FLEXI: A Robust and Flexible Social Robot Embodiment Kit

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Abstract

The social robotics market is appealing yet challenging. Though social robots are built few remain on the market for long. Many reasons account for their short lifespan with costs and context-specificity ranking high amount them. In this work, we designed, fabricated, and developed FLEXI, a social robot embodiment kit that enabled unlimited customization, making it applicable for a broad range of use cases. The hardware and software of FLEXI were entirely developed by this research team from scratch. FLEXI includes a rich set of materials and attachment pieces to allow for a diverse range of hardware customizations that ensure the embodiment is appropriate for specific customer/researcher projects. It also includes an open-source end-user programming interface to lower the barrier of robotics access to interdisciplinary teams that populate the field of Human-Robot Interaction. We present an iterative development of this cost-effective kit through the lenses of case studies, conceptual research, and soft deployment of FLEXI in three application scenarios: community-support, mental health, and education. Additionally, we provide in open-access the full list of materials and a tutorial to fabricate FLEXI, making it accessible to any maker space, research lab, or workshop space interested in working with or learning about social robots.

Authors Keywords - Social robotics; robot kit; fabrication; open access.

CSS Concepts - Hardware • Human-centered computing ~ Human computer interaction (HCI) ~ HCI design and evaluation methods • Applied computing

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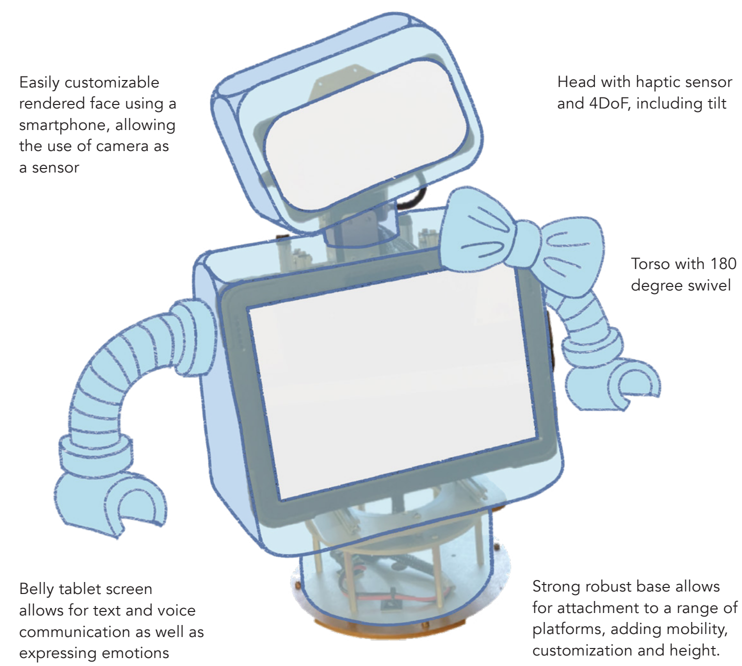
Description of the main features of FLEXI, a Social Robot Embodiment Kit developed from scratch by the research team.



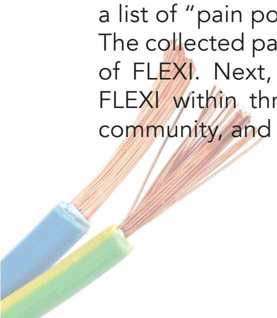
Introduction

Customization of social robots to a users' individual needs and preferences is critical in fostering acceptance, usability, and adoption of robots [1,2]. While the programmability of social robots enables customization of their behaviors and content, their physical embodiment is generally fixed. When considering the most commonly used social robots, whether consumer products or research platforms, we find that they allow very little hardware customization [3–9].

The lack of hardware-customizable social robots forces researchers to commit financial and labor resources to a robot embodiment that restricts the applications areas they can explore or to spend years developing new platforms from scratch. Our research aims to overcome these obstacles.

In this paper, we present FLEXI: a hardware design kit that allows the creation of a wide range of social robot embodiments (see Figure 1). Both the hardware and the software of FLEXI were entirely designed, developed, and fabricated from scratch by this research team. FLEXI consists of a robust robot core and attachment parts for augmenting the core in different ways, serving a variety of application areas for social robotics. The core includes a 4 degree-of-freedom neck-and-base mechanism and two screens that display the robot's face and enable input/output interactions with the user. In addition to the hardware attachments, FLEXI can be customized with common construction materials, including cardboard, foam, and 3D printed accessories. FLEXI is thus a robust robot core, intended for a wide range of application scenarios. It's versatility makes it extremely cost-competitive compared to social robots now in the market. This robot can be used by researchers, developers, and anyone interested in robotics.

To design FLEXI, we first gathered requirements by interviewing users of social robot platforms. This lead to a list of "pain points" in the current use of social robots. The collected pain points informed the design principles of FLEXI. Next, we created the conceptual design of FLEXI within three different use cases: mental health, community, and education.



Related Work

Insights to the Social Robot Market

Estimations about the size of social robot markets have been positive. A Global Social Market Review estimated that the 2017 social robot market was 288 million dollars and that would rise to 700 million by 2023 [10]. According to a 2020 market analysis conducted by BCC Research, social robots are a rapidly growing market, increasing by millions every year, with a compound annual growth rate of around 15% [11]. According to Statista, in 2018, social and entertainment robot sales reached 2.68 million units worldwide. By 2025, that number is forecast to double to 5.51 million units [12]. We see a general recognition of the potential of this field. However, many robotic companies fail in the market [13]. While the reasons for this are beyond the scope of this paper, we highlight cost and customization. This paper explores FLEXI, a price-effective social robot embodiment kit for flexible use in varied scenarios.

Spectrum of Social Robots

Though the design space for social robots is vast, the majority of social robots look alike [14,15]. They tend to be designed using only the color white [13], hard plastic shells and affording little tactile interaction. Customization of the robot's hardware (or embodiment) is not possible since robots are sold in their final "polished" state. Further, robots usually assume a humanoid shape [17,18]. According to the widely studied Uncanny Valley phenomenon [19], humanoids can create unrealistic expectations of human-like behavior and interactions, which are detrimental to their acceptance.

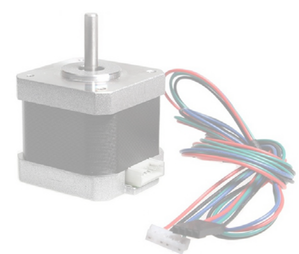
Disappointed with existing social robot platforms, roboticists have developed their own robots using non-humanoid designs. The Blossom robot lets users customize wool covers to place over the robot's core [2]. The YOLO robot has an abstract shape but does not allow for customization [20,21]. Additional non-humanoid robots non-customizable include Cellulo [22], BubbleBot [23], and Ranger [24]. This work challenges assumptions of traditional robot designs and puts forefront the importance of customization as a success metric for broader social robot acceptance.

Customizable Technologies

Though all smartphones look the same, how we organize the apps on them is part of our personal preference system. Customization can be key to ensuring that technology works for an individual user. As users become increasingly diverse, personalization and customization become increasingly important [25,26]. According to the Nielson Norman Group [27], customization is key to ensuring users can enhance and control their interactions especially when they can articulate their needs.

