

Blossom: A Handcrafted Open-Source Robot

MICHAEL SUGUITAN, Cornell University, United States

GUY HOFFMAN, Cornell University, United States

Blossom is an open-source social robotics platform responding to three gaps in existing systems: (1) Designing, manufacturing, and programming social robots requires a high level of technical knowledge; (2) social robot designs are fixed in appearance and movement capabilities, making them hard to adapt to a specific application; and (3) the use of rigid mechanisms and hard outer shells limits the robots' expressive capabilities. In contrast, Blossom aims at three design objectives: accessibility, flexibility, and expressiveness. The robot's mechanism can be quickly assembled and extended by end-users. Blossom's appearance is open-ended through handcrafted fabric exteriors created and customized by users. Smooth organic movements are achieved with tensile mechanisms, elastic components, and a soft exterior cover attached loosely to the body. Blossom's smartphone-based gesture generation requires neither programming nor character animation experience, allowing users to easily create their own behaviors. All elements in the design were conceived with low cost and a low barrier-of-entry in mind. The result is an accessible and customizable robot for researchers and hobbyists. This paper details the implementation of Blossom's design and demonstrates the platform's potential through four field deployment case studies.

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1 INTRODUCTION

The design of social robots with expressive capabilities is an active area of research in human-robot interaction (HRI). Dating back to MIT's Kismet—a robot specifically built to express internal states through facial movement and vocalizations [9, 10]—researchers in HRI have been developing methods for expressive capabilities of robots and collecting empirical evidence for the effects of these behaviors. Some of these robots use facial expressions [8, 11, 15, 27] while others express their internal states through bodily gestures [23, 26, 28, 54] or other modalities [6, 40]. More recently, consumer electronics companies have also started to explore expressive social robots as commercial products [4, 24, 35].

Designing and building such a robot, however, requires extensive knowledge and resources in mechanical and electrical engineering. Similarly, designing and implementing the robot's expressive gestures and behaviors requires professional skills in computer science and 3D character animation. This makes robot building and programming inaccessible to a large swath of users.

This lack of accessibility limits the use of social robots for both researchers and end-users. For example, most researchers in HRI have a choice of one of a handful of programmable social robots, such as the Softbank Robotics's NAO or Pepper robots, Philips's iCat, Rethink Robotics's Baxter, or the MyKeepon platform. These robots are subsequently exceedingly prevalent in the HRI literature,

Authors' addresses: Michael Suguitan, Cornell University, United States, mjs679@cornell.edu; Guy Hoffman, Cornell University, United States, hoffman@cornell.edu.

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Fig. 1. Three variations of Blossom with different embodiments and accessories. The robot on the left is knitted, and the two robots on the right are crocheted. The two robots on the left display swappable wooden ears and a number of attachable facial features, while the robot on the right features soft silicon arms as appendages.

e.g. [1, 7, 12, 19, 29, 31, 48, 55]. Each of these robot has a single outward appearance, which is overcome at times with adornments such as hats or other accessories [46]. Still, it is difficult to adapt the robot's appearance to the task at hand, rendering them inflexible with respect to specific applications and personalization.

The majority of social robots are also rigid in a more literal physical sense: Their exteriors are made of hard plastic or metal shells manufactured using additive and subtractive methods such as 3D printing, molding, and milling. These exteriors are fixed to direct or geared drive mechanisms and rigid linkages with fasteners such as bolts and adhesives to form solid connections. This mechanical rigidity restricts the robot's expressiveness and interactive capabilities. Rigid actuation mechanisms make it difficult to achieve smooth, organic movement without complicated software control or trajectory generation. Stiff direct linkage mechanisms also discourage physical interaction due to their hard tactile affordance and fear of damaging internal components.

In this work we present Blossom, an open-source robotics platform for researchers and hobbyists, with the goal of addressing the issues identified above. Blossom is designed to allow researchers and end-users to imagine and build their own robot, enabling more flexible design possibilities in the robot's appearance, structure, and behaviors. This could increase adoption and help diversify HRI research. In addition, Blossom offers a novel mechanical design with compliant, organic movement in mind, to support expressiveness and interactivity.

Blossom thus attempts to achieve three design objectives: *accessibility*, *flexibility*, and *expressiveness*, implemented through the following design choices:

- The robot can be easily put together by lay-users.
- It has modifiable degrees-of-freedom (DoFs), but is still predictably expressive.
- It uses a tensile mechanical structure that affords smooth movements and safe interaction.
- Its appearance can be handcrafted with traditional crafts.
- Both its mechanism and exterior can be made from readily available low-cost materials.
- New behaviors can be defined without requiring programming or computer animation skills.
- Behaviors are accessible through an open interface suitable for a broad range of applications.

