Original Article

Proc IMechE Part H:
J Engineering in Medicine
2018, Vol. 232(6) 605–618

DOI: 10.1177/0954411918777520
journals.sagepub.com/home/pih

Arash: A social robot buddy to support children with cancer in a hospital environment

Ali Meghdari[1], Azadeh Shariati[1,2], Minoo Alemi[3], Gholamreza R Vossoughi[1], Abdollah Eydi[1], Ehsan Ahmadi[1], Behrad Mozafari[1], Ali Amoozandeh Nobaveh[1] and Reza Tahami[1]

Abstract

This article presents the thorough design procedure, specifications, and performance of a mobile social robot friend *Arash* for educational and therapeutic involvement of children with cancer based on their interests and needs. Our research focuses on employing *Arash* in a pediatric hospital environment to entertain, assist, and educate children with cancer who suffer from physical pain caused by both the disease and its treatment process. Since cancer treatment causes emotional distress, which can reduce the efficiency of medications, using social robots to interact with children with cancer in a hospital environment could decrease this distress, thereby improving the effectiveness of their treatment. *Arash* is a 15 degree-of-freedom low-cost humanoid mobile robot buddy, carefully designed with appropriate measures and developed to interact with children ages 5–12 years old. The robot has five physical subsystems: the head, arms, torso, waist, and mobile-platform. The robot's final appearance is a significant novel concept; since it was selected based on a survey taken from 50 children with chronic diseases at three pediatric hospitals in Tehran, Iran. Founded on these measures and desires, *Arash* was designed, built, improved, and enhanced to operate successfully in pediatric cancer hospitals. Two experiments were devised to evaluate the children's level of acceptance and involvement with the robot, assess their feelings about it, and measure how much the robot was similar to the favored conceptual sketch. Both experiments were conducted in the form of storytelling and appearance/performance evaluations. The obtained results confirm high engagement and interest of pediatric cancer patients with the constructed robot.

Keyword

Children with cancer, robot design, humanoid robot, social robot, storytelling

Date received: 17 September 2017; accepted: 25 April 2018

Introduction

Cancer is one of the most serious illnesses in the world, which annually imposes high costs on patients and governments. This disease is considered the second leading cause of death among children aged 1–14, after accidents.[1] In Iran, approximately 4500 children are hospitalized with cancer every year and undergo therapeutic treatments.[2] Distress and anxiety are some of the important psychological complications of cancer. Distress complication is known to be an important issue in cancer patients and has been viewed as the sixth vital factor to be investigated. Among patients, children with cancer suffer more from distress due to the lack of knowledge and life skills.[2] Meanwhile, it has been observed that social robots are of special interest to most children and using them in therapeutic sessions

[1]Social & Cognitive Robotics Laboratory, Center of Excellence in Design, Robotics, and Automation (CEDRA), Sharif University of Technology, Tehran, Iran
[2]Department of Mechanical Engineering, Islamic Azad University, North Tehran Branch, Tehran, Iran
[3]Department of Humanities, Islamic Azad University, West Tehran Branch, Tehran, Iran

Corresponding authors:
Ali Meghdari, Social & Cognitive Robotics Laboratory, Center of Excellence in Design, Robotics, and Automation (CEDRA), Sharif University of Technology, P.O.B. 11365-9567, Tehran, Iran.
Email: meghdari@sharif.edu

Azadeh Shariati, Faculty of Engineering, Islamic Azad University -Tehran North Branch, P.O.B. 1651153311, Tehran, Iran.
Email: azadeh.shariati@mail.kntu.ac.ir

can reduce their anxiety and distress.[3,4] In prior studies, we combined psychological methodologies with the social values of a commercial humanoid to observe its impact on pediatric cancer distress management. In these studies, children with cancer were assigned into two groups: a psychotherapy group and a social robot–assisted therapy (SRAT) group. A NAO humanoid robot was involved as an assistant to the psychologist in the SRAT group to perform various scenarios in intervention sessions. The robot was programmed to play various roles in interaction sessions such as a nurse, a doctor, a cook, and an ill child. As a result, several factors including short-term changes in the children's level of anxiety, depression, and anger during the treatment process were observed.[3,4]

These observations encouraged our group to design and construct an economical mobile social robot for hospitalized children, with better stability and performance as compared to the legged humanoid robots.[5] The name *Arash* was chosen for this robot to commemorate a kind and caring young friend and physician (Dr Arash Ehteshami Rad) who recently lost his struggle with cancer in the United States.

Social robots are a group of robots designed for various objectives, behavioral, and environmental conditions. Their physical designs are distinguished by their appearance, human–robot collaboration,[6,7] and their role as an assistive tool in educational, entertainment, and therapy sessions.[8–12] Therefore, in the design of a social robot; research objectives as well as behavioral and environmental parameters dictate various physical properties (i.e. humanoids, system-like,[13] animalistic). In our study, the distinctive health conditions of the children who will interact with the robot mandate specific features to be considered along with other factors in the morphology. The robot is required to play diverse roles and produce various gestures for better interaction and communication. After considering these circumstances and consulting with psychologists, we concluded that a human-shaped appearance is preferred for the *Arash* social robot.

Based on the humanoid morphology selection, the motion mechanism of the platform was designed. Since children are generally hospitalized in different rooms and areas, the robot must be able to easily move around in hospital environments and preserve its stability in various situations. Due to these factors, a wheeled mobile-platform was chosen for the platform of *Arash* (biped walking designs were ruled-out due to their instability and loss of balance, which makes them too vulnerable to physical damage for long-term interaction with children).

There are several ways to produce facial expressions in social robots (i.e. mechanical components,[14] silicon-based skins,[15] Liquid crystal display (LCD) screens[5,13]). We chose a cost-effective LCD display screen located in the head for *Arash*. It has the ability to show a wide range of facial expressions and easily change facial features to meet the interests and needs of various age groups. Since constructing a low-cost social robot was a major design consideration for *Arash*, adequate degrees of freedom (DOFs) were considered for effective interaction with children. Finally, *Arash* was designed to meet certain specifications, that is mainly being safe and robust when interacting with children in a hospital environment.

Cancer treatment has unpleasant side-effects such as physical and psychological weakness; and therefore, the safety in utilizing a social robot like *Arash* to interact with pediatric patients becomes very important. In our work, safety is divided into two parts: physical and mental safety. Physical safety means that the robot should not create any physical threat (including the possibility of collapse, collisions, sharp edges, shocks, etc.) for the children. Mental safety means that the robot should not be the cause of any mental or psychological threat (including unpleasant body and facial shape, unpleasant voice tone, and inappropriate interaction contents) for the children.

Essentially, the goal of realizing a social robot is the ability to interact with humans and thus improve their living conditions. Human–robot interaction encompasses any kind of collaboration, cooperation, and exchange of thought and feelings that takes place between the robot and a human being. For *Arash*, interactive inputs include hearing (sound source localization (SSL)), seeing (facial expression recognition), and tactile sensation; the interactive outputs are made up of audio (speech), facial expression, and body language.

In this study, a social robot was designed and realized for interaction with children with cancer (see section "The *Arash* system specification"). The robot is a mobile-based human-shaped robot designed and developed based on a survey taken by children with cancer in three hospitals in Tehran (see section "Physical appearance of the *Arash*"). The robot has various mechanical subsystems such as a head, arm group, torso, waist, and mobile-platform (see section "Electro-mechanical design of the *Arash*"). The social robot utilizes the Robotic Operating System (ROS),[16] which provides useful tools and libraries to facilitate the development of its robotic software (see sections "Software architecture of the *Arash*" and "*Arash* interactions"). Its human–robot interaction modules include communication through voice, vision interaction, and facial/body gesture (see section "Human–robot interaction"). Social robots have a great potential to tell stories as well as create mental images and human emotional behaviors.[17] In section "Experiments: assessing social acceptance of *Arash*," two experiments are conducted to evaluate the children's level of involvement with the robot by means of storytelling and its appearance/performance. In the first experiment, *Arash* is used as a storytelling robot and compared with an Audio book. To do this, standard questionnaires were used to study the level of children's engagement with the story and their perception about the robot. In the second experiment, the children's feelings about the robot and "favored conceptual sketch" are asked and compared via another standard questionnaire.