Customizable robotic systems have been developed for a wide range of purposes, including dental procedures [28], mini-robot platforms [29], and disinfection [30]. Past efforts to develop low-cost social robotic platforms include EMAR V4 [31], Huggable [32], Dragonbot [33], TOFU [34], YOLO [20], and Romibo [35]. Costumizable robots' examples are Robot Diaries [38] (later on called Arts & Bots [37]) and Artbotics [39].

Existing customizable social robots still have shortcomings. Blossom lacks a customizable face and its core is not robust enough to afford attachments of heavy materials [2]. The EMAR V4 with flexible software for customized teenager-robot interactions, does not have a fully customizable body but rather a hard shell that does not enable individual personalization [60]. OPSORO is an inexpensive and customizable robot but lacks robustness to be used across different use cases [58], [59].Additionally, many robot kits developed for education are made with arts and crafts materials not allowing a robust robot that can be deployed in real contexts of use. There is an almost unlimited design space for robots to have different colors, heights, materials, shapes, and forms. However, current platforms target only a few of these spaces, opening rich opportunities for more research in this area.



Design Of FLEXI

Design Questions

DQ. 1 What are the design requirements for social robots?

To investigate this, we collected design requirements for robots through a need-finding study [37], [38]. We uncovered pain points with current social robot design and mapped them onto new design principles, specifically focusing on un-met needs of current social robot.

DQ. 2 What does a social robot look like when it meets these design requirements?

To investigate this, we used the methodology of conceptual design [39] to captures the designer's intent. This methodology reveals design opportunities that would be otherwise missed without such creative exploration [40]. We conceptually designed FLEXI and explored its use across three diverse case studies: community support, mental health, and education.

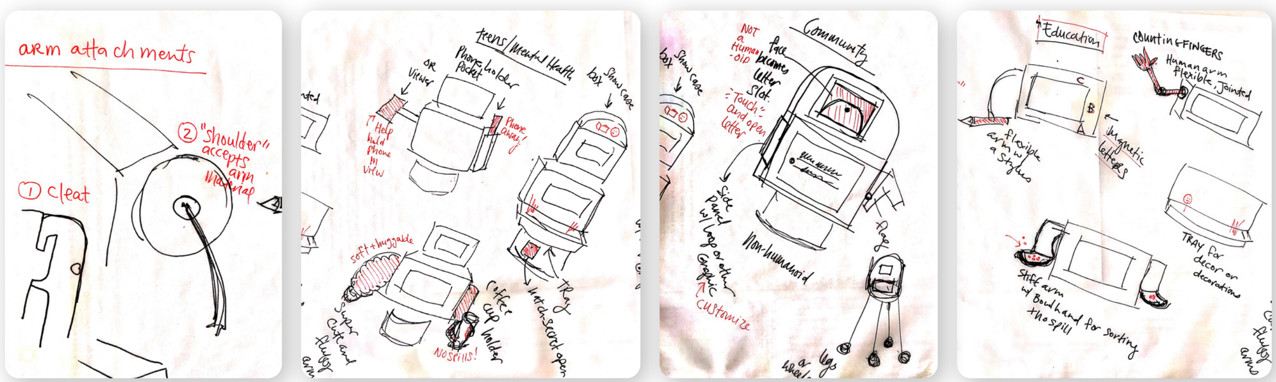
DQ. 3 Does our FLEXI Social Robot Kit meets the needs of its current users in terms of usability?

We fabricated the hardware and implemented the software of FLEXI from scratch. Then, we performed a soft deployment across the three case studies, where diverse users that work in the fields of education, mental health, and community used FLEXI to create a robot that meets the needs to their scenario. We used a case study method [41] which provides deeper insights relative to an exploratory study context.

Table with the pain points and design principles that surfaced during the study described in the next page.

Pain Points	Design Principles
Cost (1) Social robot platforms are expensive and an unstable market product. (2) Social robots are perceived as disappointing as they have unnecessary functionalities/sensors of poor quality that makes them expensive. Frequently these are not used and replaced with external sensing. (3) Integrating existing software in social robots requires a deep learning curve. While this can be learning opportunities, it also hinders students that aim for shorter projects in human-robot interaction.	**Affordability** (1) The cost should be affordable enough to buy at least a pair of the same robot. Not only this will ensure research continues if the robot breaks, as it enables research multi-robot interaction. (2) A low maintenance and high reliability social robot is preferable as frequently the functionalities/features of the robot need to be replaced due to their limitations. (3) As HRI is an interdisciplinary field there is a preference for an easy-to-use software with "low learning barrier" is preferred, accessible to more students.
Rigidity While there is an immense design space for social robots, current platforms only cover a few of these design points in a sparsely populated manner. Important points of social robot design space are left available, e.g., robots with different textures, colors.	**Customizability** Social robots that allow for easy customization are needed to afford the exploration of different scenarios and easy testing for further development. This would include the possibility to purchase parts of the robot, or to add customized parts to the attachments.
Specificity Within each application domain of social robots there are specific needs that are not met. E.g., education has specific needs considering different curriculum.	**Flexibility** Flexibility within the same application domain requires a flexible robot that can be adapted easily to the individual needs.

FLEXI Ideation and Hand Sketches



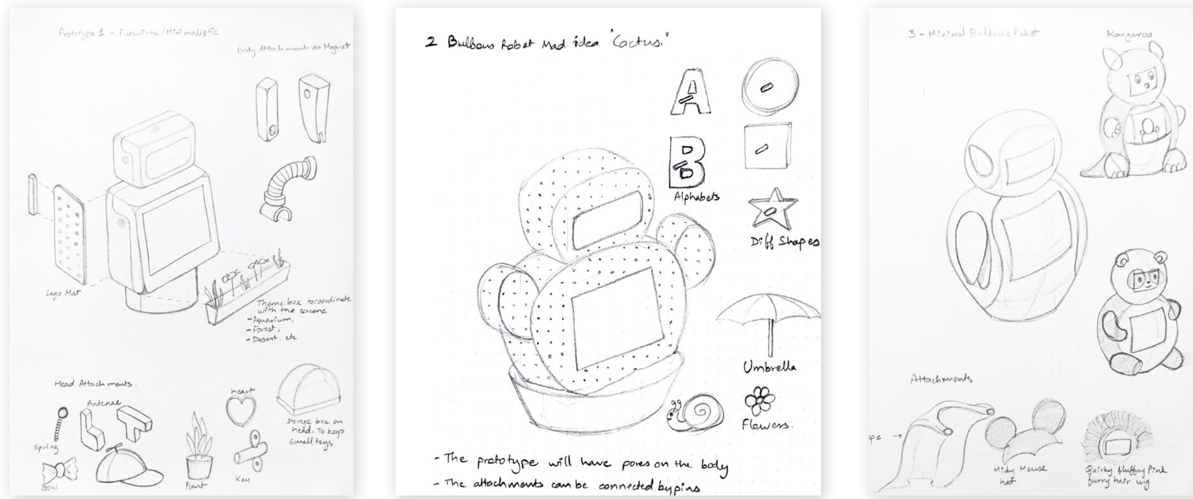
Design Practices

Throughout this work, we adopted intermediate-level knowledge as a meaningful and valid way of generating knowledge [45–47]. We go 'beyond text' into sensory research and contribute new knowledge visually by presenting sketches, storyboards, and photos as outcomes of our work. Visual modes of communicating research findings are becoming more prevalent, especially in interdisciplinary areas [48,49], including HRI [50].