Notably, Blossom is not a robotics kit in the same vein as LEGO Mindstorms™ or Meccano™, which differ in two important ways. First, these kits provide a widely open-ended design space

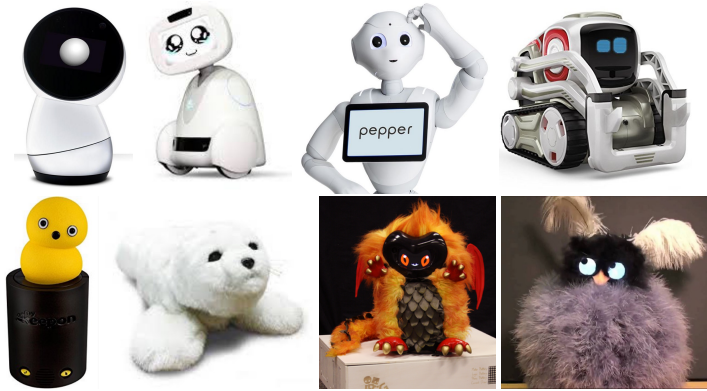


Fig. 2. Jibo, Buddy, Pepper, and Cozmo (top) are examples of social robots with similar design features related to consumer electronics devices. Keepon, Paro, DragonBot, and Tofu (bottom) exhibit softer and more zoomorphic embodiments.

which is not tailored to any specific application. In particular, they are not designed with expressive behavior or social interaction in mind. Second, these kits cater mostly to technically-oriented users and focus on the robot’s construction rather than its use. In contrast, Blossom is socially-oriented, while still being easily customized by non-technical users, and focused on the end-user of the robot.

As a use case, we imagine a social science research group with limited technical expertise but interest in a research question related to HRI. Researchers in this group should be able to quickly build, fashion, and use a Blossom robot and define behaviors specific to their application. Another scenario could be a lay-user who is uninterested in engineering and programming but wants to build a social robot for their personal use with a particular appearance and set of behaviors.

In this paper we present Blossom’s mechanical, electronics, and software implementation and detail the customizable exterior and behavior of the robot. To evaluate the design, we provide four case studies of field deployments where users implemented or interacted with Blossom robots.

2 RELATED WORK

Blossom relates to the existing literature in social robot design, gesture generation, and open-source robotics construction kits.

2.1 Social Robot Design

Aesthetic designs for social robots range from product-like to organic. Jibo, Buddy, Pepper, and Cozmo (Figure 2 top) are examples of robots with features akin to those of consumer electronics devices, such as straight lines, rounded edges, touch screens, and illuminated accents [13, 20, 25, 44]. On the other side of the spectrum are creature-like robots such as Keepon, Paro, DragonBot, and Tofu (Figure 2 bottom), evoking a more zoomorphic aesthetic [30, 49, 57, 58]. All these robots’ appearance and DoFs are fixed and not customizable by their users.

The choice of materials also plays an important role in robot design. Appliance-like robots are generally made from rigid materials such as plastics or metals with smooth finishes. While the use of alternative and handcrafted materials has been emergent in other interactive technologies [39, 59], it has been less explored in social robotics. OPSORO (Open Platform for SOcial ROBots) is an exception in that it uses fabrics in the design of its soft covers [56]. Additional examples exist in hobbyist circles, such as TJJBot, a single-DoF desktop robot, and Smartibot, a phone-controlled mobile robot, both constructed from cardboard [5, 14].

For actuation, most robots use rigid mechanisms and direct-drive motors to achieve movement. Smooth motions must thus be achieved through intricate control software and trajectory generation tailored to the robot's kinematics. Some have explored pneumatic actuators that can achieve smooth motion through mechanical design [45], but the pumps and compressors required to drive these systems are often noisy and cumbersome. Another approach is to use tensile mechanisms to trade precise control for range and smoothness of motion. One example is the prototype robot Tofu, which has a head attached to a foam column with cables pulling on the head for actuation [58]. Another example is Probo, a robot with a tensile trunk [18].

Compared to these social robots, Blossom's design differs in that it is flexible, inside and out. Blossom features an open-ended exterior meant to be customized by end-users through handcrafted materials, and its interior actuation mechanism uses compliant tensile components. This actuation mechanism is kinematically similar to Stewart platform mechanisms, which were used in the DragonBot [49] and Peeqo [50] robots. However, in contrast to those mechanisms, Blossom uses compliant components to achieve smooth and lifelike movement without requiring complicated software control. It also achieves a larger range of motion than Stewart platforms with only half the number of motors. Blossom's mechanism bears similarity to that of the Tofu robot but has a larger range of motion due to its free-floating platform; it is also simpler to manufacture. In addition, Blossom's exterior cover and internal mechanisms are not affixed to each other, allowing for more expressive movement through slip and secondary action.