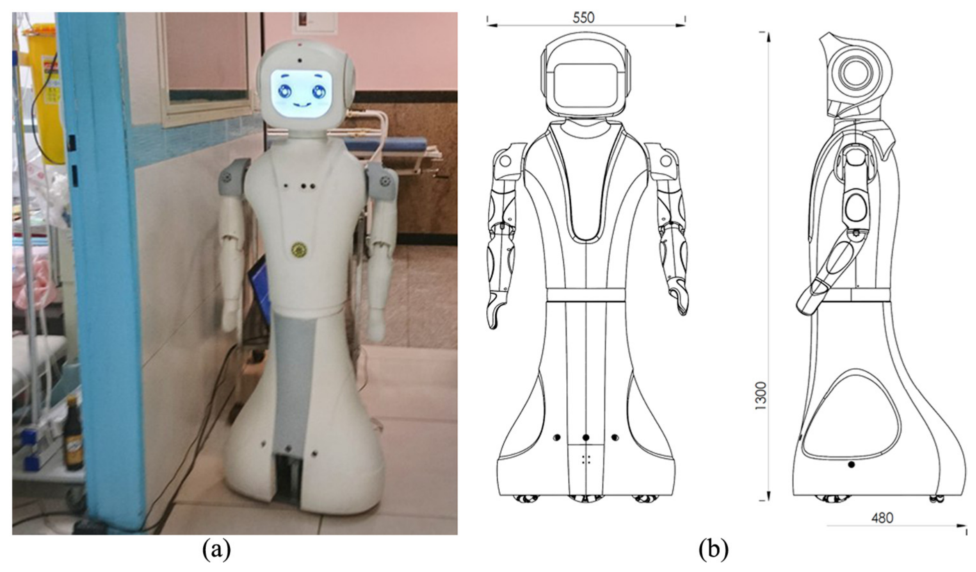

Figure 1. (a) The *Arash* mobile social robot in a hospital environment and (b) shape of the *Arash* mobile social robot.

The *Arash* system specification

The portable social robot *Arash* is designed and fabricated for educational and therapeutic interventions for children with chronic disease, particularly cancer, in clinical and hospital settings. This robot is able to navigate in different areas of the hospital and interact with children with cancer in order to answer their questions, to motivate, entertain, help alleviate their pain and distress, and improve their collaboration with the hospital staff. Figure 1 displays the schematics of the *Arash* mobile social robot and Table 1 delivers its constructed design features and specifications. The robot has 15 DOFs, stands 130 cm tall, has a 55 cm round base, weighs 24 kg, and employs a humanoid shape in the upper body. It has 2 DOFs in the waist, 8 DOFs in the arms, 2 DOFs in the neck, and 3 DOFs in the mobile-platform. A very important feature of the *Arash* robot is the ability to develop it at a reasonably low-cost (approximately US $ 6000). As a result, custom-made mechanical parts, sensors, and actuators are employed. Costly parts and options like fingers are avoided in the final design.

Physical appearance of the *Arash*

The social robot's physical appearance is an important issue since it makes the first impression with children. For better interaction, the approximate height and appearance of the social robot were set to conform to the height and taste of elementary school children with socially acceptable dimensions and shape, as described in Figure 1. The design of *Arash's* look was based on a survey taken by children with chronic diseases. Collaborating with psychologists and an industrial art designer, five sketches were prepared for a survey for children in hospital environments (see Figure 2 (a)-(e)). Fifty hospitalized children participated in the survey conducted at the Ali Asghar, Mahak, Mofid, and Shohada (Behnam Daheshpour) Hospitals in Tehran (see Figure 3(a)).

Participants were divided into two age groups. The majority of the participants in this study were 7 years old or older making up 58% (frequency = 29) of all participants, and those aged 6 or under were 42% (frequency = 21) of the population that took part in this survey. The processes followed were in accordance with the ethical standards of the responsible committee on human experimentation at Sharif University of Technology and with the Helsinki Declaration of 1975, as revised in 1983.

In this study, the number of males accounted for 80% (frequency = 40), whereas females made up only 20% (frequency = 10) of all participants. A total of 50 ill children participated in the survey to choose the most favorable *Arash* drawing among the five different sketches. The popularity of the different choices is illustrated in Table 2. Twenty out of fifty participants (40%) picked the first choice, followed by the third choice selected by 16 kids (32%). Choices (b) and (e) were equally popular and chosen by five participants (10%) each and only four kids (8%) favored choice (d) making it the least popular. Due to the results obtained from statistical data of this section, sketch (a) in Figure 2 was favored and nominated to be designed and fabricated as the *Arash* mobile social robot (see Figure 3(b)).

Electro-mechanical design of the *Arash*

The detailed design of *Arash* based on the robot's specifications and the selected drawing are presented here. At this stage, it was crucial for the research group to match the detailed design with the primary

Table 1. Design specifications of the *Arash* social robot.

Height	130 cm
Weight	24 kg
Moving speed	0.8 m/s
Actuator	9 Servomotors, 5 DC motors, 1 linear motor
Control unit	High-level control, Low-level control
Sensors	
Head and neck	Microphones, camera, touch sensor
Torso	Three-axis gyro, accelerometer, Kinect
Arms and hands	Encoders, touch sensors
Mobile-platform	Ultrasonic sensors, encoders, LiDAR sensor
Power section	
Battery	4 Lead-acid battery, 12 V, 7.5 Ah each
Operation section	Intel® NUC Home Mini PC, Arduino Mega 2560
Operating system	ROS on Ubuntu 14.04
Degrees of freedom	15 DOFs

ROS: Robotic Operating System; DOF: degree of freedom.

appearance chosen by the children (see Figure 3(b)). The five main subsystems of the *Arash* robot are the head and neck, torso, arm groups, waist, and the mobile-platform:

The main role of the head is to interact with the children and hospital staff by receiving data from various sensors and then respond appropriately. An 8-in LCD display screen is used to produce human-like facial expressions. There are 2 DOFs in the neck resulting from two interconnected perpendicular actuators (see Figure 4(a)). The robot spots a face or identifies a voice with the help of the neck actuators; associated sensors (camera, Kinect sensor, and microphone array) help it to follow the utterance.

The arm assembly consists of four mechanical components: the upper arm (upper arm inside and upper arm outside), the forearm (forearm inside and forearm outside), the wrist, and the shoulder cover. Two perpendicular servomotors connect the torso and the upper arm, while the shoulder cover supports and protects these actuators. Due to limited space, a direct current (DC) geared motor is used in the wrist joint of the arm.

A mini PC, a Kinect sensor, and an audio card were all installed in the torso of the robot. The structure of the torso was constructed using aluminum profiles and plates; several other plates and holders were utilized to support the mini PC, Kinect sensor, audio card, and other components.

Arash has 2 DOFs at the waist, which are rotations about the vertical and horizontal axes. A servomotor with an internal gear set (ratio 16:100) was selected to generate the torque required to rotate the upper body. Since bending at the upper body requires high torque in a limited range, a linear actuator was used with a lever mechanism to fulfill this requirement. A

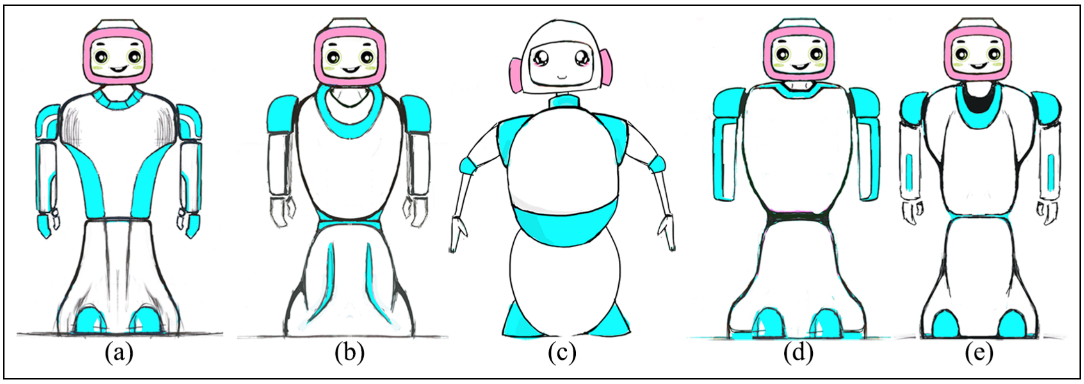

Figure 2. The final *Arash* robot drawings used in the survey.

