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Cost-Effective Research Platform for Child-Robot Interaction Studies Using a Smartphone-Based Humanoid Robot with Double Gesture Arms

Dr. Sumito Nagasawa Ph.D. in Engineering, Shibaura Institute of Technology

Dr. Sumito Nagasawa received Ph.D. in Engineering from the University of Tokyo in 2001. He is a Professor, College of Engineering at SIT. His research interests include miniaturized robots using Micro-Electro-Mechanical Systems technologies and robot education for STEM.

Prof. Hatsuko Yoshikubo Ph.D., Shibaura Institute of Technology

Dr. Hatsuko Yoshikubo obtained Ph. D in English Literature from Chiba University in Japan in 2002. She is currently a Professor in the Innovative Global Program, a research-based full English degree engineering program at the College of Engineering at Shibaura Institute of Technology, Tokyo, Japan. She is a Principal Investigator of the Japan Society for the Promotion of Science Research Grants 24K06133 and the Shibaura Institute of Technology Grants for Educational Reform and Research Activity in the AY2024. Her current main research interests are: 1) how including humanities courses in an engineering education curriculum can help students to gain flexibility, and an appreciation of equity, and a greater richness of ideas; and 2) systematic issues impacting the effectiveness of engineering education, specifically in the context of project-based learnings for the engineering education. Below are her recent presentations at international conferences: ASEE 2023, WERA 2023, 2022, 2019, APAIE 2023, 2022, IIAI DSIR 2021, 2020. She obtained the Multidisciplinary Engineering Division's Best Diversity Paper Award in ASEE 2023 and the Outstanding Paper Award in DSIR 2021.

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Abstract

Background

This research aims to develop a smartphone-based interface robot with dual gesture arms for Child-Robot Interaction (CRI). The robot features two gesture arms powered by shape memory alloy (SMA) actuators, facilitating offering a CRI research platform.

Using a smartphone as the system base, functionality, affordability, and internet connectivity were achieved. In the CRI research, these robots serve as tutors for children, maintaining children's motivation, enhancing learning outcomes. The proposed robot offers child-friendly interfaces, incorporates various sensors, and ensures constant internet connectivity. Essential functions include dual gesture arms for natural communication, a locomotion system for mobility, and an expression presentation function for conveying emotions effectively.

Research Objectives

A CRI research platform equipped with a smartphone-based interface robot is proposed. The achievable functions are defined as the following three features and set them as the research goals of this study.

1. **Dual Gesture Arms**
2. **Mobility Mechanism**
3. **Expression Presentation Function**

Methodology (System Design)

Since our robot uses the smartphone as a core of the system, it achieves required features with affordable cost. The smartphone-based robot provides a high processing power and incorporates various sensors (including camera, accelerometers, gyroscopes, magnetometers, touch panel, microphone, infrared sensor, atmospheric pressure, GPS, and fingerprint authentication). Additionally, it offers constant internet connectivity and tools for safeguarding users' confidential personal information.

Results and Discussion (Experimental Assessment)

The integration of each function was carried out to prototype and evaluate the interface robot for the CRI research platform. Each joint of the dual gesture arms achieved movements within 2 seconds, necessary for natural communication with children. The prototype gesture arms driven by SMA has 3 degrees of freedom. Although the yaw axis of the shoulder is omitted, by combining the pitch and roll axes of the shoulder, movements similar to the yaw axis can be achieved. Additionally, a thicker frame structure was designed, resulting in higher visibility of the gesture arms.

Conclusion

To summarize, our proposal advances the idea of a cost-effective CRI research platform centered around a child learning partner robot, which has dual gesture arms and utilize a smartphone as a core of the system. We plan to deploy this proposed system for actual CRI research and for learning effectiveness measurements.

1. Introduction

In this research project, we aim to develop a humanoid robot with double 'gesture-arms' which can be controlled by smartphone, presenting a cost-effective approach to Child-Robot Interaction (CRI). Our interdisciplinary project combines robotics technology and CRI education, introducing the 4-degree-of-freedom (4-DOF), 12g gesture arm driven by shape memory alloy (SMA) actuators. Our robot possesses two of these arms and is set up for smartphone-based control, providing a versatile CRI research platform with high computational power and built-in sensors. By leveraging smartphones as the system foundation, we have achieved a balance of functionality, affordability, and internet connectivity, making the humanoid robot a generally practical tool for CRI research.

As a field of study, CRI research explores the use of robots as tutors, or as companions for children's spontaneous learning. Reports suggest that children perceive robots as interactive entities, and that using them as tutors or companions enhances learning motivation and other outcomes ([1] R. Zviel-Girshin *et al*., 2018; [2] J. K. Westlund *et al*., 2016). One of the most well-known models of robot used in this type of research is called 'Nao' ([11] manufactured by Aldebaran Robotics) ([3] M. Y. Mustar *et al.*, 2022), with thousands of this model being used in over 70 countries worldwide. However, the price of 'Nao' units starts from $11,000; this has prompted the need for a more cost-effective alternative to widen the accessibility of CRI research and product deployment.