2.2 Robot Gesture Generation

Generating smooth and natural movements and gestures for social robots can be a lengthy and complicated process. Traditional methods for gesture generation are generally programmatic, require knowledge of the robot's kinematics, and are not accessible to novice users. Allowing users to create their own gestures affords a novel method of personalizing the robot and could help mitigate the novelty effect stemming from robot movements being repetitive and predictable.

In efforts to make robot gesture generation more accessible and intuitive, researchers have developed methods involving physical manipulation of the robot. Mirror puppeteering involves placing markers on parts of the robot and manipulating it in front of a camera to record movements [51]. Robots like Topobo and ChainFORM implement "kinetic memory" which allows gestures to be recorded by physically moving the robot's appendages by using back-drivable motors with position encoders [37, 41]. Learning from Demonstration supplements either approach by having the user provide corrective demonstrations to iteratively teach the proper movements [3]. These approaches are more intuitive than programmatic methods, but make it difficult to perform full gesture generation in real-time, often requiring a layered approach in which each DoF is actuated one at a time. In some cases, keyframes and interpolation are used to complement the puppeteering activity. This approach makes it hard to achieve high-quality expressive movements.

In contrast, Blossom allows lay-users to create gestures using a smartphone as a puppeteering interface. The robot's actuation mechanism kinematically resembles a free-floating platform and is controlled by mapping the orientation of the phone to that of the robot's head platform directly, enabling real-time exploration and recording of gestures.

2.3 Open-source Robots

There are a few existing open-source robotics projects that allow users to build their own robot from openly accessible online data files. Robots like iCub, Poppy, and InMoov are examples of open-source platforms that have humanoid bodies and intricate mechanical and software designs [32, 33, 36]. Non-anthropomorphic open-source robots such as Hexy and TurtleBot are comparatively simpler [2, 17], owing to their more abstract embodiments. While the design of these robots are

openly accessible, their appearances are largely fixed, and the systems require a high degree of technical knowledge to build, program, and use. Some of these robots can be programmed through visual block-based languages such as Scratch or Blockly [16, 42], but this programmatic approach does not support the authoring of new expressive gestures, making them ill-adapted for social robotics applications.

Among open-source robot platforms, OPSORO is specifically socially-oriented. It is comprised of modular components representing different facial features and a customizable exterior cover that is made from soft materials [56]. This makes it more accessible and expressive than most other open-source social robots. A semester-long deployment of the robot in a student design course produced several unique embodiments ranging from animals to the likeness of Albert Einstein. That said, OPSORO was largely designed for facial expressions, and its behaviors must be defined programmatically.

3 DESIGN OBJECTIVES

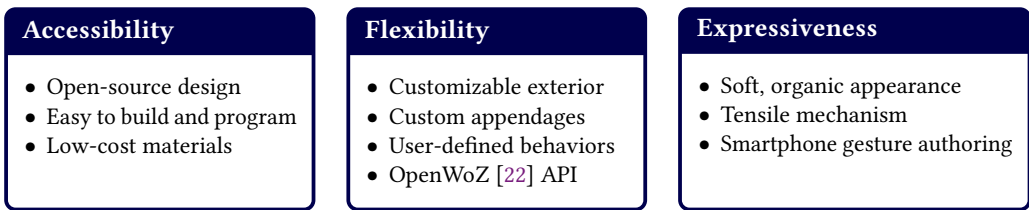


Fig. 3. Design objectives of the Blossom platform and features that address these objectives.

Blossom, in contrast, is designed to allow lay-users to create their own robot end-to-end, from building its structure, through the design of its appearance, to the authoring of new gestures and the combination of these gestures into behaviors. It addresses the gaps identified in existing social robot design by addressing three design objectives (Figure 3):

Accessibility. Lay-users without technical knowledge should be able to contribute to all aspects of building and programming the robot.

Flexibility. The robot's design should allow end-users to alter aspects of its appearance, mechanical structure, and interactive capabilities.

Expressiveness. Despite the accessibility and flexibility of the robot's design, it should maintain a high degree of expressiveness in its appearance and movement. The movement should be smooth without relying on complicated control software.

4 IMPLEMENTATION

This section describes the technical implementation of Blossom in pursuit of the above objectives. It serves to enable the replication and extension of the technical aspects of the robot design. In overview, the robot's mechanical structure is made up of flat components which can be cut from sheets of wood or acrylic and uses snap and press fits to reduce the need for fasteners. It is actuated by a non-rigid tensile mechanism constructed from elastic components to achieve compliant, organic movement. One of the DoFs is open-ended and can be used to actuate custom appendages. The electrical design uses mostly snap connectors that do not require soldering, and allows the robot to be either controlled by an external computer via USB or run untethered using an on-board battery-powered microcomputer. In both cases, an open Hypertext Transport Protocol (HTTP)

application programming interface (API) allows remote control and programming of the robot's behaviors. The robot's gestures are authored using a smartphone-based puppeteering application which can be recorded and played back in real-time during operation, or saved on the robot to be triggered by the remote HTTP API.