We adopted visual research methods, including conceptual design [42] and hardware fabrication by prototyping with 3D printing and fabric materials [51]. This work is also anchored in qualitative research methods [52] including co-design [54], need-finding [40,41], and semi-formal interviews [55]. These are well suited methods for exploratory studies such as ours that support inductive practices and research spaces where little information is known. They can lead to prominent emerging themes without existing prior hypotheses [53].

Conceptual Design Of FLEXI

To create the Social Robot Kit, we used conceptual design methodologies. We explored three case studies that are commonly investigated in HRI: community-support robot, mental health robot, and education robot.



Hand-sketches of explored ideas for FLEXI.

FLEXI Design Requirements

Recruitment and Sample

Participants were robot users from universities, research labs, or schools. We sampled purposefully for maximum variability, ensuring representation from a range of countries, professional backgrounds, and types of robots used [56]. We interviewed a total of 10 participants who worked in the field of HRI. Six were university professors, 1 was a STEM teacher in a high school, 1 a former STEM consultant, 1 a doctoral student, and 1 a postdoctoral researcher. Regarding demographics, 6 participants identified as female and 4 as male; 2 were Asian, 4 European, and 4 from North America. We stopped recruiting additional participants when we reached thematic saturation [57].

Method and Procedure

We explored need-finding through interviews with experts in HRI to collect untapped opportunities for social robots [58,59]. Need-finding is a methodological tool for both grounding and inspiring research and allows us to quickly enter a user's world, casting the user as an expert who can teach us the meaning of a given task, objects, or technology. Interviews took 30min each, were conducted online using Zoom, recorded, and post analyzed. We adopted a semi-structured interview process as our method for data collection [55], which allows participants to be asked the same questions within a flexible framework. Additionally, participants were encouraged to talk about their experiences through open-ended questions, and the ordering of further questions was determined by their responses [55]. A sample of the interview questions is shown.

Analysis of Pain Points

We comprehensively identified different pain points voiced by experts in HRI towards current robot platforms, which enabled us to gain a deeper understanding into yet un-met design requirements for social robots. See Table in previous page.

Semi-Structured Interview Sample.

- What tools do you use to teach about social robotics?
- What are the advantages and pain points/frustrations of these tools?
- How do university professors and school teachers measure if a new tool is successful?
- If anything were possible, what do you need to bring your curriculum about social robots to the next level?

Community Support Case Study

Outline

It is important to feel a sense of community to belong to a place. However, we can often feel lost when physically relocate and need to start building a new community. We envision this as a robot for the community that can provide moments of brief connection to the city.

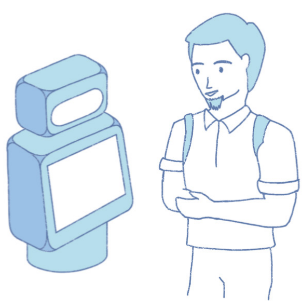
This Community-Support Robot Kit is composed of several creative attachment pieces, such as an umbrella that can be used if raining when people are interacting with the robot; a pocket with pens and pencils that people can use to write down a message for someone; a light bulb that can be placed on the head of the robot that flashes to notify people about a new message; an envelope that can be attached to the body of the robot to signal the robot's functionality: to receive and deliver messages.

We explored two different scenarios using the attachment pieces. Trivia Robot is a scenario where the robot helps newcomers establish connections to the city by providing information, such as fun facts about the city. The Happy Mail Robot is part of a university campus and is meant to encourage students. It does so by receiving and displaying messages from other students and fostering a sense of community. In both scenarios, the robot is used a safeguard of difficult emotions, e.g., alienation, loneliness, and a promotor of well being.

Trivia Robot

Sam just arrived in a new city. He feels lost and does not really know where to go. He decides to look for a park. In the park, he sees a robot and decides to approach it.

This robot gives trivia information about the park and the city. Sam clicks on the first trivia item, and the robot says "Did you know that in one hour there will be a dance performance? Stick around!" Sam smiles, in this moment, he feels connected to the city with new opportunities to meet people.



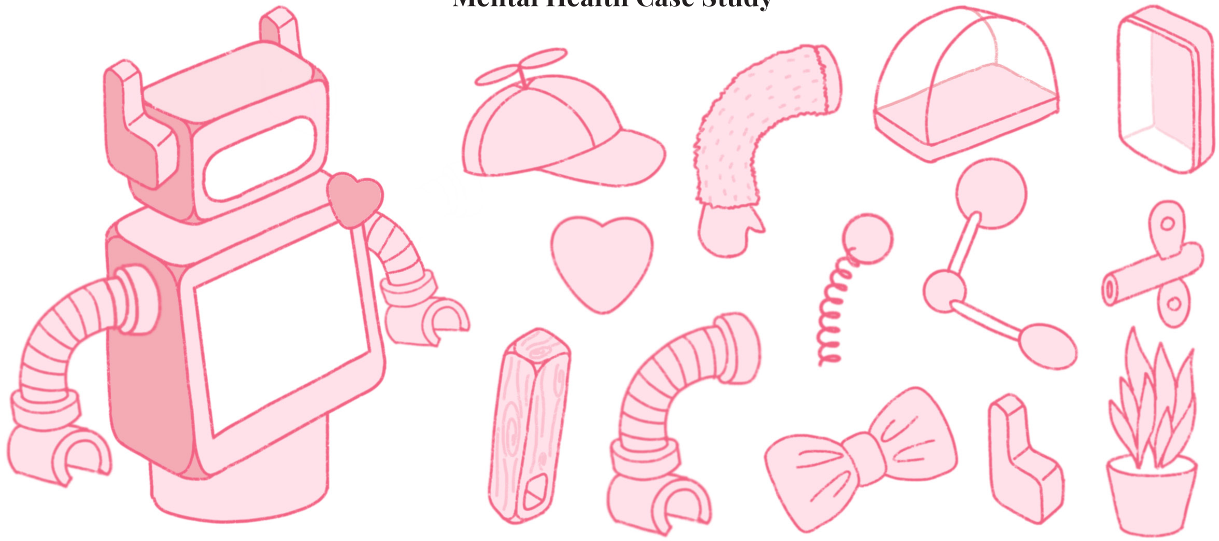
Happy Mail

The life of a student is not always easy. Sometimes, students need encouragement, specially after a tough day. The student Nora approaches the robot, which is part of the university campus property. This robot contains a message, and Nora clicks on it.

The message was sent from someone named Kate to Nora, and says "Believe in yourself. You got this!" Nora smiles. She needed to hear this to be reminded that she is doing her best, even on this difficult day. She secretly thanks Kate, who she actually has never met!