Regarding the number of students needing learning support at home, for instance in Japan, according to data released by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2023, approximately 300,000 students are in a state of non-attendance. The number is increasing, with an additional 50,000 students compared to 2022, partly due to the impact of COVID-19.

Key features required for a CRI research platform include a 'child-friendly' robot interface and a display device presenting educational materials ([4] C. Clabaugh *et al.*, 2015). Since our robot uses the smartphone as a core of the system, it achieves required features with affordable cost. The smartphone-based robot provides a high processing power and incorporates various sensors (including camera, accelerometers, gyroscopes, magnetometers, touch panel, microphone, infrared sensor, atmospheric pressure, GPS, and fingerprint authentication). Additionally, it offers constant internet connectivity and tools for safeguarding users' confidential personal information.

Our proposed system assumes that each tutee can provide their own smartphone and communication carrier. The hardware cost for constructing our robot system except smartphone is estimated to be around 500 US dollars. Including software such as online learning materials, we believe it falls within the budget for educational institution ICT promotion. Considering that similar commercial communication robots are priced about 1,500 US dollars ([12] Vstone Japan, communication robot “Sota”) - 5,800 US dollars (Vstone Japan, communication robot “CommU”), to use the smartphone functionality in our proposed system provides a significant cost advantage. In research involving the use of robots during infancy to around age 3, the focus is on aspects of cognitive and emotional development such as language expression and emotion comprehension ([10] A. Arita et al., 2005). In this study, cooperative learning facilitated by robots targets elementary to junior high school students, typically aged 6 to 15 years old.

The study authors believe that for children to benefit from CRI, it is necessary that they adopt a view of humanoid robots as 'more than mere machines'; when this occurs, the robot can provide a moderate level of supervision, providing children with a sense of tension and concentration. As a result, children come to trust the robot as a cooperative partner, thereby enhancing learning efficiency in a way that would be impossible with just computer or tablet-based learning. When children learn alone using such as e-learning materials, it is considered difficult for them to continue learning by only themselves without any compulsion (tension). In several research reports using robots for educational purposes, children seem to perceive robots as partners in cooperative learning. Cooperative learning effects have been reported in various papers, when the robot teaches learning content to children ([8] J. Han et al., 2008) (Care-Giver use) or when children teach the robot ([9] F. Tanaka et al., 2010) (Care-Receiver use).

For children to perceive the robot as a cooperative partner, it is important that the robots have functions that allow children to empathize with it emotionally. Functions such as natural communication capabilities with dual gesture arms, mobility features for changing position and direction naturally, and expression presentation capabilities to convey the robot's emotions at the moment are useful.

Figure 1 illustrates the schematic diagram of our CRI research platform, which is based around a child-friendly, smartphone-controlled tutor robot. Our proposed CRI research system includes three key functionalities:

1) Dual Gesture Arms:

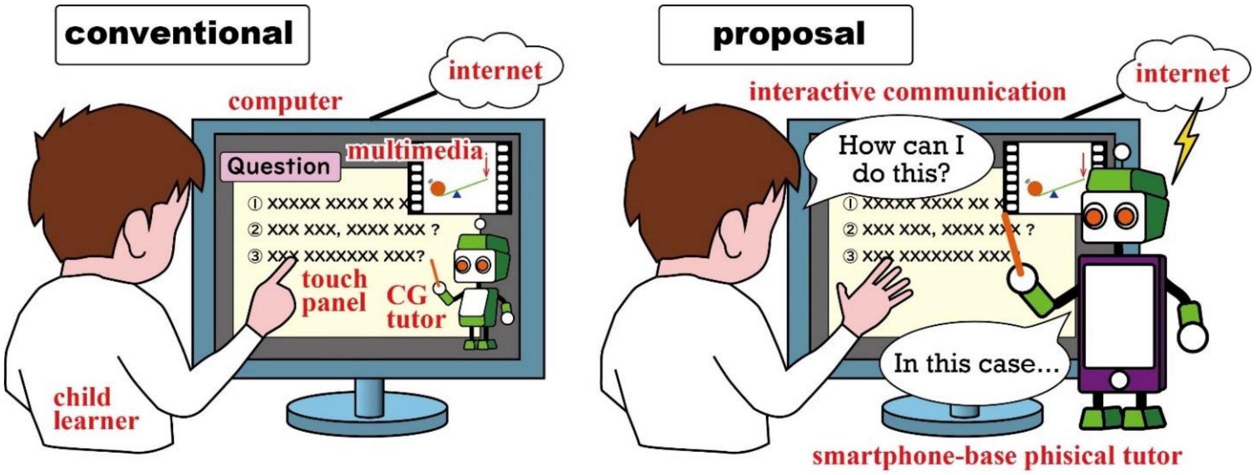
Implementing a small and lightweight gesture arm using SMA wires, suitable for a tabletop robot incorporating a smartphone-based system for control and student interaction. Existing research suggests that 'natural communication' between humans almost always involves response times of less than two seconds; therefore, the dual gesture arms we developed responds within two seconds at each joint. Finally, with regard to cost, versatility, and environmental considerations we can say that its power consumption is less than 15W for all functions that will be used in real-world deployment （[5] Nagasawa S. *et al.*, 2021）.