4.1 Mechanics

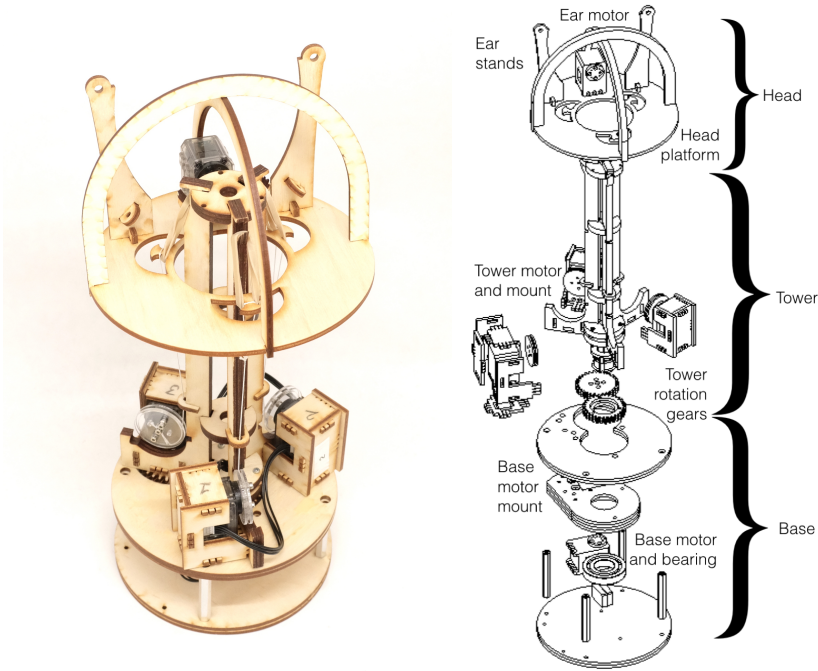


Fig. 4. The inner tensile actuation mechanism and exploded view. The main expressive element is the head platform which is suspended from a tower by rubber bands and actuated by cables driven by motors at the bottom of the tower. The tower itself is rotated by the base motor. As an example of an appendage, the head platform features ear stands and a motor for actuating the ears.

Blossom's mechanical design is centered around a free-floating "head" platform, which is actuated using a tensile mechanism for power transmission (Figure 4). The head is suspended from the top of the central tower structure with rubber bands and is actuated by reeling in cables from the bottom of the tower. The design is related to the Stewart platform mechanism which has been used in other social robots [47, 50], but Blossom's design is non-rigid and allows for a larger range of motion than a Stewart platform, all while reducing the number of motors from six to three. This is made possible through the variable lengths of the tensile components, whereas a Stewart platform is limited by the fixed lengths of its rigid linkages.

This actuation mechanism also bears similarity to the one used in the prototype Tofu robot [58]. While there is not much published information about the robot, it is described as also using an elastic element (a cylindrical foam core) to hold a head which is actuated by cables. However, unlike the foam core used in Tofu to which the head and skin are rigidly attached, Blossom uses a free-floating head with elastic bands (Figure 7 left), as well as a freely moving exterior cover. This not only lowers the cost and difficulty of assembly, but also allows for larger range of motion that

is accentuated by secondary motions. Additional movement is produced by a fourth motor in the base to rotate the tower assembly and a fifth motor on the head platform that actuates customizable appendages.

4.1.1 Range of Motion. Figure 5 shows examples of the head platform’s range of motion. The gestures of the inner mechanism can be classified as superpositions of several basic motion primitives: moving all the tower motors synchronously causes vertical translation, asynchronous motion results in pitching or rolling, and moving the base motor produces yawing. These fundamental motions are combined in timed sequences to create expressive gestures.

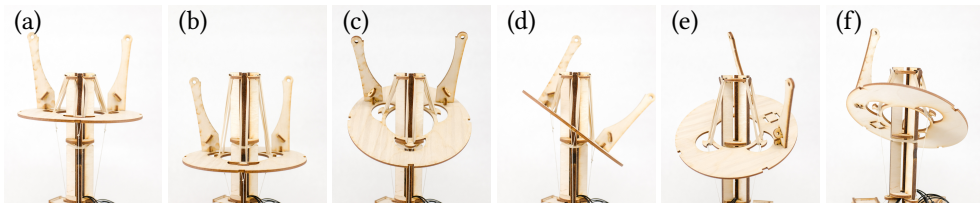


Fig. 5. Examples of the mechanism’s range of motion. Vertical translation (a→b) and rotations (c, d) are combined to create more complex gestures (e, f).