This messages fills her heart with hope, and she decides to print it using the robot's mini printer. This way, she can carry the message with her anytime she needs a reminder. Nora decides to leave a message in the robot too. Maybe other student needs to hear something positive.

Mental Health Case Study



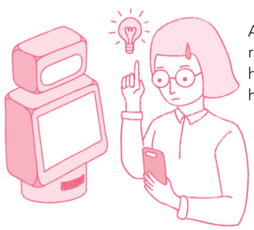
Outline

Mental health is a rising problem among the youth. In this case study, we propose a social robot kit to support the metal health of the youth. This robot is envisioned to live in a high school and help to de-stress and relax.

This Mental Health Robot Kit is composed of a mixed set of attachment pieces that vary in their form and function to provide a flexible embodiment that meets the youth's personal preferences. The pieces' design originated from the data collected from the youth directly. The youth voiced several elements that matter for their robot, including ambient decorations, such as flowers, to practical day-today considerations, such as a slot to keep their belongings. The kit also explores materiality, where some attachments are made in wood, fur, plastic, or fabric.

We explored three different scenarios using the attachment pieces for a mental health robot. Phone Away is a scenario where the youth uses the robot to help focusing attention to study better; Stress Reduction is a scenario where the youth voices out heavy emotional experiences while finding comfort in touching the soft furry arm of the robot; Comfort through Safety is a scenario that explores the feeling of belonging and "being present" with a robot as a form of safety, comfort, and re-balance.

Phone Away

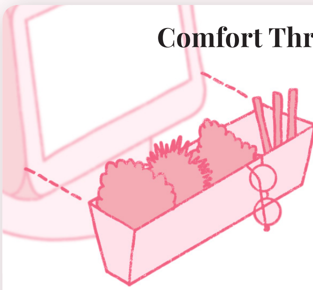


A teenage girl is struggling to focus on her readings due to smartphone notifications from her friends. She has an idea for what could help her focus.

She gives her smartphone to the robot that has a special slot to insert and lock the phone. The robot keeps her phone and she can focus on her reading.

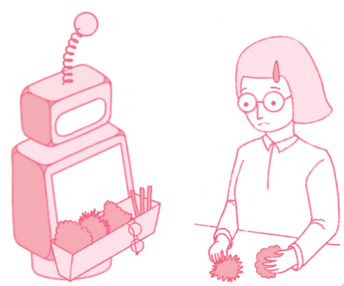
Every time the girls wants to check her phone, the robot reassures that she will feel more proud if she finishes her readings first, and then connects with friends.

Comfort Through Safety

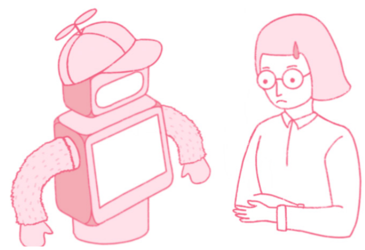


This robot's embodiment is meant to be a stress and anxiety reducing playground. It has an attached tray that contains stress-reducing objects, such as a sponge, a stress ball, a fidget toy. The robot has other attachments, such as a spring in its head.

A teenager girl is feeling anxious but she does not feel like talking about it. She starts to fidget with the robot's attachments and this helps her cope with her anxiety, while at the same time promoting relaxation and stress relief.

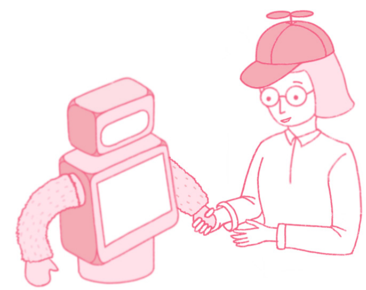


Stress Reduction

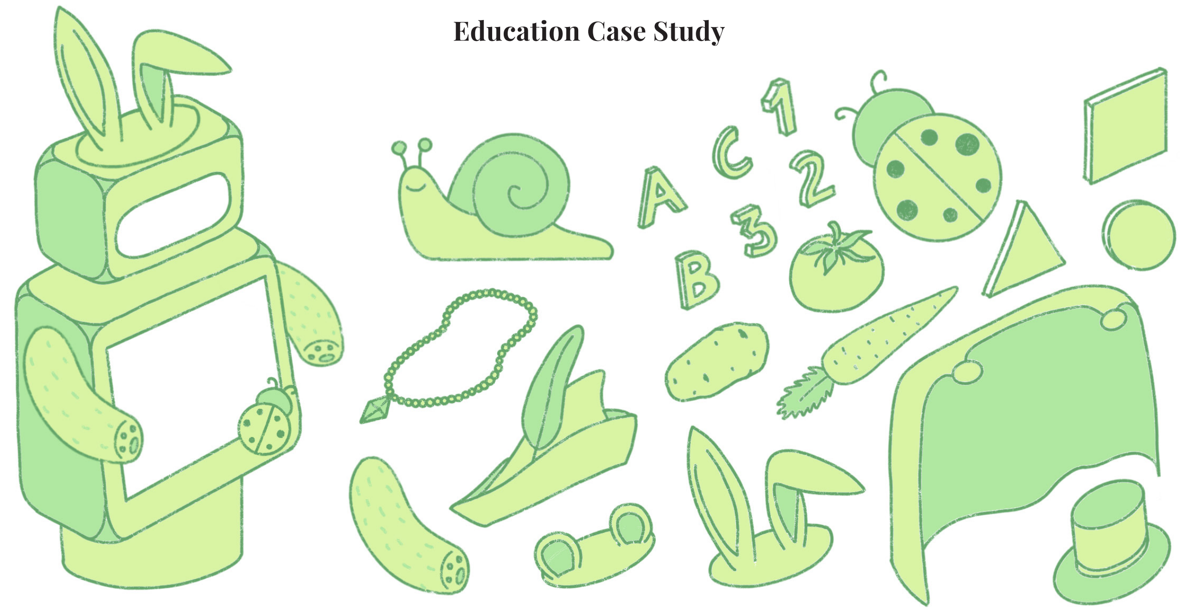


A teenager is extremely stressed from school. She feels like sharing her feelings without judgement and goes to the robot. This robot lives in her school and is meant to support teens with high stress levels. It is a complementary school technology for mental health when counselors are unaccessible.

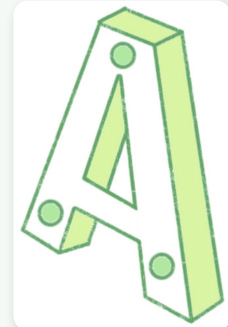
While sharing her stressors with the robot, she holds its fluffy hand. This makes her feel comfort and safety, which are important feelings in moments of high stress. She also uses the robot's cap as a way to feel close to the robot, similar to how friends share belongings.



Education Case Study



Outline



The most effective education scenarios exist when children feel safe to make mistakes and learn from them. However, often children feel embarrassed when they make a mistake in front of their peers or even their teacher. This robot is envisioned to be a non-judgemental educational tool that children can use during learning.