2) Mobility mechanism:

Implementing a movement mechanism for tabletop navigation and orientation towards children. As the robot will frequently move around and orientate itself towards the student, efficient power management is crucial for making the overall platform cost effective - even with a CRI system based on the use of smartphones, which typically weigh no more than 200 grams.

3) Expression Presentation Function:

In interactions between children and robots, the robot's expression is also crucial. Proposing a method to add expressions onto a 3D face-shaped display using a small optical projector, enhancing emotional communication between children and the robot.



・Improving learning efficiency using internet and media.	・Recognizing robots as partners helps maintain learning motivation and enhances learning outcomes.
・Intuitive operation is possible with touch panels and similar interfaces.	・In a CRI study report a robot costing over 11,000 US dollars was used. Similar commercial communication robots are priced about 1,500 - 5,800 US dollars.
・Interactivity with CG tutor on the monitor is low.	・Realized affordably using smartphone as system base.

Figure 1. Schematic diagram of our CRI platform including a 'child-friendly' smartphone-base tutor robot.

2. Design of Real-World Home Tutor Robot Based on Smartphone

2.1 Overview of Smartphone-Based Interface Robot

For the CRI research platform, it is essential for the interface robot to have human-like and approachable features. Hardware components such as dual gesture arms for expressing movements, a mobility mechanism for naturally changing positions and directions, and a small display for expressing robot emotions are indispensable. Supplying power to these hardware components directly from the smartphone's battery is challenging. Even if possible, it would significantly reduce the system's operational time. To ensure safety, it is desirable for the system to operate on commercially available mobile batteries, complying with the USB PD (Power Delivery) standard, with a power supply of around 30W and a capacity of 10,000mAh. Considering children's study time, the design goal is to operate continuously for over two hours.

In this study, our objective is to provide the necessary functionalities for robots as partners in cooperative learning, serving as a learning platform. Essential functionalities for achieving this goal, include a camera capable of image recognition of children, processing capabilities such as machine learning to presume from captured images and videos, real-time access to databases containing online learning materials, children's comprehension levels, and progress, the ability to understand commands from voice inputs, etc. As evident from such functionalities, these are either already implemented in current smartphones or are planned for implementation. Therefore, utilizing smartphones as our system foundation core for robots as partners in cooperative learning is a rational approach.

2.2 Dual Gesture Arms Driven by SMA

The selection of actuators is crucial for realizing dual gesture arms in smartphone-sized configurations. In conventional small robots, DC servo units are commonly employed as actuators. They are favored for their ease of control programming, availability, and affordability, with prices typically around $10 USD per unit. Small DC servo units widely used for simple applications include TOWER Pro's SG90 series, which are sufficiently compact with dimensions of 30 x 30 x 10 mm for typical purposes. However, for basic gestures, four degrees of freedom per arm (four units) are required, posing challenges in the design of mounting space for tabletop robots based on smartphones. Moreover, the arms themselves become thinner, making it impossible to mount servo units on them. Consequently, it becomes difficult to transmit driving forces to each joint using wires or belts. The power consumption of servo units is approximately 500mW to 1W under steady-state conditions (peaking at around 5W momentarily). With eight degrees of freedom for dual arms, the estimated power consumption under steady-state operation is about 4W, so using a mobile battery compliant with the USB PD standard ensures sufficient operating time.

In this study, SMA was adopted as the actuator for the arms. SMA is characterized by its small size, light weight, and extremely high force generation per unit weight. SMA undergoes deformation and displacement by changing from the martensitic phase to the austenitic phase due to temperature rise. Although it is a temperature-induced actuator, it can be heated by Joule heating through electrical current, making it practical for implementation. However, during extension, it is necessary to dissipate heat into the air, and this process is fatally slow for SMA actuators in robotics applications, leading to limited practical adoption. When the diameter of the SMA wire is reduced, the ratio of surface area to heat capacity per unit length of the SMA wire increases, resulting in faster heat dissipation. If the response during extension becomes faster, the force generation of SMA wire is significantly superior to that of other actuators, making SMA wire ideal for actuators in small systems.

The SMA wire has four physical quantities, namely temperature, length, force (stress), and internal resistance, which are system variables (physical quantities necessary to uniquely determine the state). Characteristics of temperature-induced actuators often exhibit temperature hysteresis, and feedback control is commonly used for accurate displacement and force control due to their nonlinear characteristics. For feedback control of joint angles in the gesture arm, sensors are required to measure joint angles. One of the system variables of SMA, the internal resistance, changes due to phase transformation of composition caused by temperature variation. By measuring the internal resistance, it is possible to estimate the joint drive angle. This eliminates the need for angle sensors at the joint, which is advantageous for miniaturization and simplification of the system. Figure 2a) shows the setup of the SMA resistance characteristic evaluation experiment, b) presents the measured results of internal resistance, and c) illustrates the drive circuit of SMA (left) and the internal resistance measurement circuit (right).

In the joint drive of the gesture arm using SMA wire, the design of attaching the SMA wire to the arm frame is crucial. As shown in Figure 3a), the position of the anchor relative to the joint rotation center affects the driving force and operating range of the joint. We investigated the required operating range for each joint during gesture and designed accordingly. Implementation photos are shown in Figure 3b).