Figure 3. (a) Survey sessions at *Mahak* and *Mofid* hospitals in Tehran and (b) the favored *Arash* sketch.

Table 2. Sketch of the *Arash* robot chosen by participants in the survey.

Choice	Frequency	Percent
(a)	20	40.0
(b)	5	10.0
(c)	16	32.0
(d)	4	8.0
(e)	5	10.0
Total	50	100.0

semi-spherical cover was designed to conceal the waist joints for protection and a nicer appearance.

The *Arash* social robot should be able to move instantly in any arbitrary direction and orientation to approach a final pose. As a result, omni-directional wheels drive system were carefully chosen to achieve this goal. For this purpose, three geared DC motors were used to insure sufficient drive power (see Figure 4(b)). The robot should be able to move freely through doors and navigate around in rooms and corridors in hospital environments. Moreover, architectural codes mandate a 65 cm maximum width for the robot, which is compatible with the standard door width in hospitals.[18] As a result, the robot's somewhat oval-shaped base diameter does not exceed 55 cm in diameter.

The stability issue in wheeled mobile robots is a challenging factor that should be considered in the design phase. The issue, in addition to being influenced by the initial design of the wheeled mobile robot, is also influenced by the maneuvering of the robot in different situations. Wheeled-mobile robots with more than two wheels are inherently statically stable as the center of mass of the robot is within the support polygon. In the case of accelerating and maneuvering outside the defined range or being hit, the stability of the robot is diminished. The concept of zero moment point (ZMP) is an important tool in measuring a humanoid robot's stability. The most important characteristic in ZMP computation is that the horizontal components of the torque caused by inertial, gravitational, and external forces on the support polygon surface are zero.

According to the geometric characteristics of the robot ($h = 0.380\,m$, $L_1 = 0.228\,m$, $L_2 = 0.097\,m$ (see Figure 5)) and ZMP analysis (equation (1)[19]), the maximum forward acceleration of the *Arash* robot is $5.88\,\mathrm{m/s^2}$, and the maximum backward acceleration (braking acceleration) is $2.5\,\mathrm{m/s^2}$

$$p^x = b^x - \frac{h}{g}\ddot{b}^x \tag{1}$$

where x indicates motion in the x-direction. If the robot accelerates higher than the maximum accelerations, it will lose its stable state meaning that it no longer stands on its three wheels. In addition, the results of ZMP

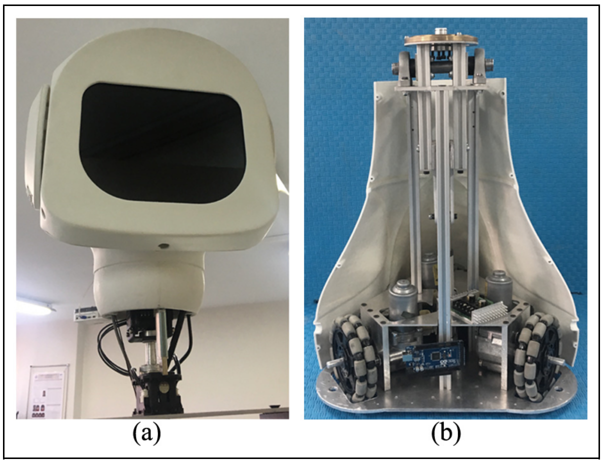

Figure 4. (a) The head mechanism and its components and (b) the mobile-platform and its components.

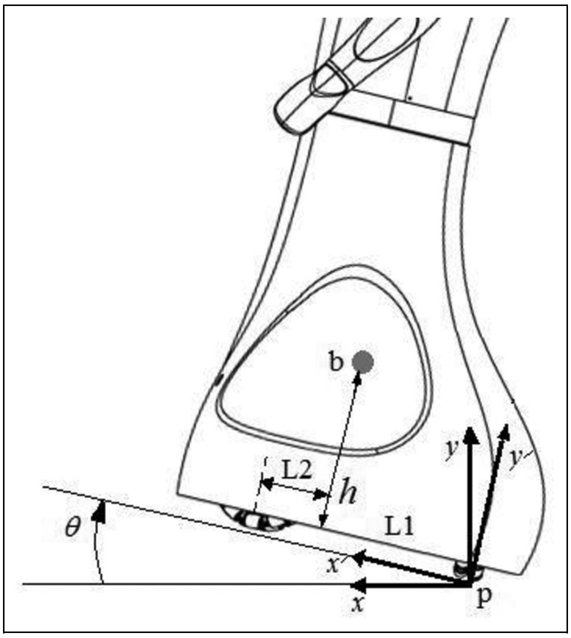

Figure 5. The *Arash* robot riding on a slope for stability analysis.

analysis show that the ZMP of the robot at constant speed has no effect on its stability. The maximum forward acceleration of the robot while going uphill and the maximum braking acceleration while going downhill at different slope angles according to the ZMP concept ((equation (2)[19]) are presented in Table 3

$$\ddot{b}^{x'} = \frac{b^{x'} - p^{x'}}{h} g\cos\theta - g\sin\theta \tag{2}$$

where x' indicates motion in the x'-direction.

Based on the Americans with Disabilities Act (ADA) standards, maximum allowable ramps in the hospital environment should be at 1:12 slope ratio.[18] Therefore, according to Table 3, *Arash* can move on the 1/12 slope ratio in both uphill and downhill directions and passes

Table 3. Maximum forward/braking accelerations while the robot moves uphill/downhill at different slopes.

Slope angle (θ) (°)	0°	2°	4.8°*	10°	14°
Maximum forward acceleration (uphill) (m/s^2)	5.88	5.54	5.04	4.09	3.37
Maximum braking acceleration (downhill) (m/s^2)	2.5	2.16	1.67	0.76	0.05

*Maximum ramp slope in a hospital according to the Americans with Disabilities Act (ADA) is 4.8°

this standard. As mentioned in Table 1, *Arash's* maximum speed is about 0.8 m/s; hence, on flat surfaces, it can stop in 8 cm from maximum speed without losing stability. In uphill and downhill conditions, the controller reduces the robot's speed to half of its maximum, so in a worst case scenario the robot can stop in 7 cm.

Hardware architecture of the *Arash*

A central PC and a high-level controller, with the help of some local controllers, regulate the *Arash* robot. Local controllers perform low-level control tasks for velocity and position control of the wrists, the linear actuator, and the mobile-platform. Three types of actuators drive the robot:

Servomotors: Six servomotors drive the upper arms and forearms. Two servomotors drive the neck, and another one is used for yaw motion of the waist. Servomotors seemed an ideal choice due to the need for precise control and setup limitation in the arms and neck of the robot.
DC motors: geared brushed DC motors are used to drive the wrists due to space limitations. The motor controller L298N drives two DC motors, and three brushed DC motors drive the mobile-platform.
Linear actuator: a LA25 linear actuator is utilized for pitch motion of the waist. It is a 12 V DC permanent magnet motor.