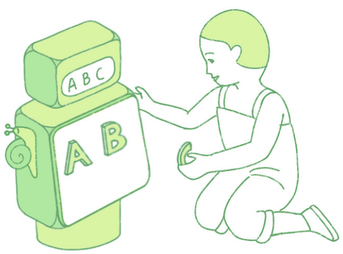
The Educational Robot Kit is composed of attachment pieces that bring feelings of safety and non-judgement while learning. The pieces originated from data collected with children focusing on moments where they struggled to learn. Children expressed a desire for a robot to resemble animal and sometimes human traits. This Kit includes bunny ears, bear arms, and small insects that can be attached to the robot. The Kit includes a super hero cape and a pearl collar that signifies learning gains. One unique aspect of the Educational Kit is that pieces can be attached to the robot easily with the help of magnets.

We explored the use of the Educational Kit across three different cases (visual learning, spelling, and reading) and across different age-groups.

Visual Learning

A child is learning about the alphabet with the robot through visual-aid and physical objects. The robot display's in the eye screen a letter for the child to find.

The child finds the corresponding letter and places it on the magnetic board that the robot has on its belly. Seeing the letter and finding it in a physical object enhances the learning of the alphabet.

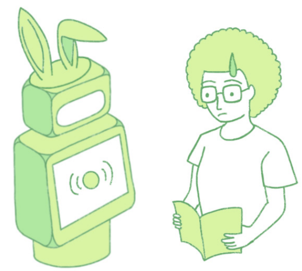


Spelling

The robot helps a child to spell correctly. It shows the image of an object on its belly and prompts the child to spell it out in their notebook.

When the child finishes writing, the robot displays the correct spelling on its belly. Children can compare their spelling with the robot's and correct their own mistakes, which empowers self learning. The child can put on the robot's cape as a reward for the learning gain.

Reading



Reading in a new language is challenging for every child. This child feels judged for not being able to read fluently compared to their peers. The robot will listen patiently to the child's reading without judgement.

The robot plays back the reading of the child, making them aware of where they can improve. The child understands their shortcomings and tries reading again.

FLEXI Hardware

Regarding FLEXI actuators, the robot integrates four dynamixel motors, one is allocated at the base for swiveling, one in the neck enabling the robot to lean forward/backward, one in the head enabling head nods, and one in the face to enable tilting. The combinatory of these of these actuators enable movements that signify active listening, curiosity, interest.

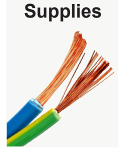
Regarding FLEXI sensors, the robot integrates a capacitive sensor on the head that enables touch recognition. Additionally, the smartphone and the tablet enable input through those interfaces. This includes voice recognition, touch, and the cameras can be used as sensors. The sensors enable the robot to perceive the user in a multimodal way. Additional hardware materials can be found in the website: https://osf.io/dbg6h/?view_only=51a4b157f8cd40aaa0be532e51dbd824. The hardware of FLEXI was entirely developed by the research team.

FLEXI Interactions

FLEXI was designed and fabricated to be a Social Robot, capable of engaging in meaningful interactions with human counterparts. FLEXI robot is capable of a wide range of behavior for a successful human-robot interaction. FLEXI uses both non-verbal behaviors (i.e., eye gaze/ blinking, emotionally evocative animations, head tilt, leaning backward/forward), and verbal behaviors (i.e., sounds and natural language expression).

Additional modalities are possible, such as speech recognition from the smartphone/ tablet. The multiple interaction modalities of FLEXI enable this social robot to interact with different users, from children, to teenagers, adults, and the elderly in a broad range of human-robot interaction scenarios.

BILL OF MATERIALS FOR FLEXI ROBOT KIT Note: Materials are available according to source availability. Prices might fluctuate.

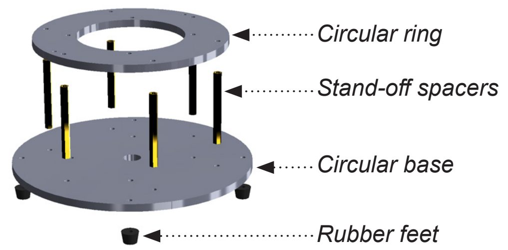
CATEGORY	DESIGNATOR	QTY	COST USD	SOURCE	INFO
Accessories and Fasteners	9mm Rubber Feet	6	$ 8.19	Amazon	Sold in packs of 20
	M4x60mm Standoff	6	$ 9.99	Amazon	Sold in packs of 10
	M4 Button Head Screws + Washers	1	$ 19.99	Amazon	Use 16x 16mm screws and 12x washers from set
	M3 Socket Head Cap Screws + Nuts	1	$ 19.99	Amazon	Use 16x12mm screws, 7x10mm screws, 2x30 mm screws, 65 hex nuts
	M2x8mm Flathead Cap Screw	8	$ 8.99	Amazon	Any M2x8mm cap screw can work
	M3 Spacer	6	$ 5.99	Amazon	Comes in packs of 250
	M3 Nylon Set	1	$ 11.99	Amazon	Use 2x 10mm screws, 4x12mm standoffs, 2x8mm standoffs, 1x6mm standoffs, 1x 6+10mm standoff, 4x 6+12mm standoffs, 8x hex nuts
Robotics	Joint Motor	1	$ 219.90	Robotis	2XC430-W250-T motor; use 4x M2x5mm bolts included
	Joint Motor Idler	1	$ 6.40	Robotis	Nh11-I101 idler; idler cap,1x M3x55 flush head stud bolt included
	Joint Motor (2x)	2	$ 979.80	Smart Robot Works	XH540-W270-T motor; use HN13-N101 gear and teflon washer included; use 14x M2.5x4mm and 8x M2.5x5mm wrench bolts
	Joint Motor Idler	1	$ 39.10	Trossen	Use 6701ZZ bearing; HN13-I101 idler, DC13 idler cap included
	U2D2 Power Hub Board	1	$ 17.30	Robotis	Attach with U2D2 using parts in set
	U2D2	1	$ 29.30	Robotis	Attach with U2D2 power hub board using parts in set
Industrial Hardware	Makerbeam 100	3	$ 16.66	Amazon	Comes in pack of 16
	Makerbeam 200	6	$ 16.66	Amazon	Comes in pack of 8
	Makerbeam 150	2	$ 9.28	Amazon	Comes in pack of 6
	Makerbeam hinges	4	$ 21.00	Amazon	Comes in pack of 4; use all items in set
	Makerbeam straight	4	$ 6.99	Amazon	Comes in pack of 12
	Makerbeam L	4	$ 6.99	Amazon	Comes in pack of 12
	Makerbeam T	2	$ 6.99	Amazon	Comes in pack of 12
	Makerbeam square bolts	57	$ 15.30	Amazon	Comes in pack of 250
Electronics: Supplies	Silicone Wire	1	$ 24.01	Amazon	Comes w/25 feet of cable; max 2 feet will be used
	Surface Car Charger	1	$ 49.99	Amazon	N/A
	Car Charger Adapter	1	$ 5.25	Amazon	N/A
	Yellow Crimp Connectors	2	$ 24.98	Amazon	Use 2 yellow butt splice crimp connectors (female/female)
	Techflex Cable Sleeve	1	$ 12.95	Amazon	Use as much as needed to conceal wiring
Electronics: Components and Cases	Surface Tablet	1	$ 299.99	Microsoft Store	May replace with Windows tablet of equivalent size
	Surface Case	1	$ 25.99	Amazon	N/A
	Pixel 3 XL Phone	1	$ 429.00	Backmarket	Prices may vary; may replace w/ iOs or Android of equivalent size
	Pixel 3 XL Case	1	$ 11.99	Amazon	N/A
TOTAL COST			$2,330.21		