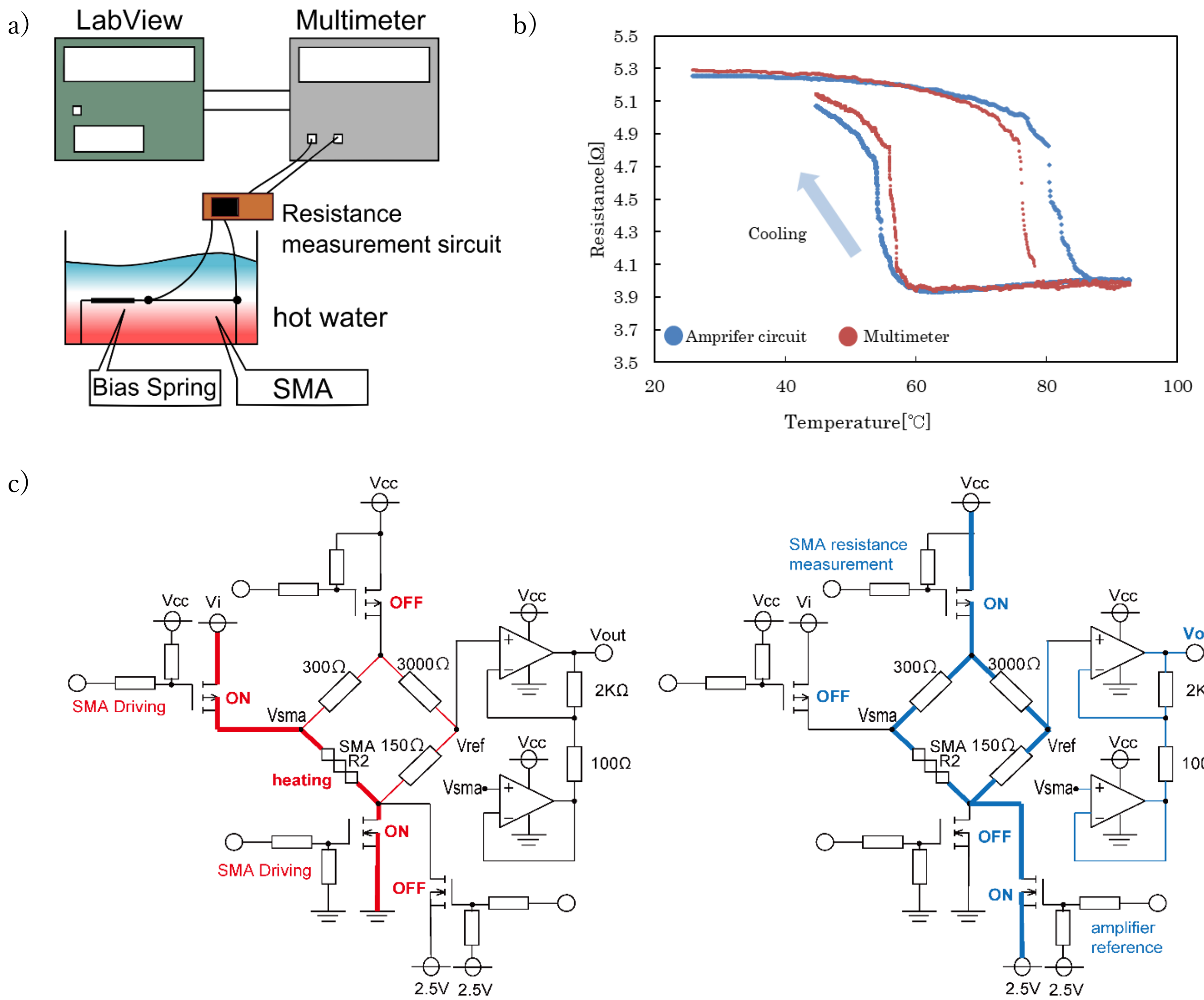
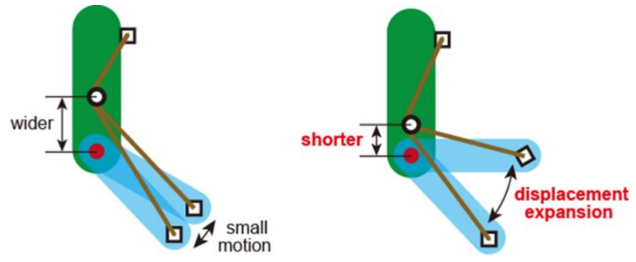


Figure 2. SMA characteristic assessment measuring its electric resistance. a) Experimental setup. b) Characteristics of the SMA resistance (hysteresis loop). c) SMA driving circuit (left) and measurement circuit for the SMA resistance (right).