The different types of sensors used in the *Arash* robot are as follows:

Localization sensors: Six sonar range finders, an inertial measurement unit (IMU) (three-axis accelerometer, three-axis Gyro, compass), and a LiDAR (light detection and range) sensor are integrated into the base of the robot. These sensors are utilized for vehicle localization in the hospital environment.
Interaction sensors: Touch sensors, microphone array, and a camera are located in the head of the robot, as well as a Kinect Xbox 360 located in the torso. These sensors are effectively used in the interaction process.

Software architecture of the *Arash*

The ROS was selected as an open-source software[16] to control the *Arash* robot. The reasoning was that the ROS could facilitate the development of robotic software by providing useful tools and libraries. ROS, as an operating system, manages services like hardware abstraction, low-level control of devices and actuators, data transferring among different processes, and software package management. It also has the tools and libraries for developing and executing program codes between different machines; as a result, the robot can be controlled with another computer connected via a network.

Arash interactions

Arash interactions are classified into two categories: the first includes the interaction of the robot with its environment and the second contains the human–robot interaction. Figure 6 demonstrates the various modules that provide these interactions. The modules shown in blue represent the sensors and those marked in red demonstrate the actuators of the robot. Since some modules simultaneously contain sensors and actuators, they are shown in both blue and red. For instance, the Dynamixel motor management unit, which is shown in blue and red, is able to send motion commands to the motors and simultaneously receive joint state angles from the encoders.

The majority of *Arash's* human–robot interactions are conducted through the microphone array, the camera, the display screen, the tactile sensors, the speakers, and the Kinect sensor. The microphone array is used for SSL; the camera and Kinect sensor are utilized for facial expression recognition. In addition, Kinect is also used for gesture recognition and environmental visualization.

In ROS, upon distribution of all duties, each task is executed using a certain node. These nodes communicate with each other via concepts called topics.

As shown in Figure 7, the base interface node runs on the main computer. After receiving the desired linear and angular velocity of the mobile unit from other corresponding nodes (e.g. a node which is in charge of high-level control of the robot's base), the main computer will first compute the velocity of base motors and then send these data to the interface microprocessor to control the speed of motors. In addition, the base interface node receives data transmitted by means of the interface board from the encoders of the three motors and then computes and distributes to the odometer topic. This topic is then utilized in the high-level robot position control.

The interface board is in communication with the DC motor drivers using the universal asynchronous

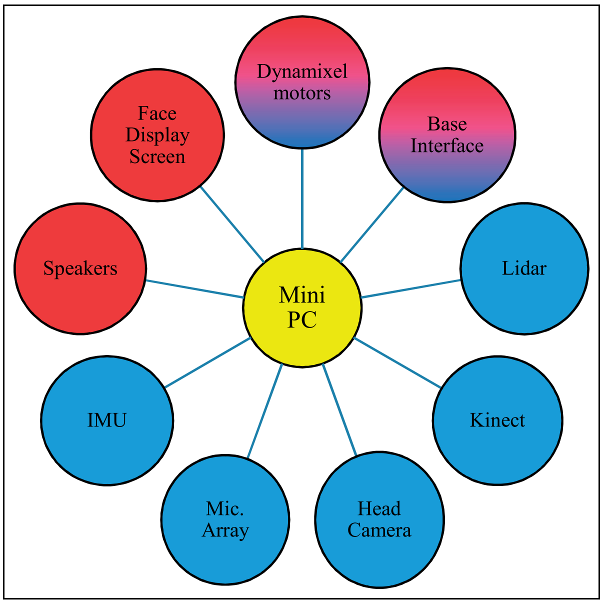

Figure 6. The modules connected to the *Arash* robot main computer.

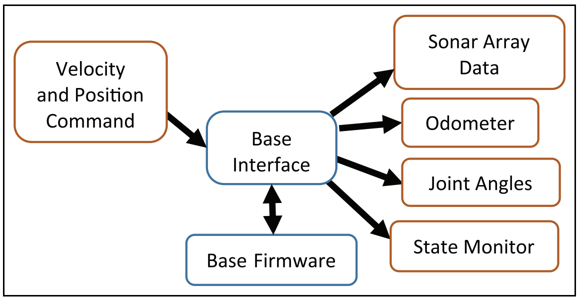

Figure 7. Position control software architecture of *Arash*.

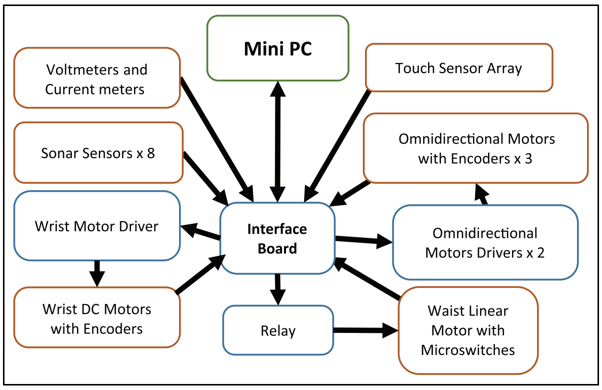

Figure 8. Interface board and its connections.

receiver-transmitter (UART) protocol (see Figure 8) which is also connected to the encoders. The velocity of the wheels is computed using their optical incremental encoders, and the joint state angle of the waist and the wrists is computed using their conductive absolute encoders. In addition, the rotation direction of each wheel is determined from its two-channel 120-pulse encoders in which the channels have some phase shift.

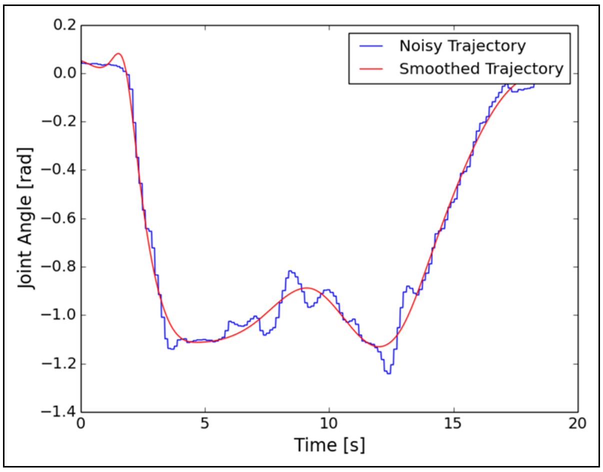

Figure 9. Recorded trajectory of an arbitrary scenario.

The hands, the head, and the waist are controlled by Dynamixel servomotors that are connected directly to the main PC. The "Dynamixel manager" node is in charge of this communication sending desired joint state angles and monitoring the real joint state angles of the Dynamixel motors. The *Arash* robot must be able to perform predesigned scenarios. A smoothening process is used to ensure smooth motion during the scenarios; thus, an operator first directs the joint trajectory. The operator moves all joints in a desired manner while the "Rosbag" package simultaneously records the topic containing the real joint state angles. Once the trajectories are smoothened using third-order spline curves, they are recorded and applied to move the actuators to implement the scenario. For instance, Figure 9 illustrates the shoulder servomotor's trajectory of an arbitrary scenario before and after smoothening.

Human–Arash robot interaction

The *Arash* robot has the ability to interact with humans in many ways. Some of these are communication through voice, vision interaction, and facial/body gesture. The vision interaction system involves facial expression recognition of an applicant and facial expression production by the robot, and the gesture production module includes motion generation by the robot actuators. Another of the robot's interaction module is the voice interaction system. *Arash's* voice system allows the robot to speak with and listen to the communicators in Persian. Text to speech, SSL and the robot's speech acts are diverse parts of the robot's voice system. Currently, there exists no software for dialog management in Persian, so the robot's speech ability is limited to broadcasting pre-recorded sounds (Wizard-of-Oz technique). In future endeavors, *Arash* will be able to produce audio content in the Persian language. *Arash's* interaction features are discussed in detail in the following sections.