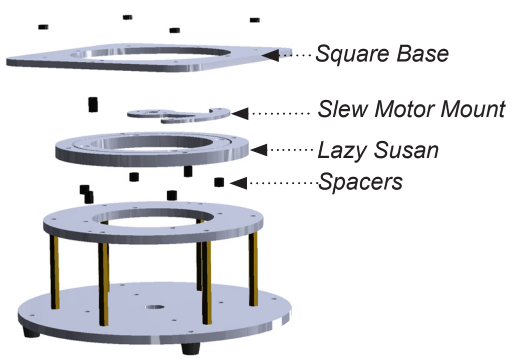
GUIDELINES FOR BUILDING FLEXI

Note: Time and difficulty level will vary depending on experience of the builder with robot hardware

1 Build the Base

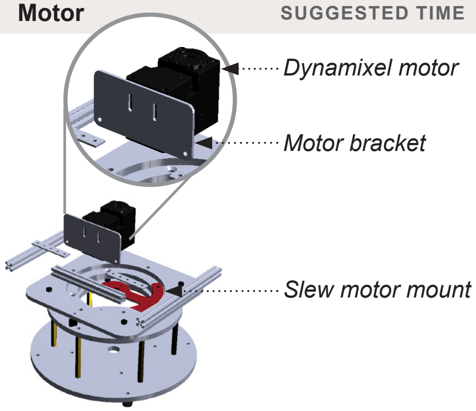
DIFFICULTY LEVEL ★☆☆
SUGGESTED TIME 1 HOUR





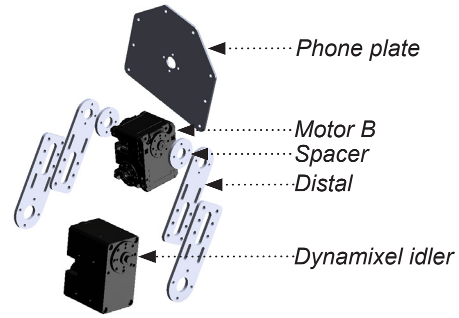
2 Attach Dynamixel Motor

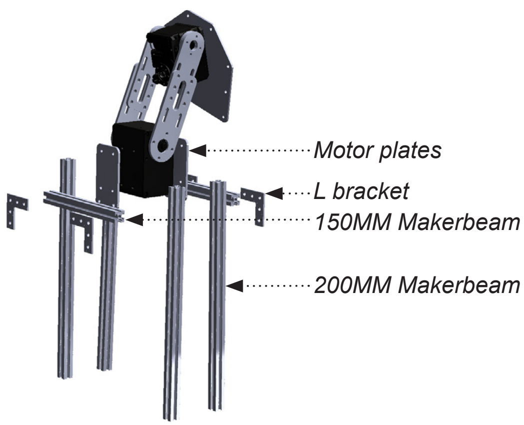
DIFFICULTY LEVEL ★★☆
SUGGESTED TIME 1 HOUR



3 Build the Head

DIFFICULTY LEVEL ★★☆
SUGGESTED TIME 3 HOURS

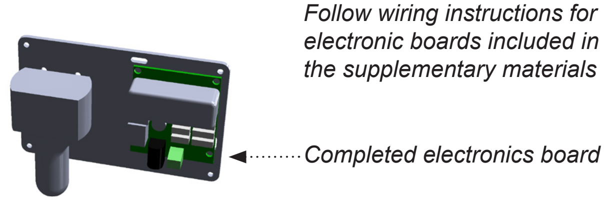




4 Build Electronics Board

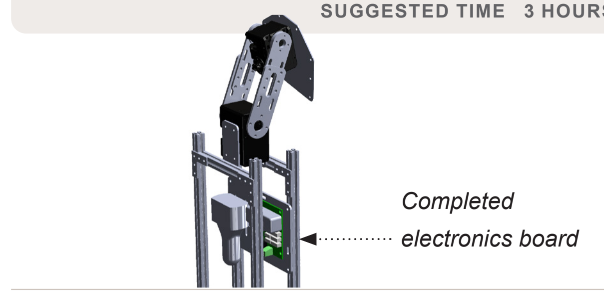
DIFFICULTY LEVEL ★★☆
SUGGESTED TIME 2 HOURS

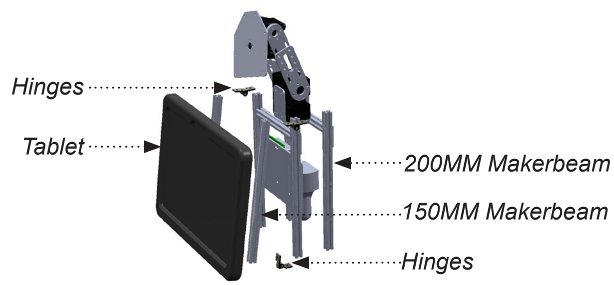
Follow wiring instructions for electronic boards included in the supplementary materials