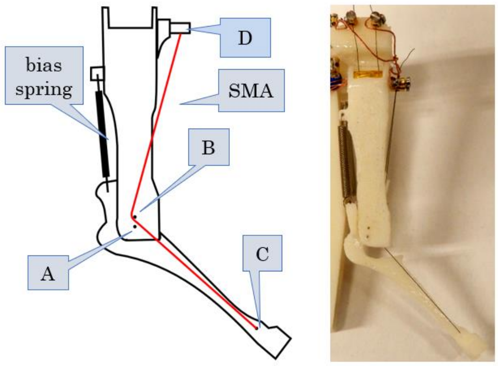
For the method using SMA wire for both extension and contraction of the joint, two sets of SMA drive systems (control of current to SMA and measurement of internal resistance) are required for each joint. To minimize the size and weight of the gesture arm, we adopted the use of bias springs for extension. During extension, as SMA is not energized, the joint can be easily extended by the restoring force of the bias spring as the temperature decreases due to heat dissipation. Figure 3c) shows a photo of the prototype 4-degree-of-freedom SMA gesture arm and the operating range of each joint. It weighs only 12g, making it suitable for implementation in the interface robot of this study.

Additionally, for natural communication with humans, a response time of less than 2 seconds is desirable ([7] R.B. Miller et al, 1968). By PWM controlling the SMA to prevent overheating, we achieved improvements in response time, with a maximum power consumption of 11.7W, bending time of 1.87 seconds, and extension time of 1.27 seconds (S. Nagasawa et al, 2021). If only the dual gesture arms are driven, continuous operation for over 4 hours is possible with a USB PD compliant mobile battery.

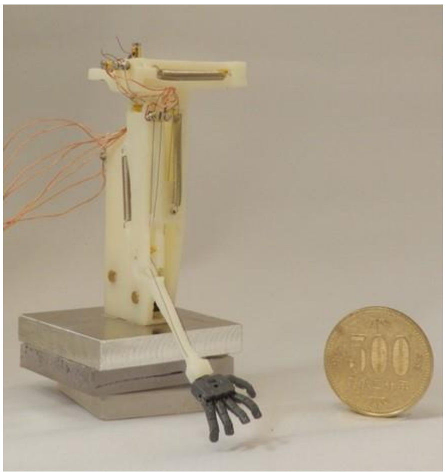
a)



b)



c)



specification	
Elbow	34[deg]
Shoulder – roll	20[deg]
Shoulder – Pitch	35[deg]
Shoulder - Yaw	75[deg]
Weight	**12g**
Material	ABS resin

Figure 3. SMA ultra-light arm. a) Effect of the archer point. b) Actual implementation. c) Specification of this 4-DOF SMA arm.

2.3 Mobility mechanism

For effective interaction with children in the CRI research platform, the interface robot needs to move on the tabletop and adjust its direction towards the child or the monitor. To achieve this, our proposed interface robot adopts a two-wheeled mobility mechanism. Additionally, it detects the direction of the child using the built-in camera of the smartphone and estimates the current position and orientation of the robot using the built-in IMU sensor (acceleration and gyro composite sensor).

The system configuration of the mobility mechanism is illustrated in Figure 4. By utilizing DC motors with rotary encoders as drive actuators, we can estimate the current position and orientation of the robot and obtain sufficient torque and responsiveness for movement.

Conventionally, as shown in Figure 4, high-performance embedded computers and the IMU sensor were provided externally to the smartphone to facilitate implementation. However, these externally provided components (highlighted in red frames in Figure 4) are costly, contributing to the overall high cost of the system. In this study, the smartphone was used as the system base and maximize the utilization of the sensors integrated within the smartphone.