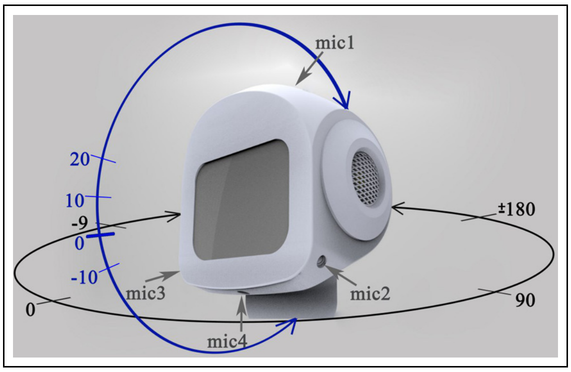

Figure 10. Location of Arash microphones and the environmental sound received in horizontal and vertical planes.

SSL

Verbal communication has a significant role in a mutual interaction. To have a natural human–robot interaction, the robot should be able to turn its head toward the speaker. Four microphones were used in *Arash's* head to design the SSL system. Two microphones on both sides of the head (microphones 2 and 3) are called the horizontal microphones, and a microphone at the top and a microphone on the bottom of the head (microphones 1 and 4) are referred to as the vertical microphones. These microphones enable the robot to localize the sound source in both vertical and horizontal directions.

The robot is first placed in an acoustic room to localize the sound source. Then, the speech segments in the sound are recognized using the speech activity detection (SAD) modules. If the sound is in the form of speech, SSL will be performed. By making a practice sound at different angles in the acoustic room, the sound features are extracted for the horizontal and vertical microphones. In this case, the sounds were released in $[-180°, -170°, \ldots, 170°, 180°]$ degrees in the horizontal plane, and $[-10°, 0°, 10°, 20°]$ degrees in the vertical plane (see Figure 10). As a result, 144 sound data sets were produced (each data set contains four data corresponding to each microphone). For SSL, two features from each data set were extracted. These features are as follows: (a) interaural time difference (ITD) and (b) interaural level difference (ILD).[20]

ITD. Various methods have been proposed to calculate ITD. One of the most commonly used methods is the generalized cross-correlation (GCC) algorithm.[20]

Using the phase transform (PhaT) function for the cross power spectral (CPS) estimation of two signals, G(f), the GCC function is obtained as follows[21]

$$G(f) = \frac{X_L(f)[X_R(f)]^*}{|X_L(f)[X_R(f)]^*|} \quad (3)$$

where $[X_R(f)]^*$ is the complex conjugate of $[X_R(f)]$.

Using equation (4), ΔT is obtained as a feature of the ITD of two signals, which is actually the time delay that both signals for maximum correlation have with respect to each other

$$\Delta T = arg_\tau \max(g(\tau)) \quad (4)$$

where $g(\tau)$ is the inverse Fourier transform of $G(f)$.

ILD. The intensity level of the sound decreases when it collides with the head of the robot. Depending on the size of the head, this effect occurs at a certain frequency range (in the *Arash* robot, the drop in intensity level occurs for frequencies higher than 2500 Hz.) To extract the ILD feature, the energy difference of two signals in terms of frequency is calculated as follows[22]

$$ILD(f) = 20\, log\left(\frac{|X_L(f)|}{|X_R(f)|}\right) \quad (5)$$

where $|X_L|^2$, $|X_R|^2$, and f are the spectral energy density in the left microphone, the right microphone, and the frequency, respectively. As a result, the average of $ILD(f)$ in the frequency range of [2500, 9000] Hz can be used as a feature.

Neural network training. Two features of ITD and ILD are used to train the four multilayer perceptron (MLP) neural network. The ILD and ITD features for horizontal and vertical microphones are calculated in terms of various horizontal and vertical angles, and four feature vectors are obtained. For example, the ITD feature vector is plotted in terms of horizontal angles at different vertical angles (see Figure 11). The obtained features are considered as network inputs and the corresponding angles of the sound source are considered as network labels (see Table 4).

To perform the test, we placed the robot in a real environment and released the audio signal at various angles. Figure 12 shows the vertical angle SSL estimation error via various horizontal and vertical angles. According to Figure 12, the SSL estimation error will be less than 5° for the vertical angles.

Figure 13(a) shows the horizontal angle SSL estimation error via various horizontal and vertical angles. As it is obvious, the SSL estimation error is less than 20°; specifically at the horizontal angle of −70° to 70°, the SSL estimation error will be less than 5°; so, as it is expected, the rotation of the robot head toward the sound source will make the estimated sound source direction more accurate. For clarification, the horizontal angle SSL estimation error at various horizontal and a specific vertical angle of 0° is demonstrated in Figure 13(b); where the maximum SSL estimation error is 10°.

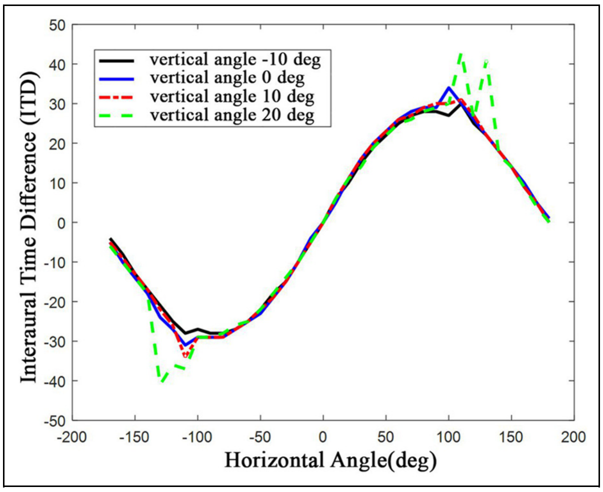

Figure 11. Interaural time difference (ITD) feature via horizontal angles at different vertical angles.

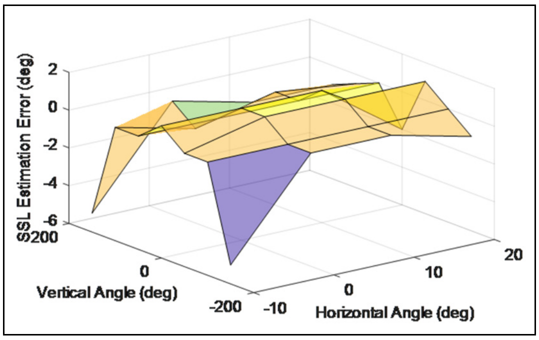

Figure 12. The vertical angle SSL estimation error via various horizontal and vertical angles.

Facial expression of Arash

To finalize the general appearance of *Arash*, our group have not only examined and relied on ill children taste but also consulted with psychologists, graphic designers, and industrial designers (see Figure 3(b)). In addition, to design the robot's facial appearance, we have consulted with specialized graphic designers. *Arash's* current face has been selected from several proposed sketches (sketch (c) in Figure 14(a) to (g)).

A deep convolutional neural network is in charge of facial expression recognition. A camera is located in the head of the robot to send a picture of the applicant's facial expression to the neural network. The deep convolutional neural network recognizes six facial expressions of happiness, sadness, fear, surprise, anger, and disgust. Depending on the detected expressions (volunteer participants were used to teach *Arash* the six expressions), the robot displays appropriate facial responses. Scalable vector graphics (SVG) is used to display the robot face. A large number of vectors with different thickness and color are connected with each other to create the face of the robot. Six facial expressions (SVGs) were produced and given to the robot in advance (see Figure 15). The robot expresses his facial moods by switching between these pre-produced SVGs. KUTE.js Javascript Animation Engine is utilized to switch between expressions.[23] The engine is free and accomplishes the morphing operation with acceptable visual appeal.

Experiments: assessing social acceptance of *Arash*

When presenting *Arash* to pediatric cancer patients in a hospital environment, it was important to examine the children's feelings and desire to interact with the social robot as an interactive solution for interventions, education, and entertainment. In order to have a fair comparison, two experiments were conducted. In the first experiment, two stories are narrated by the *Arash* robot and an Audio storyteller; some questionnaires are asked from the children to evaluate their *imagination, emotion, cognition*, and *transportation*. In the second experiment, children are asked to evaluate the constructed *Arash* robot and compare it with its conceptual favored sketch (Figure 3(b)). In short, the devised research questions (RQs) are as follows;

RQ1: Do the children accept to interact with *Arach* robot?
RQ2: Are they emotionally affected by *Arash* robot?
RQ3: Do they like the robot?
RQ4: Do they enjoy interacting with the robot?
RQ5: Is their imagination fired by the *Arash* robot, is it similar to the Audio book?
RQ6: Do they feel safe while interacting with the robot?
RQ7: How close is the constructed *Arash* robot to its favored conceptual sketch?