In addition to the increased range of motion, the tensile mechanism affords gestures that are smooth and organic-looking to an extent that would be challenging to replicate through software alone. The physical elasticity specifically supports several principles of animation [34, 43]. The cables and elastic bands provide a springiness that enables ease-in and -out in smooth arcs. The variable lengths of these components allow for greater exaggeration in motion. The momentum of the platform during quick movements elicits natural secondary motions such as overshoot and oscillation that would otherwise necessitate complex trajectory generation in motion planning software.

Given the novel mechanical structure of Blossom’s design, we present a full derivation of the robot’s forward and inverse kinematics in Appendix A.

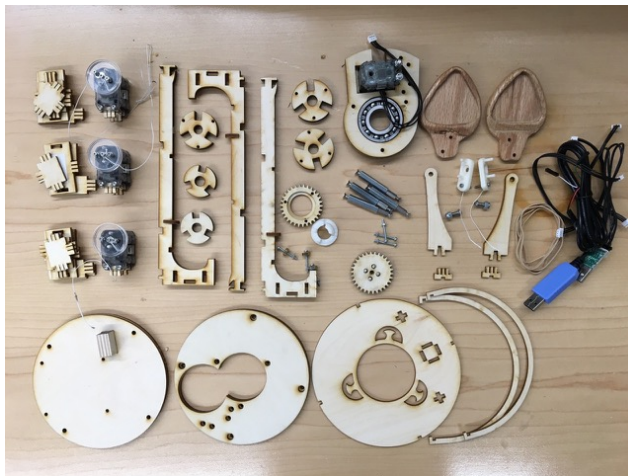


Fig. 6. Layout of the components used to assemble the mechanism.



Fig. 7. Detail of the compliant components (elastic bands and strings) used to suspend the head platform (left) and a snap-fit motor mount (right). Snap and press fits are used throughout the structure for ease of assembly and to reduce the amount of required hardware.

4.1.2 Fabrication. Blossom’s fabrication process relies almost exclusively on laser cutting, which has advantages over 3D printing for its reproducibility and speed, as well as for the affordance of low-cost, recyclable, and readily available materials such as wood and cardboard. The structure uses snap fits similar to OPSORO’s design to reduce the amount of required hardware fasteners while being expandable with different appendages and motor configurations. Figure 6 shows all of components needed to build one Blossom robot with ears as appendages. Figure 7 (right) shows the motor mount as an example of a snap-fit component.

4.2 Electronics

The electronics system also supports the design principle of accessibility by consisting of commercially-available components that use simple mechanical connectors, reducing the need for soldering.

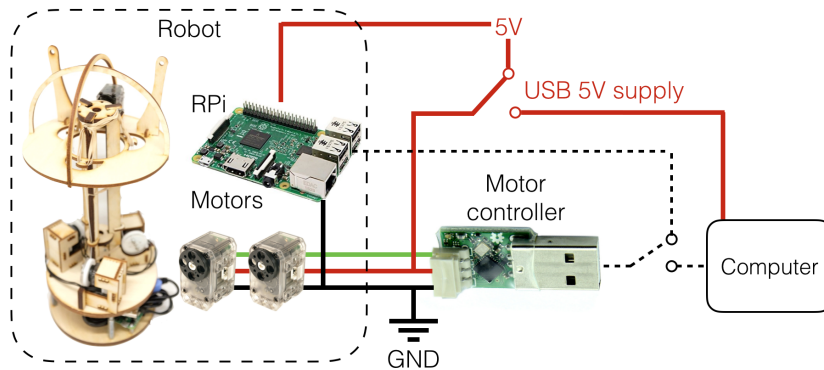


Fig. 8. Electrical component diagram. The robot can be used both in self-contained mode through an internal system-on-board, or controlled by an external computer. The motors within the robot are daisy-chained and thus only require one connection to the computer via the USB motor controller.

Figure 8 shows the components of the robot’s electronics system. The robot consists of five daisy-chained servo motors and a Raspberry Pi (RPi) microcomputer running the Linux operating system. The motors are controlled by the computer via a USB motor controller, which contains

hardware to translate the USB protocol to Transistor-Transistor Logic (TTL) signals, and manages the half-duplex communication protocol of the servo motors.¹

The robot can be used in one of two modes: self-contained or externally controlled. In the self-contained mode, the motors are connected to the RPi with the motor controller. Both the RPi and motors are powered by a 5-Volt (5V) power source such as a portable battery pack, but separate power connectors are used to prevent current overload on the logic components.