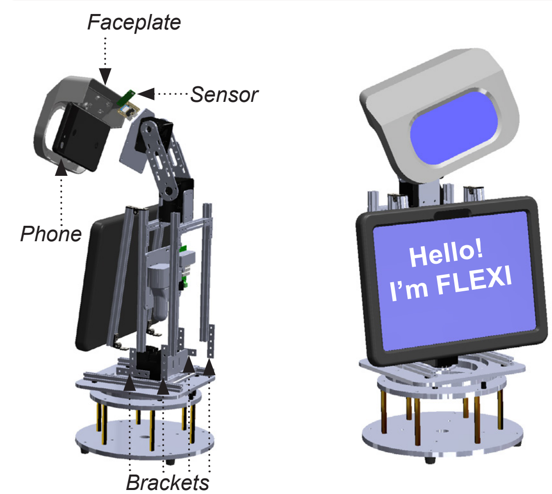
5 Build the Body

DIFFICULTY LEVEL ★★★
SUGGESTED TIME 3 HOURS





6 Completed Flexi

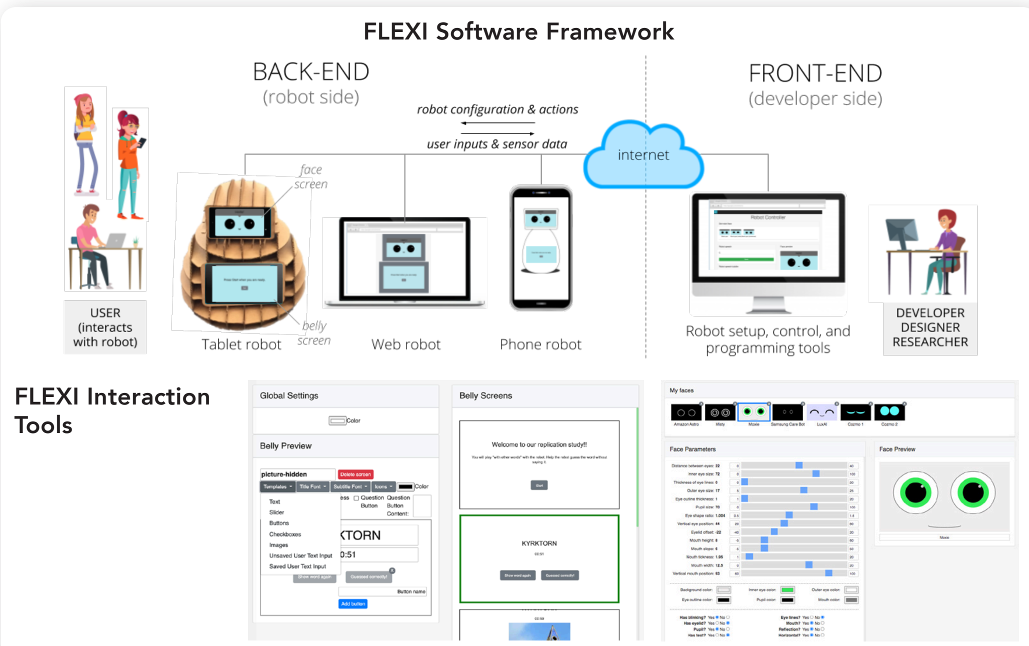


FLEXI Software

FLEXI's software consists of an easy-to-use browser-based tools that integrates end-user programming, implemented with HTML, CSS, and JavaScript. The robot software enables (i) creating interactive content for a social robot, (ii) rendering such content on the robot, (iii) direct user control of the robot (commonly called 'Wizard-of-Oz', where a human called 'wizard' teleoperates the robot), (iv) programming the robot to autonomously interact with users.

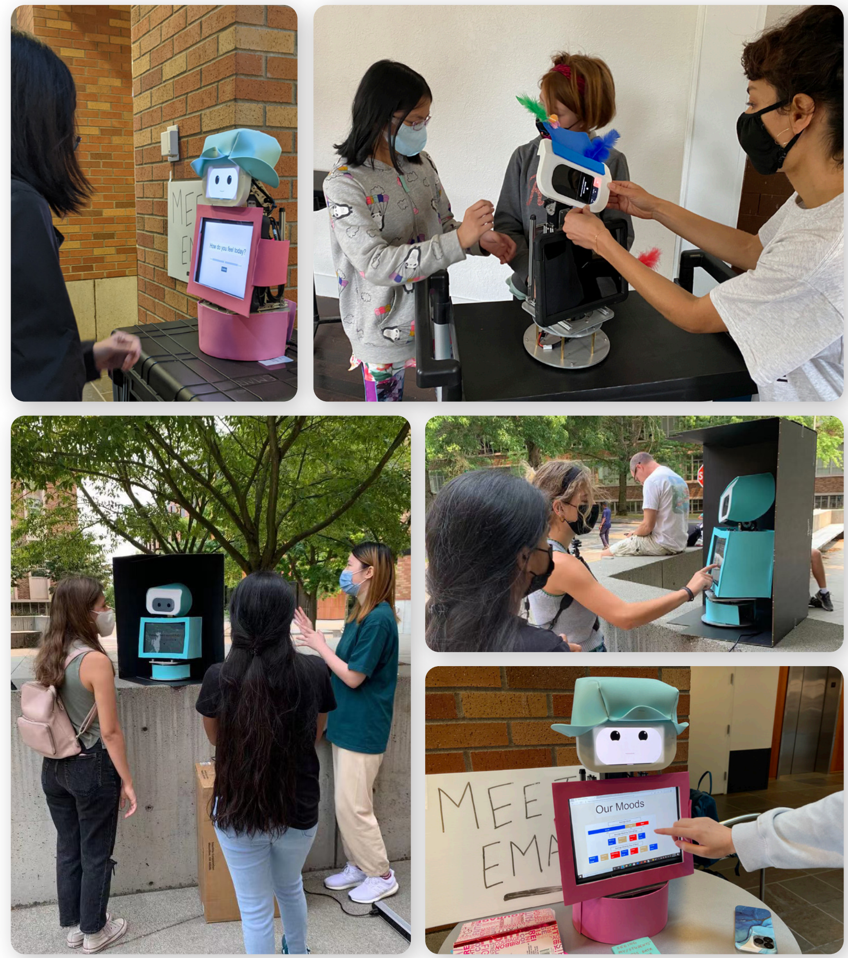
The software is split into two parts. The back-end software runs on the robot side. It renders the robot's face and belly screens, receives and executes robot actions (like 'say' or 'setFace'), and captures user input and sensor data from the robot. All robot configuration data is stored in the cloud. The back-end software retrieves all relevant information from the database and sends back user input and sensor data to the database. The back-end does not run interaction programs; rather, it serves like a reactive shell that continuously waits to receive action commands and executes them when received. This results in a fully customizable software as the user not only can choose from pre-defined options but also create new customized ones. These features makes it easy to reuse and re-purpose ideas developed across different scenarios.

Software functionalities include a face editing tool that allows users to create social robot faces from basic face elements like eyes and mouth. The software was completely developed by the researchers of this project. The software of FLEXI is available in open-access in this weblink: https://mayacakmak.github.io/emarsoftware/



Soft Deployment

We conducted a soft deployment of FLEXI across three application scenarios: community-support, mental health, and education. This was not a controlled experimental study, but rather a usability study with the goal of assessing the flexibility of FLEXI in three different HRI scenarios. The procedure for each application case was similar: we provided general guidelines on how to use FLEXI and enabled the participants to explore the Kit. Participants used FLEXI independently and with minimal support from the research team.



Community Robot

Robot that delivers inspiring messages to passengers. It lives outdoors in a public space, such as a city park. This robot is meant to be used by passengers of all ages, serving as an inclusive technology.

A. FLEXI Applied To Community Support

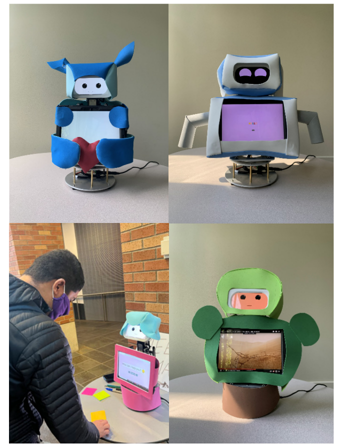
CONTEXT: We delivered FLEXI to a human-centered design researcher at a university. The researcher programmed FLEXI to be a message delivery robot, whose role was to provide cheerful messages to passengers in public spaces to promote an inclusive community. During two days, one hour each day, FLEXI was displayed outdoors, and the researcher collected feedback about the robot looks and feels.