Table 4. Characteristics of the neural network for sound source direction estimation.

No.	Type	Neurons of hidden layer	Hidden layer activation function	Learning algorithm	Output layer activation function	Output (sound source direction)
1	MLP	8	Relu	SGD	Tanh	Forward or backward
2	MLP	15	Relu	Adam	X	Horizontal angle (forward)
3	MLP	15	Relu	Adam	X	Horizontal angle (backward)
4	MLP	8	Relu	Adam	X	Vertical angle (forward or backward)

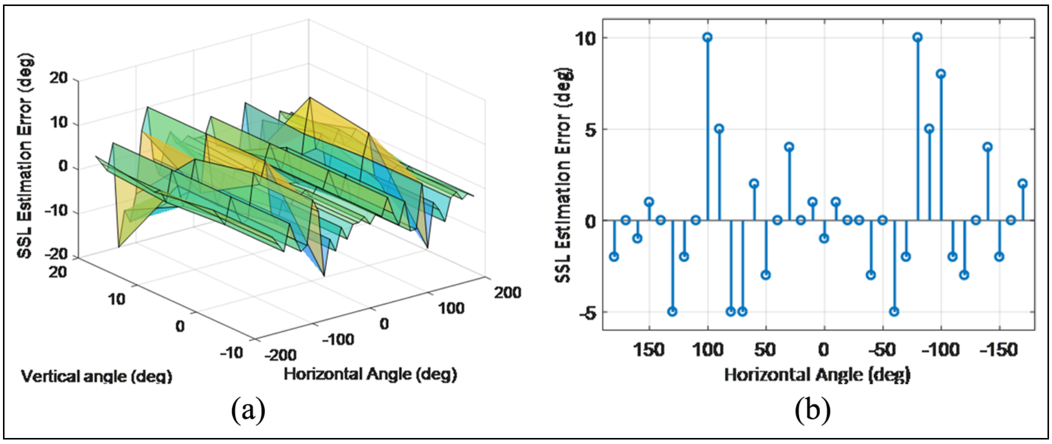

Figure 13. (a) The horizontal angle SSL estimation error via various horizontal and vertical angles and (b) the horizontal angle SSL estimation error via various horizontal angles at vertical angle of 0°.

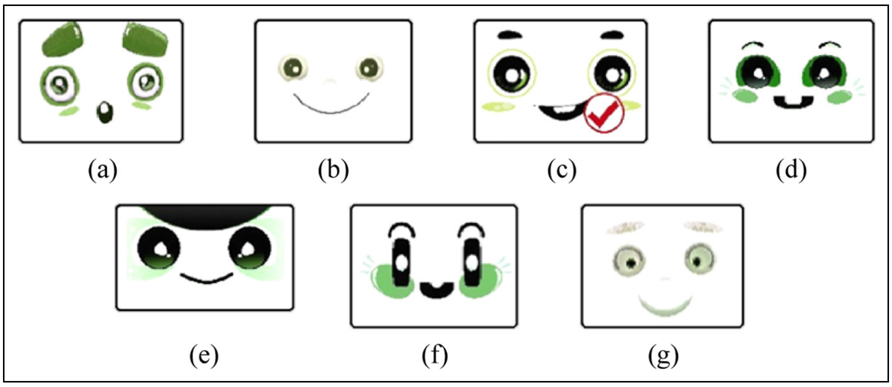

Figure 14. Initial sketches of a possible face for the *Arash* social robot.

Experimental setup

First experiment. In the first experiment, we employed *Arash* as a storyteller to evaluate its acceptance and the enjoyment of children while listening to the robot. To have a fair comparison, an Audio storyteller was also employed along with the *Arash* robot. The children listened to two stories and then answered some questions. The stories were selected by consulting with child psychologists associated with the hospital. Both stories were recorded with the help of a female voice actor, who also performs as the voice actor of *Arash* robot.

The first story is the story of *The Birds and the Hunter*, and the second one is the story of *The Mouse and the Lion*. In both stories, the animals become free and succeed with teamwork. Time duration of each experiment (*Arash* as storyteller and Audio storyteller) is about 3 min. The test was counterbalanced, that is, half of the participants (randomly selected) listened to the story of *The Birds and the Hunter* by the robot and the story of the *The Mouse and the Lion* by Audio book, and vice versa for the other half of the participants. In addition, in each of the two groups, half of the participants listened first to the robot storyteller, and the other half listened to the Audio book first. The study was held in the game room of the hospitals, with either the *Arash* robot or an MP3 player positioned in it. Due to the curiosity of the hospitalized children, *Arash* introduced himself for 2 min to the group before starting the experiment (see Figure 16). However, after the introduction session, the experiment was individually performed for each child. Children were asked to listen to a 3-min story carefully, and they were informed that after listening to the story, they would answer some questionnaires. While the children listened to the Audio book, the robot was covered up. All the questionnaires were asked by one instructor in a separate room. The test room is shown in Figure 17.

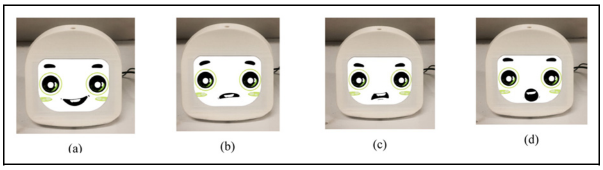

Figure 15. Facial expressions of the *Arash* robot (a) happiness, (b) sadness, (c) anger, and (d) surprise.

Figure 16. The introduction session of *Arash* before conducting the experiments at Mahak Hospital.

Figure 17. The test room while *Arash* is narrating the story for pediatric cancer in Ali Asghar Hospital.

The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation at Sharif University of Technology and with the Helsinki Declaration of 1975, as revised in 1983.

Second experiment. After the ill children visited *Arash*, they were asked to fill in another questionnaire, which evaluates the *anthropomorphism, animacy, likability, intelligence*, and *safety* of the robot from the child's point of view.[24] On the other hand, we wanted to evaluate how closely the constructed *Arash* robot was to its favored conceptual sketch (see Figure 3(b)). The sketch, with approximately the same dimension as the constructed *Arash* robot, was shown to the ill children. Once again, the questionnaire is all about the sketch and the actual robot. During the questioning, the sketch is always in front of the child and it was emphasized to him or her to look at it and answer the questions.

Participants

A total of 14 pediatric cancer patients took part in the experiment to evaluate the acceptance of the *Arash* robot. The survey was conducted at Ali Asghar and Mahak Hospitals in Tehran. Males made up 72% ($f = 10$) of all participants and females accounted for 28% of all participants. Ages ranged from 5 to 12 ($M = 9.5$, standard deviation (SD) = 1.2). None of the children had previous interaction with a social robot. Three children had previously heard the story of *The Mouse and the Lion* and two had heard the story of *The Birds and the Hunter*.

Assessment tools

Three questionnaires were used in the experiments. The *Transportation Scale—Short Form* (TS-SF)[25,26] and *Self-Assessment Manikin* (SAM) questionnaire[27] were used for the first experiment, and the *Godspeed* questionnaire was used for the second experiment.[28–30]

1. The *TS-SF* was used to capture the experience of being immersed into the story by both the Audio book and *Arash* robot storytellers.
2. The SAM was employed to evaluate the perceived valance, arousal, and dominance level of the children's reaction to the story told by the *Arash* robot or the Audio book.
3. Finally, the *Godspeed* questionnaires by Bartneck were used for the second experiment. It evaluates *anthropomorphism, animacy, likeability*, perceived *intelligence*, and perceived *safety* of the favored sketch of the robot and the constructed *Arash* robot.[24]
4. All items were measured in 5-point *Likert-type smiley face scale*,[28] and all the scores were over 5.