In the externally controlled mode, the RPi is unused and the motor controller is plugged into an external UNIX-based computer. Because power cannot be supplied through the motor controller and to prevent overcurrent on the computer's USB port, the motors must be powered from a separate 5V source such as an additional USB port or an external power supply.

4.3 Software

The software system of Blossom supports the objectives of flexibility and accessibility. The same software runs whether the robot is run in self-contained mode or externally controlled with a computer. The software uses the OpenWoZ framework [22], allowing for flexibility in application by exposing each of the robot's behaviors to an HTTP Universal Resource Identifier (URI)-based interface. This provides a flexible interface for creating behaviors, from high-level control of the robot to programming it in code.

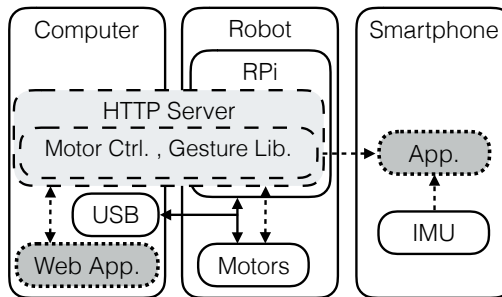


Fig. 9. Combined hardware and software diagram. Solid lines denote hardware, dashed lines and light gray shading denotes back-end software, and dotted lines with dark gray shading denotes user interfaces. Physical connections are denoted by solid arrows and software communication is denoted by dashed arrows.

The robot's software is made up of three main components (Figure 9): a motor control module and gesture library to command the motors as well as to store and play back authored movements (shaded light gray); an HTTP server which listens to incoming requests and activates the appropriate gestures (shaded light gray); and the various user interfaces (UIs) for commanding the robot (shaded dark gray).

4.3.1 Motor Control Module and Gesture Library. The motor control is built on top of the PyPot motor control library [33], which abstracts the low-level serial communication for the servo motors to higher-level commands such as addressing motors and setting goal positions and speeds.

In the motor control module, robots are defined by the motors used and their respective ranges. The motors can be commanded directly, or controlled by executing gestures from a library. Gestures are stored as timed sequences of positions for each motor on the robot. The gestures can be played back with modulations to the speed, range, or posture.

¹The motors are Dynamixel™XL-320 and the USB motor controller is either a Xevelabs™USB2AX USB-to-TTL interface or a Dynamixel™U2D2.

4.3.2 HTTP Server. The control computer includes an HTTP server that enables Representational State Transfer (“RESTful”) communication with the robot, allowing for the robot to be commanded from any device on the local network. This enables an open-ended method for interfacing with the robot and makes it easy to build Wizard-of-Oz (WoZ) interfaces, create custom applications that use sensor information, or communicate with existing web-based services or Internet-enabled devices.

The RESTful API receives the desired command or gesture and modulation parameters. For example, to play back a gesture titled “nodding” at 0.8 times the recorded speed and 1.4 times the amplitude of the original range of motion, the REST command would be `/s/nodding?speed=0.8&=1.4`. Examples of other functions include retrieving a list of available gestures and commanding the robot to a given position. This implementation follows the modular command structure of OpenWoZ [22] and affords flexible communication between the robot and clients built into user interfaces.

Additional behaviors can be added to the open-source HTTP server simply by defining a function and linking it to a RESTful command. Parameters are passed to the function as a URI string, and the custom behavior can parse the parameters. This is, for example, how different “breathing” and other programmatic idle behaviors are implemented.

4.3.3 User Interfaces. We demonstrate the flexibility afforded by the software architecture by presenting several methods we have developed to control the robot. In the simplest case, users can use the command line interface (CLI) on the terminal that started the robot HTTP server to trigger any command available to the RESTful API by simply typing in the REST URI. Beyond the CLI, we developed web and smartphone WoZ applications for high-level operation of the robot. A “soundboard” design enables the creation of buttons for triggering gestures, or for gesture/modulation combinations (Figure 11 (b)).