INTERACTION: The researcher created brief and captivating interactions, such as having the robot say: *"There is a message for you. It says you are brave, bold, and beautiful."* Participants would interact with the robot by opening a secret message delivered by the robot. The robot also invited them to write a message for the next person by giving this option through the belly screen.

RESULTS: The researcher collected qualitative feedback from 10 pedestrians, which was used to create a set of attachment pieces appropriate for a community-support robot, as seen in the Figure on the top. We interviewed the researcher, who reported high usability levels and noted how working with FLEXI expanded their creativity as a content creator, allowing them to create a diverse set of robot behaviors and embodiments.

Mental Health Robot

Robot provides micro-interventions to decrease levels of stress and anxiety. It lives in libraries, schools, or at home. This robot is meant to be used by the youth.



B. FLEXI Applied To Mental Health

CONTEXT: FLEXI was used as a mental health tool to support well being routines of adolescents. We delivered FLEXI to an interaction designer who works in museums for youth to create interactive experiences using FLEXI.

INTERACTION: The designer conducted two sessions with adolescents to collect requirements for the robot. In total, 19 adolescents participated in customizing the robot and their final designs are shown in the Figure on the top. Adolescents could program the robot and build attachment pieces. To test their designs, they invited adolescents from the group to briefly interact with the robot and improved their designs according to the feedback received. Adolescents explored different rotations and speeds of the robot's motors to create complex behaviors, e.g., the robot moves towards someone to greet them.

RESULTS: Adolescents created two types of mental health robots: "Being Present", and "Listening" robots. When we interviewed the designer, they emphasized how the robot was an easy-to use tool that each adolescent could customize to serve their individual preference system.

Educational Robot

Robot enables the training of educational skills by repeating exercises with students. It lives in a school or a summer camp. This robot is meant to be used by children.

C. FLEXI Applied To Education

CONTEXT: FLEXI was used as a learning tool to support the acquisition of educational content. We delivered FLEXI to a middle school teacher who teaches Chinese children to speak English. During one full day, the teacher shared the robot with groups of children in a school who customized the robot for a reading scenario.

INTERACTION: English language learners are a vulnerable population that often does not participate in classes for fear of being criticized for their English-speaking skills. In this scenario, the teacher asked students to create a listening robot, and the results are shown in the Figure on the top. Children decorate the robot and were able to interact with it by telling the robot a story. The robot exhibited non-verbal behaviors of active listening, e.g., tilting the head.

RESULTS: In total, 22 children contributed their designs. When we interviewed the teacher, they mentioned how the robot empowered children since they were the ones deciding how it should look and behave, contrary to the dis-empowered state they generally felt while learning.

Fabrication Safeguards

Assembling FLEXI is a process that involves interacting with mechanical tools and machinery for which safety guards are required. To the best of our knowledge, no safety guidelines for personal fabrication have been formally established, and misuses have been considered users' responsibility [60]. As such, we strongly advise FLEXI makers to build the robot under the supervision of experienced makers.

FLEXI Kit Open-Access

One of the major contributions of this work is to provide open-access to all the materials and documentation for fabricating, assembling, and operating FLEXI (Supplementary material for this submission is included in the Open Science Framework, accessible in the webpage: https://osf.io/dbg6h/?view_only=51a4b157f8cd40aaa0be532e51dbd824). The software for this robot is available in open access in GitHub: https://github.com/mayacakmak/emarsoftware/wiki.

The concept behind the FLEXI Robot Kit robot is not to be a prepared to kit to ship. Rather, we share the full list of hardware materials that can be purchased anywhere in the world, alongside with the tutorial for FLEXI fabrication, to enable anyone interested in robotics to create their own kit. Given the low-medium learning curve in fabricating and operating FLEXI, creating this robot consist of an accessible entry-point to social robotics and STEM education.

We produced a conceptual unboxing video of FLEXI to inspire the future users of this robot: https://youtu.be/sUJE2NSXgbM

CUSTOM-MADE DESIGN FILES FOR FLEXI — Files using: https://sendcutsend.com

FILE NAME	FILE TYPE	THICKNESS	LICENSE	LOCATION	QTY
Base ring	DXF	4.7mm	CC BY 4.0	OSF website link	1
Mounting plate	DXF	2.5mm	CC BY 4.0	OSF website link	1
Neck bracket spacer	DXF	2.5mm	CC BY 4.0	OSF website link	4
Neck bracket distal	DXF	2.5mm	CC BY 4.0	OSF website link	2
Neck bracket proximal	DXF	2.5mm	CC BY 4.0	OSF website link	2
Circular base	DXF	4.7mm	CC BY 4.0	OSF website link	1
Phone Plate	DXF	2.0mm	CC BY 4.0	OSF website link	1
Neck motor plate	DXF	2.0mm	CC BY 4.0	OSF website link	2
Slew motor bracket	DXF	2.0mm	CC BY 4.0	OSF website link	1
Torque tongue lazy	DXF	2.0mm	CC BY 4.0	OSF website link	1
Outer ring	DXF	4.7mm	CC BY 4.0	OSF website link	1

Limitations and Future Directions

FLEXI is a flexible robot toolkit, easy to use across multidisciplinary teams, to learn, teach, and perform research on Human-Robot Interaction. Despite its many qualities as a novel platform, there are limitations that we want to acknowledge. In its current version, FLEXI has limited sensing of the user, e.g., the user can interact with FLEXI through the iPad by clicking on buttons. In the future, we plan on expanding the interaction capabilities of FLEXI by relying on microphones and cameras from the iPad and smartphone to provide the robot with additional sensing capabilities. FLEXI has demonstrated its potential across a variety of case studies. However, we have not compared its performance with existing robot platforms, and we also have not studied how this platform performs in long-term HRI, which we intend to study in the future. Towards future work, we aim to conduct movement studies to document the effect that attachment pieces of different materials have on the robot's range of motion and expressivity. After this, we aim to conduct experimental studies to evaluate the effectiveness of a human-robot interaction using FLEXI.

Reflection and Conclusion

The many social robots on the market have shortcomings. They do not allow for easy customization since designing a robot's appearance is challenging. The design should be both aesthetically appealing and physically functional. We connect the goal of customization and functionality with FLEXI, a social robot embodiment kit. This robot can be customized for a range of use cases by easily connecting attachment pieces. The kit is flexible, robust, affordable, and easy-to-use.

Our main motivation with FLEXI was to challenge how social robots are now designed, since at present they are a one-answer solution, instead of meeting the needs of people with different tastes, cultures, and experiences. Since it is hard to create a robot that in itself meets all needs, we propose a robot kit that can be adapted to every person and to every need by letting users themselves customize it.

Acknowledgments

We are grateful to Roberto Aimi and Guy Hoffman for their guidance, inspiration, and work on FLEXI. We also thank all the participants involved in this study, including Belinda Louie and Yufei Zhang. This work was supported with funding from the Innovation Gap Fund from CoMotion at the University of Washington and by the NSF NRI: INT EMAR Project Award #1734100.

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