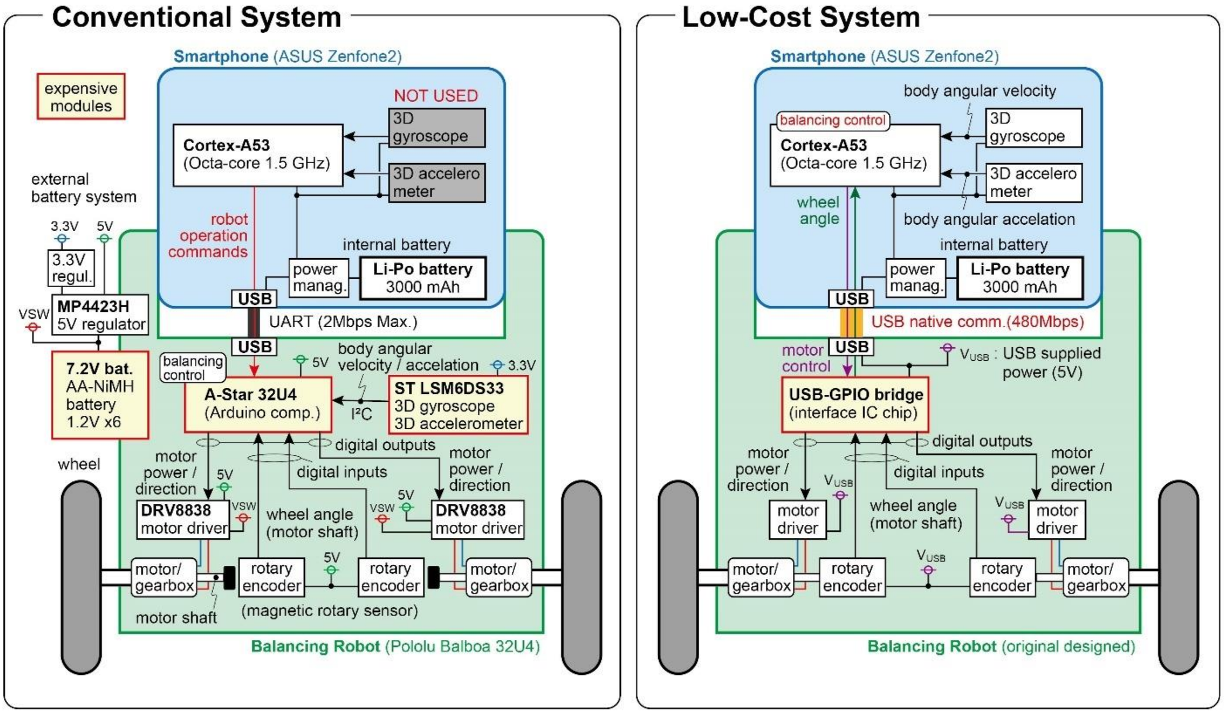


Figure 4. System configuration of the mobility mechanism. Conventionally, implementation was facilitated by providing expensive embedded computers and an IMU unit externally. In this study, by utilizing the smartphone as the system base and use sensors integrated within the smartphone for minimizing costs .

2.4 Face Expression Display Function

The face expression display function is crucial for the interface robot designed for the CRI research platform to facilitate children's empathy with the robot. While systems proposing the use of small LCD displays for face expression display have been suggested, they often result in cartoonish expressions due to the entire face being displayed on completely flat plane.

Almost of smartphones have a touch display. Since it is positioned at the body of the robot, using them more suitable for displaying information and options and for inputting selections rather than the face expressing emotions. As depicted in Figure 5, if expressions could be displayed on a three-dimensional facial display, emotions could be conveyed more distinctly. Furthermore, by incorporating actuators such as SMA, functions such as outlining the facial contour, blinking, and lip-syncing to match speech could be realized, as shown in Figure 5 a).

In this study, we prototyped a method of projecting expressions onto a 3D facial screen using a compact optical projector, as illustrated in Figure 5 b). While we succeeded in projecting expressions onto the 3D facial screen, the focal length of the projector is too long as we utilized a micro projector directly. Moving forward, we plan to develop a projection system with a shorter focal length and a wide projection angle by designing optical systems using 3D printers or similar technologies.

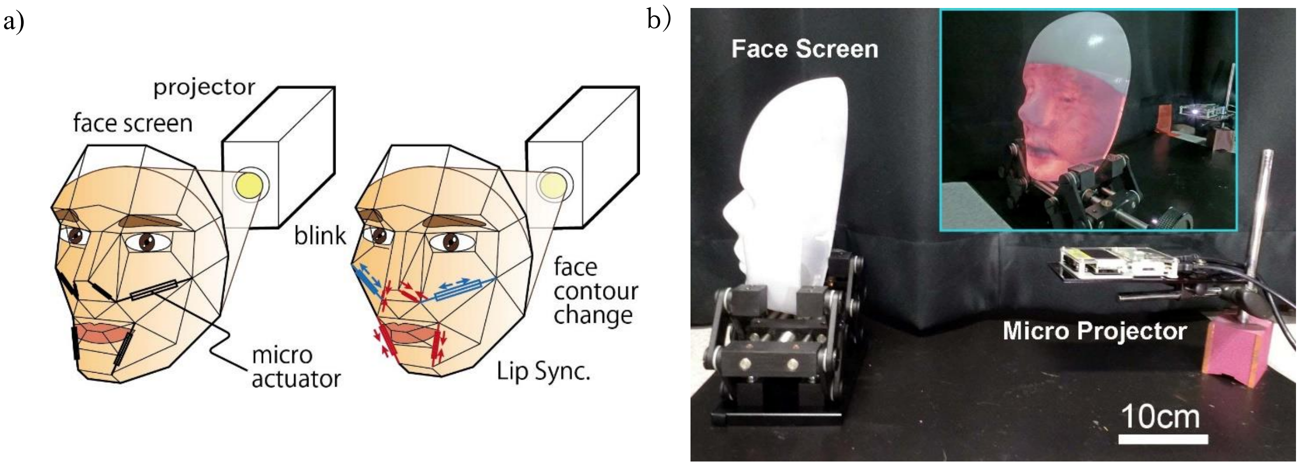


Figure 5. Prototype of face expression display function: a) Concept of movable face screen. b) Experiment of projecting onto the implemented face screen.

3. Prototype and Evaluation of Interface Robot for CRI Research Platform

The integration of each function explained in Section 2 was carried out to prototype and evaluate the interface robot for the CRI research platform. Figure 6 shows the system block diagram of the entire interface robot. Due to the pin constraints of the ESP32 embedded computer used in this experiment, the measurement of internal resistance of SMA was not performed, and the input power control to SMA was conducted through PWM-based open-loop control. To mitigate noise (ensuring stable power supply to the embedded computer), separate power supplies were implemented for the embedded computer and SMA/mobility drive motors. From this prototype development, the power consumption of drive motors and SMA during gestures was analyzed, and eventually, power management will be consolidated to a single external mobile battery.