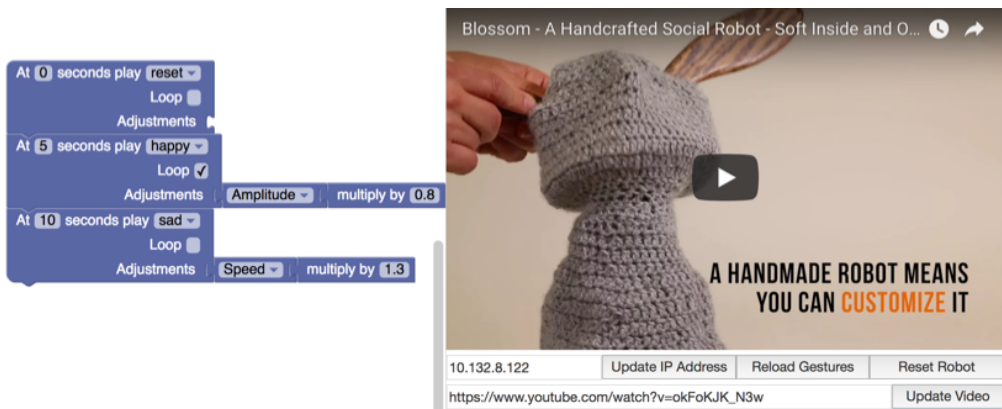


Fig. 10. The web application used to trigger gestures timed to a video. The Blockly interface is used to denote when to trigger gestures and how to modify playback speed, amplitude, posture, or looping. In this example, the robot resets at the beginning of the video, plays the “happy” gesture at 5 seconds at 0.8 times the original amplitude (range of movement) and loops until 10 seconds, at which it then plays the “sad” gesture sped up by a factor of 1.3.

An additional web application is embedded in a web page (Figure 10). It allows Blossom to “react” to an online video as part of a research project in our laboratory, in which Blossom acts as a video-watching companion. The web page includes a video player and a Blockly interface

for triggering gestures at specified timestamps and modulating them, allowing users to easily choreograph movement sequences to videos.

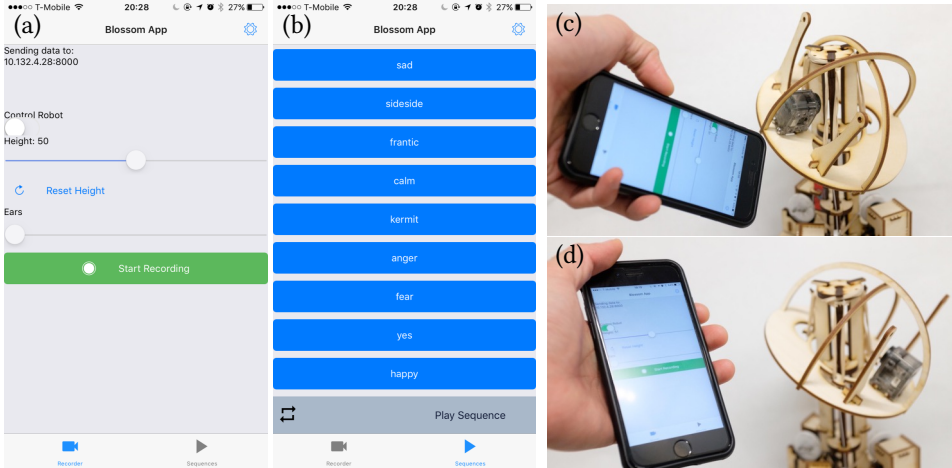


Fig. 11. Screenshots of the phone app for controlling the robot (a) and playing back gestures from within the app (b). The orientation of the phone is mapped to the orientation of the robot’s head (c and d).

The mobile application (Figure 11) also supports triggering and modulating gestures but, more importantly, utilizes the phone as a puppeteering device to control the robot’s expressive elements. Using smartphones as an input device supports the accessibility design objective by allowing lay-users to easily create behaviors for the robot without having to manually program its movements.

The puppeteering system leverages the smartphone’s built-in inertial measurement unit (IMU) to map the phone’s orientation to the orientation of the platform. Phone data (kinematic orientation, slider positions) is sent from the phone to the robot using the same RESTful API as previously mentioned. The inverse kinematics of the robot as derived in Appendix A is used to determine the motor positions required to achieve a given orientation. Currently, the IMU only controls the 3D orientation of the head, but not the vertical offset of the platform’s height. This is because integrating the IMU’s raw accelerometer measurements at the current data rate (approximately 10 Hz) would quickly result in sensor drift. To solve this, a slider adjusts the platform’s resting height. Another slider controls the appendage motor. A mirror mode can be toggled to reflect the motion horizontally to make it easier to control the robot while it faces the user. Gestures can be recorded and played back within the application and can also be looped indefinitely to make idling motions such as breathing or looking around.

5 APPEARANCE

The robot’s flexibility extends to its outer appearance design. Its exterior is created from soft fabrics that are not rigidly attached to the interior skeleton, and its appendages are interchangeable and in principle open to any tensile mechanism. Concept sketches from the ideation process of various exterior options are shown in Figure 12, illustrating the flexibility in the robot’s appearance.

