum of the position of the spine as well as the arms reach and contribute to the robot movements so that they will become more diverse and human-like.

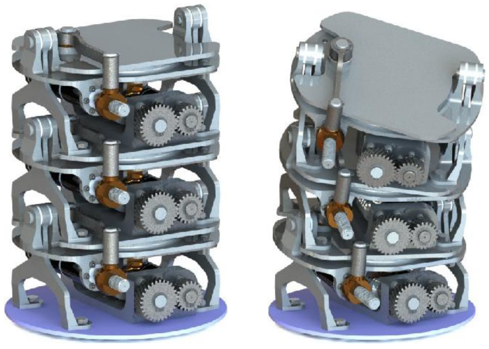


Fig. 5. The self-locking multi-segment and low backlash lumbar structure with 6 DOFs: (left) upright posture and (right) lateral flexion + right rotation

C. *Shrug mechanism*

Shrug is one of the most important aspects of the human nonverbal communication. It is a relatively fast action and therefore the duration of the movement should be very short. By reviewing available literature it is determined that there are only two robots that are able to realize shrug. The first one is the WE-4RII [26] having a shrug mechanism with 4 DOFs that enables independent movements of the shoulder in two directions, and the second one is BARTHOC [43], which has embedded elements above the shoulders and their activation simulates shoulder shrugging.

In Fig. 6 shrug mechanism is proposed. It has 1 DOF and enables simultaneous shrugging of both shoulders [44,45]. It consists of driving and working mechanisms. Driving mechanism is an actuator which is coupled to the ballscrew spindle and which transforms a rotary motion into linear. Working mechanism is based on the lever linkage mechanism whose input link is a ball nut. Shrug mechanism has low backlash, enables high shrug speed and requires small driving force on the input link of the lever mechanism. Neck and arms of the robot are attached to the shrug mechanism. It should be noted that two shrug mechanisms are developed which by size and power fulfill the requirements [46,47].

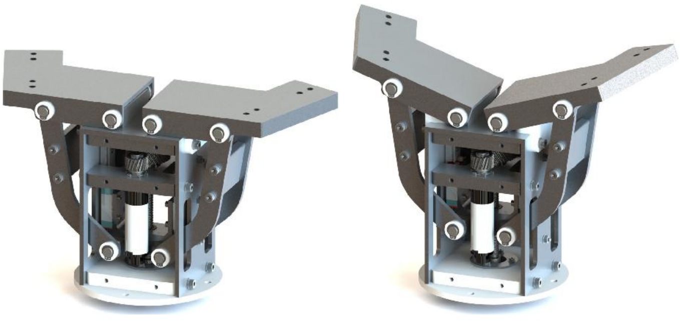


Fig. 6. The shrug mechanism with 1 DOF – starting and final position

D. *Arm and hand*

The basic problems in the realization of the robot hand occur due to the masses of the segments and backlash in the joints. In order to minimize the driving torques in the joints it is necessary that the masses of segments are as small as possible, and their center of gravity is positioned as close as possible to the shoulder joint. Therefore it is suitable to place the actuators for shoulders in the shoulder itself, because then the pedestal bears their mass. Actuators for upper/lower arm should be placed as close as possible to the shoulder. Arms of modern design [48-50] have segments made of carbon fiber with flanges embedded at their end and low backlash harmonic drive mechanisms.

Fig. 7 shows a low cost robot arm having 7 DOFs: 2 DOFs shoulder, 1 DOF upper arm, 1 DOF elbow, 1 DOF lower arm and 2 DOFs wrist. Besides the harmonic drive which is used to rotate the upper arm, all other reducers are based on low backlash gears. Low backlash at bevel gears is achieved by a radial and/or axial movement of the actuator considering that a driving gear is mounted directly on the shaft of actuator/gearhead, while at helical gears low backlash is achieved by precise manufacture and gears preloading – center distance has negative tolerance.

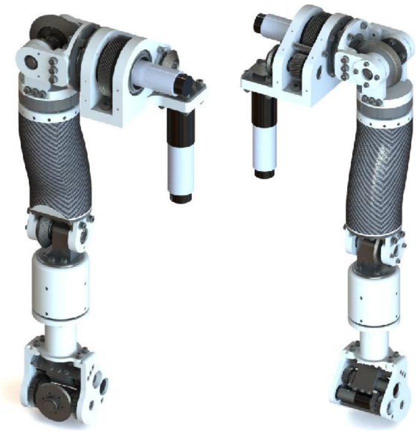


Fig. 7. The right arm with 7 DOFs – front and back view

Proposed underactuated hand which has 5 DOFs [51] is shown in Fig. 8. It consists of 5 fingers whereby each finger has three joints, except for the thumb, which has four. The total number of joints is 16. All 5 DC motors are located within the hand. Index and middle finger are actuated by one motor independently, while small and ring finger are both actuated by one motor. Thumb is actuated by two motors – one for the movements of flexion, and the other for rotation of the thumb. In each joint there is a torsion spring, which sprawls the finger, and in each segment there is a channel for conducting tendon. Actuator draws the tendons and thus bends the fingers, while the spring sprawls them. In the first and the third segment of each finger there is a miniature 3-axis force sensor [52] consisting of 4 Hall sensors and a permanent magnet between them. Everything is coated with silicone rubber thus forming a fingertip.

Fig. 8. The underactuated hand with 5 DOFs and total 16 joints

IV. CONCLUSION

Paper presents the mechanical structure development of humanoid robot Sara which is designed to research the social behavior of robot in everyday human environment that is dynamic and unstructured. From the aspect of the mechanical structure only the upper part of the body is discussed in detail and solutions of face with the eyes, movable neck, lumbar spine, torso with a shrug mechanism, arms and hands are described. However, the problem of movement realization is not discussed. The robot can move by bipedal locomotion or so that the upper part of the body is placed on a movable platform. The proposed solution of a torso enables application of both ways of the motion. Issue of the robot locomotion will be considered in the future research. In addition, a special problem which is only mentioned, but not specifically elaborated in the work, is the cognitive control system which should enable adequate and meaningful functioning of the robot. This problem is particularly serious and extensive and it will also be part of research activities in the future period.

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