Results and discussion

First experiment. In the first experiment, we examined how well the children got involved with the story told by the robot/the Audio book. Fourteen out of 14 participants (100%) accepted to listen to the robot and 14 participants (100%) accepted to listen to the Audio book. After performing the exercises, children were asked again which device they preferred to listen. Twelve children preferred the robot (85.7%), and two preferred the Audio book (14.3%). After the story was told by each of the two devices, TS-SF and SAM questionnaires were asked of the children. Figure 18 and Table 5 demonstrate the performance of participants while listened to the Audio book and *Arash* robot, where mean score, standard deviation, and p-value of a t-test are reported. As it is clear from Table 5, the mean

Table 5. The mean, standard deviation, and *p*-value of *t*-test of the children's scores after listening to the *Arash* robot/Audio book.

No.	Item	Score's mean[a] (SD)		*p*-value
		Robot	Audio	
1	Cognition	3.36 (0.80)	3.63 (0.83)	0.455
2	Emotion	3.48 (0.94)	2.52 (1.00)	0.033
3	Imagination	4.27 (0.67)	4.30 (0.82)	0.91
4	Transportation	3.60 (0.57)	3.37 (0.51)	0.33
5	Valance	4.46 (0.60)	4.03 (1.15)	0.22
6	Arousal	3.14 (1.44)	2.82 (1.48)	0.56
7	Dominance	3.73 (1.18)	3.61 (1.06)	0.79

SD: standard deviation.
[a]Score's mean is based on a 0-5 scale.

Table 6. The mean score, standard deviation, and *p*-value of scores of the *anthropomorphism, animacy, likability, intelligence*, and *safety* of the *Arash* robot and the children's favored conceptual sketch of *Arash*.

No.	Item	Score's mean[a] (SD)		*p*-value
		Robot	Poster	
1	Anthropomorphism	4.14 (0.80)	3.67)1.30)	0.35
2	Animacy	4.25 (0.75)	3.98 (0.92)	0.45
3	Likability	4.90 (0.30)	4.76 (0.51)	0.42
4	Intelligence	4.69 (0.59)	4.65 (0.63)	0.89
5	Safety	4.51 (0.80)	4.63 (0.48)	0.68

SD: standard deviation.
[a]Score's mean is over 5.

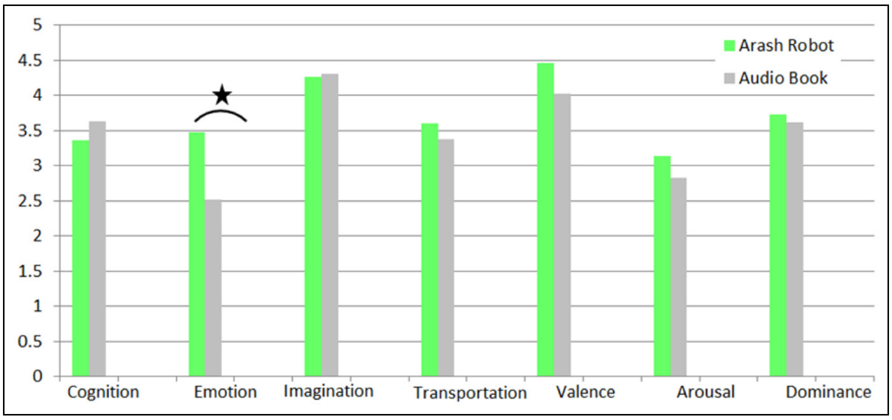

Figure 18. Mean scores of the *cognition, emotion, imagination, transportation* (TS-SF test), *valence, arousal*, and *dominance* (SAM test) of children while listening to the *Arash* robot/Audio book.
The symbol "*" demonstrates significant difference

score of the robot storyteller in *emotion, transportation, valance, arousal*, and *dominance* are higher than the Audio storyteller; however, the difference is only significant in the *emotion* category (p-value = 0.03 < 0.05). The mean score of *cognition* and *imagination* for the Audio storyteller is higher; however, the difference is not significant (p-value = 0.45, 0.91 > 0.05).

Second experiment. In the second experiment, the *Godspeed* questionnaire was asked from the children to evaluate *Arash's* design. The test was performed to evaluate the *anthropomorphism, animacy, likeability*, perceived *intelligence*, and perceived *safety* of the *Arash* robot/its favored conceptual sketch. The scores are shown in Table 6 and Figure 19. As it is clear from the *likability* score, the children liked the robot and its favored conceptual sketch very much (4.9 vs 4.9). Also, they perceived the robot and its sketch as an intelligent creature (4.69 vs 4.65). On the other hand, the mean scores of the *anthropomorphism*, which measures the

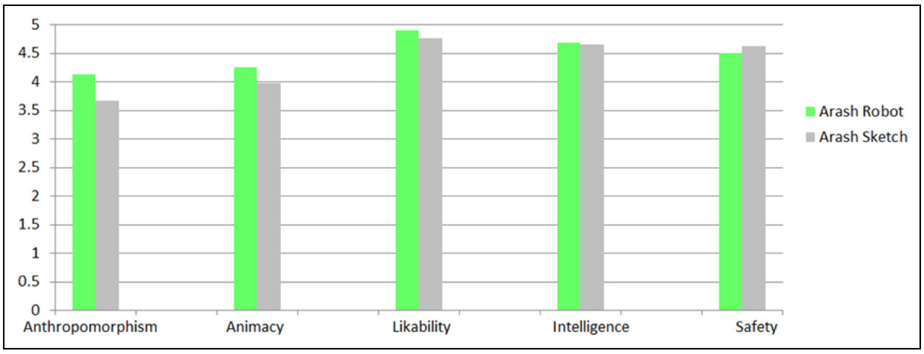

Figure 19. Mean scores of the anthropomorphism, animacy, likability, intelligence, and *safety* of the *Arash* robot and the children's favored conceptual sketch of *Arash*.

human-like character, is 4.14 versus 3.67 for the *Arash* robot versus its sketch. The score of 4.14 shows that the robot is not completely human-like, thereby the *uncanny valley* was avoided. The mean score of the *safety* of the sketch was a bit higher than the robot; which is reasonable since children would feel more secure facing a sketch versus a first-time visit with the robot. However, no significant difference is observed on any item, which insured that the constructed robot is very similar to the children's favored conceptual sketch.

Conclusion

In this study, a thorough design procedure and performance evaluation of the social robot companion "*Arash*" (as a friend for interaction with children with cancer) based on their interests and needs is presented. The research focuses on employing *Arash* in a pediatric hospital environment to entertain, assist, and educate children with cancer who suffer from physical pains caused by both the disease and its treatment process. *Arash* is a low-cost humanoid mobile robot buddy carefully designed with appropriate measures and developed to interact with children ages 5–12 years old. The robot has five physical subsystems: the head, arms, torso, waist, and the mobile-platform unit. The robot is a mobile-based human-shaped robot designed and developed based on a survey taken from children with cancer. Designing the robot's appearance based on a survey taken from 50 children with chronic diseases at three pediatric hospitals in the city of Tehran is a significant and novel concept. The social robot utilizes ROS, which provides useful tools and libraries to facilitate development of robotic software. One of its human–robot interaction modules is SSL, which can localize a sound source in two directions with low estimation error. Other human–robot interaction modules are facial expression recognition and facial expression production. After completing the mechanical, mechatronics hardware, and software of the robot, the realized social robot *Arash* was presented to the children with cancer to examine its favorability and the desire to interact with the robot. In order to have a fair comparison, two experiments were designed and conducted. In the first experiment, the children listened to two stories narrated by the *Arash* robot and an Audio storyteller; then TS-SF and SAM questionnaires were completed to evaluate their *imagination, emotion, cognition*, and *transportation* about the different storytellers. In the second experiment, children were asked to evaluate the constructed *Arash* robot and compare it with its conceptual favored sketch via the *Godspeed* questionnaire. The test was performed to evaluate the *anthropomorphism, animacy, likeability*, perceived *intelligence*, and perceived *safety* of the *Arash* robot and its favored conceptual sketch. The obtained results are very promising, with all the robot scores being more than 3 (based on a 0-5 scale). Particularly, emotion stimulated by the robot storyteller has a significant difference with the emotion stimulated by the Audio book. This is very promising since emotion played a crucial factor in designing *Arash* and its objective to help reduce distress in children with cancer. The score of the robot's likability was approximately 5, which means that children totally liked the robot's appearance and performance. Overall, the experimental results indicate *Arash* was a true success among children with cancer in hospital environments.