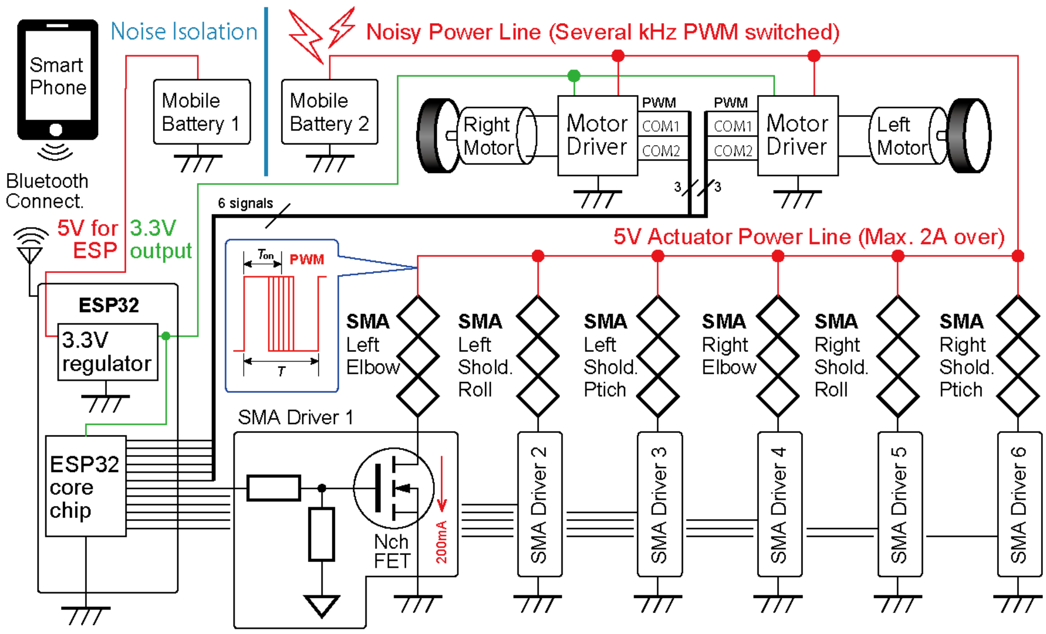


Figure 6 System block diagram of the prototype interface robot.

Design Overview of the Prototype Gesture Arm in this study is illustrated in Figure 7 a). It consists of a single arm with 3 degrees of freedom. Although the yaw axis of the shoulder is omitted, by combining the pitch and roll axes of the shoulder, movements similar to the yaw axis can be achieved. Additionally, compared to the SMA arm described in section 2.2, a thicker frame structure was designed, resulting in higher visibility of the arm.

The relationship between the torques acting around the elbow joint axis is depicted in Figure 7b). The torques include the driving torque T_{sma} generated by the SMA, the torque T_{mg} acting to prevent contraction due to gravity, and the restoring torque T_{spr} generated by the bias spring. Each torque varies in magnitude depending on the rotation angle of the arm. During contraction, the synthesized torque T_{com} of all torques is positive across the entire operating range, while during extension, all synthesized torques T_{com} are negative across the entire operating range, ensuring proper design for both movements.

a) b)

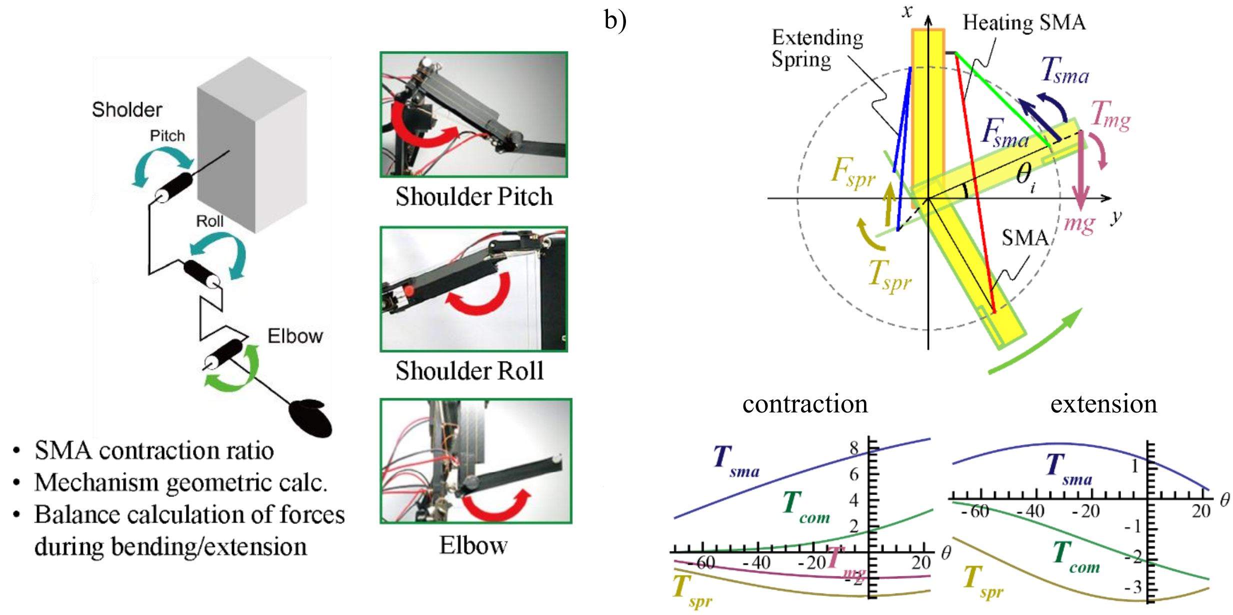


Figure 7 a) Design of the gesture arm. b) Relationship between the torques around the elbow joint axis.