Acknowledgements

This project is supported and funded by the Iranian National Science Foundation-INSF (http://en.insf.org/) and the Office of the Vice-President in Science and Technology. Special thanks to Dr Khadijeh Arjmandi Rafsanjani of Iran University of Medical Sciences with expertise in Hematology and Oncology at *Ali Asghar* Hospital and Mr R. Rafatnejad for his valuable cooperation. Cooperation of *Ali Asghar* and *Mahak* Hospitals staff in preparing the ground for experimentations is also appreciated. We also thank Mrs S. L. Holderread for the english editing of the paper.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This project was funded in part by the Iranian National Science Foundation (INSF) and the Office of the Vice-President in Science and Technology, Iran.

References

1. Siegel RL, Miller KD and Jemal A. Cancer statistics, 2018. *Cancer J Clin* 2018; 68(1): 7–30.
2. Carlson LE, Angen M, Cullum J, et al. High levels of untreated distress and fatigue in cancer patients. *Br J Cancer* 2004; 90(12): 2297–2304.
3. Alemi M, Ghanbarzadeh A, Meghdari A, et al. Clinical application of a humanoid robot in pediatric cancer interventions. *Int J Soc Robot* 2016; 8(5): 743–759.
4. Alemi M, Meghdari A, Ghanbarzadeh A, et al. Impact of a social humanoid robot as a therapy assistant in children cancer treatment. In: *Proceedings of the international conference on social robotics*, 27 October 2014, pp.11–22. Cham: Springer. Sydney, NSW, Australia.
5. Meghdari A, Alemi M, Khamooshi M, et al. Conceptual design of a social robot for pediatric hospitals. In: *Proceedings of the 4th international conference on robotics and mechatronics*, Tehran, Iran, 26–28 October 2016, pp.566–571. New York: IEEE.
6. Meghdari A, Shouraki SB, Siamy A, et al. The real-time facial imitation by a social humanoid robot. In: *Proceedings of the 4th international conference on robotics and mechatronics*, Tehran, Iran, 26–28 October 2016, pp.524–529. New York: IEEE.
7. Meghdari A, Alemi M, Pour AG, et al. Spontaneous human-robot emotional interaction through facial expressions. In: *Proceedings of the international conference on social robotics*, 7 October 2016, pp.351–361. Cham: Springer. Kansas City, MO, USA.
8. Zakipour M, Meghdari A and Alemi M. RASA: a low-cost upper-torso social robot acting as a sign language teaching assistant. In: *Proceedings of the international conference on social robotics*, 7 October 2016, pp.630–639. Cham: Springer. Kansas City, MO, USA.
9. Elahi MT, Korayem AH, Shariati A, et al. “Xylotism”: a tablet-based application to teach music to children with autism. In: *Proceedings of the international conference on social robotics*, 24 October 2017, pp.728–738. Cham.: Springer. Tsukuba, Japan.
10. Alemi M, Meghdari A and Ghazisaedy M. Employing humanoid robots for teaching English language in Iranian junior high-schools. *Int J Hum Robot* 2014; 11(03): 1450022.
11. Taheri AR, Alemi M, Meghdari A, et al. Social robots as assistants for autism therapy in Iran: research in progress. In: *Proceedings of the 2nd RSI/ISM international conference on robotics and mechatronics*, Tehran, Iran, 15–17 October 2014, pp.760–766. New York: IEEE.
12. Taheri AR, Alemi M, Meghdari A, et al. Clinical application of humanoid robots in playing imitation games for autistic children in Iran. *Procd Soc Behv* 2015; 176: 898–906.
13. Van den Heuvel RJ, Lexis MA and de Witte LP. Can the IROMEC robot support play in children with severe physical disabilities? A pilot study. *Int J Rehabil Res* 2017; 40(1): 53–59.
14. Georgia Institute of Technology. Socially intelligent machines lab: Simon the robot, http://www.cc.gatech. edu/social-machines/projects.html (accessed 30 March 2015).
15. Pioggia G, Sica ML, Ferro M, et al. Human-robot interaction in autism:FACE,an android-based social therapy. In: *Proceedings of the 16th international symposium on robot and human interactive communication*, Jeju, South Korea, 26–29 August 2007, pp.605–612. New York: IEEE
16. Quigley M, Conley K, Gerkey B, et al. ROS: an open-source robot operating system. *ICRA Workshop Open Source Softw* 2009; 3(3.2): 5.
17. Striepe H and Lugrin B. There once was a robot storyteller: measuring the effects of emotion and non-verbal behavior. In: *Proceedings of the international conference on social robotics*, 24 October 2017, pp.126–136. Cham: Springer. Tsukuba, Japan.
18. U.S. Architectural and Transportation Barriers Compliance Board (Access Board). Americans with Disabilities Act (ADA) accessibility guidelines for buildings and facilities. *Fed Regist* 1991; 56: 173.
19. Lafaye J, Collette C and Wieber PB. Model predictive control for tilt recovery of an omnidirectional wheeled humanoid robot. In: *Proceedings of the international conference on robotics and automation*, Seattle, WA, 26–30 May 2015, pp.5134–5139. New York: IEEE.
20. Argentieri S, Danès P and Souères P. A survey on sound source localization in robotics: from binaural to array processing methods. *Comput Speech Lang* 2015; 34(1): 87–112.
21. Saffari E, Meghdari A, Vazirnezhad B, et al. Ava (a social robot): design and performance of a robotic hearing apparatus. In: *Proceedings of the international conference on social robotics*, 28 October 2015, pp.440–450. Cham: Springer. Paris, France
22. Parisi R, Camoes F, Scarpiniti M, et al. Cepstrum prefiltering for binaural source localization in reverberant environments. *IEEE Signal Proc Let* 2012; 19(2): 99–102.
23. KUTE, http://thednp.github.io/kute.js/
24. Bartneck C, Kulić D, Croft E, et al. Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. *Int J Soc Robot* 2009; 1(1): 71–81.
25. Appel M, Gnambs T, Richter T, et al. The Transportation Scale—Short Form (TS-SF). *Media Psychol* 2015; 18(2): 243–266.
26. Green MC and Brock TC. The role of transportation in the persuasiveness of public narratives. *J Pers Soc Psychol* 2000; 79(5): 701–721.
27. Bradley MM and Lang PJ. Measuring emotion: the Self-Assessment Manikin and the Semantic Differential. *J Behav Ther Exp Psy* 1994; 25(1): 49–59.
28. Read JC, MacFarlane SJ and Casey C. Endurability, engagement and expectations: measuring children’s fun. In: *Interaction design and children*, vol. 2. Eindhoven: Shaker Publishing, 2002, pp.1–23.
29. Taheri AR, Meghdari A, Alemi M, et al. Clinical interventions of social humanoid robots in the treatment of a pair of high- and low-functioning autistic Iranian twins. *Sci Iran Trans B*. Epub ahead of print 30 August 2017. DOI: 10.24200/sci.2017.4337.
30. Taheri AR, Meghdari A, Alemi M, et al. Teaching music to children with autism: a social robotics challenge. *Sci Iran Trans G*. Epub ahead of print 5 December 2017. DOI: 10.24200/sci.2017. 4608.