Figure 8 shows a photo of the prototype of the Interface Robot Prototype. In Figure 9, the evaluation of the operating range and response of each joint of the gesture arm is presented. The target operating range was achieved for each axis, and the response speed also met the goal of moving 60 degrees within 2 seconds.

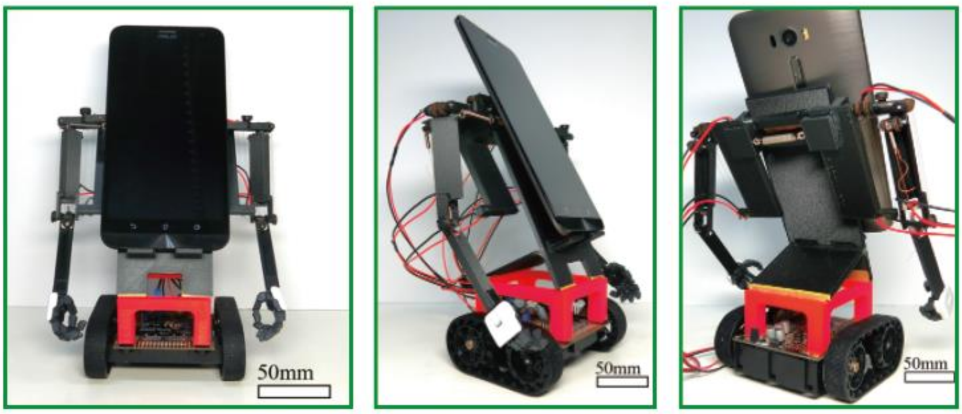


Figure 8 A photo of the prototype of the Interface Robot Prototype.

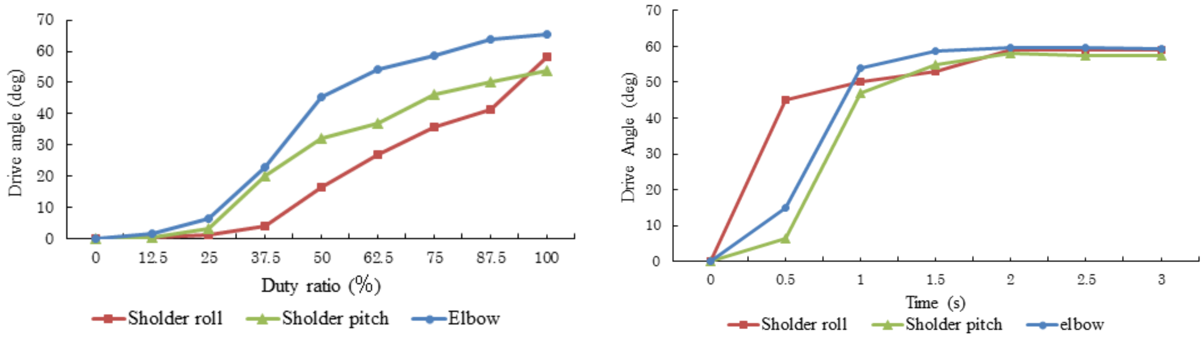


Figure 9 Evaluation of the operating range and response of each joint of the gesture arm.

4. Conclusion

We propose an affordable CRI research platform utilizing a lightweight and compact dual gesture arm, with a smartphone serving as the foundation for a child-learning tutor robot. By providing an SDK (Software Development Kit) for controlling the gesture arms and mobility mechanism similar to the built-in sensors, our proposed system can be operated by individuals with programming skills for smartphone apps, even without robotics knowledge. Additionally, to enhance usability as a CRI research platform, we plan to make it compatible with ROS (Robot Operating System) and RSNP (Robot Service Network Protocol) for generalization purposes. Furthermore, we aim to expand its application to practical CRI research scenarios and conduct evaluations of learning outcomes in the future.

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Appendix

We provide information about the components used in our tutor robots.

components	Vender & product	references
shape memory alloy (SMA) actuator	TOKI corporation Bio Metal Fiber	https://www.toki.co.jp/biometal/english/contents.php
Mobile base robot kit	Pololu Robotics and Electronics, ZUMO	https://www.pololu.com/category/129/zumo-robots-and-accessories
Smart phone	ASUS zenfone2	https://www.asus.com/
Micro Projector for Raspberry pi	Ultimems HD301D1	https://www.ultimems.com/#product
springs for restored force	Accurate Helical Extension Spring	https://www.accurate.jp/eng/