5.1 Soft Exterior

The soft woven exterior of the robot supports expressiveness in two ways: by augmenting the compliance of the internal mechanism through its bending and folding, and due to the fact that

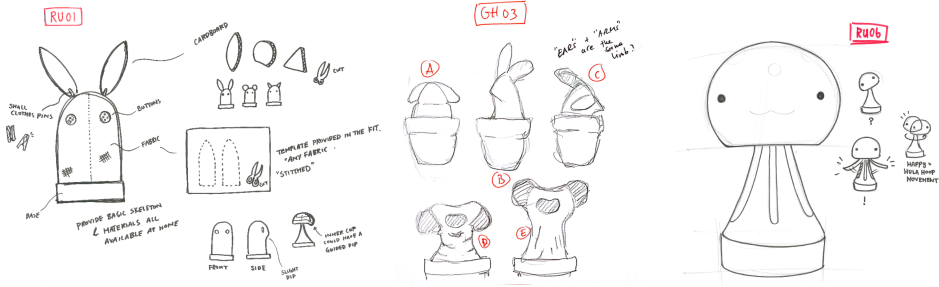


Fig. 12. Concept sketches exploring different embodiments and movements. The sketches show ideas for interchangeable exterior shapes, and appendages, meant to be hand-crafted by end-users.

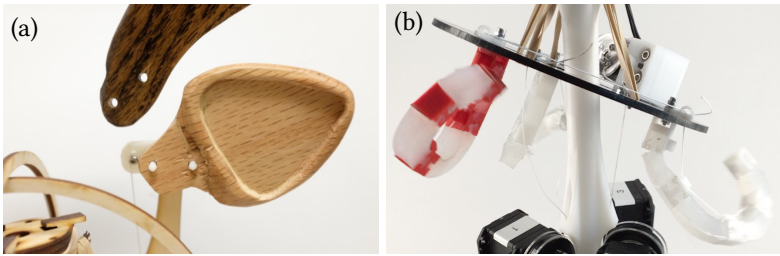


Fig. 13. Two examples of the swappable appendages: (a) two versions of pluggable wooden ears and (b) flexible silicon arms. Both appendages are actuated using the same tensile mechanism from the appendage motor mounted on the main head platform.

it flows freely over the structure. This helps the robot to appear more lifelike by accentuating the organic movement and providing mechanical flexibility to its exterior. Using traditional crafts rather than CAD and rigid manufacturing techniques also supports the design goal of accessibility by enabling a diverse user population to participate in robot-building.

Three examples of crocheted covers are shown in Figure 1, one in the likeness of a blue bunny clown, one in the shape of a gray mouse or cat, and the third modeled after a blue jellyfish. They are knit or crocheted out of wool. The blue-and-white design is constructed as a single pull-over piece; the exterior for the mouse design is also single piece but it is open at the top and closes with a button in the back of the head; the jellyfish cover is made of two pieces (one for the head and one for the lower body) that button together at the base of the head. The covers are designed to be loose-fitting to support the organic movement aesthetic and to not constrain the actuation mechanism.

5.2 Swappable Appendages

The robot’s flexibility is further emphasized by its swappable and open-ended appendage mechanism. The head platform features an additional motor that can interface with various accessories and appendages matched to different exterior designs. Control of the appendages is also tensile, with the motor reeling in a cable and either gravity or an elastic element restoring the DoF.

Figure 13(a) shows the mechanism for the ears. The ears attach to posts on a rotating hinge adapter with two hooks, allowing them to be easily interchanged. The hinge adapter itself is tethered to the accessory motor. The jellyfish configuration features flexible arms as shown in Figure 13(b). The arms are fabricated by first 3D printing a “skeleton” mold which is then filled

with silicone². The rigid skeleton segments act as vertebrae with the silicone serving as ligaments that connect all of the segments. In both cases, gravity restores the DoF. We implemented two examples of swappable appendages, but in theory any single tensile DoF could be added to the robot's design. In the prototyping phase of the robot's design, we explored tails and spinal spikes as additional DoFs.

6 CASE STUDIES

To evaluate the extent to which Blossom achieves its design objectives, we have deployed it in the field in four contexts. These deployments were useful in getting feedback on the design and provided insight on how Blossom can interact with a diverse range of users.

6.1 Providing the Design to External Research Groups

We provided Blossom prototypes to several external research groups. These collaborations have been useful in evaluating Blossom's accessibility as a research platform by testing the reproducibility of the design.

The first prototype was sent completely pre-built to a company-based research team studying robot companions for children with autism. The research team was able to set up the robot and control it from the RPi. They then used it in technology demonstrations when meeting with therapists and user populations. A second prototype of the robot was given to a university-based research team. We provided the basic components (as laid out in Figure 6) and a repository with the assembly instructions and software library [52]. The group was able to successfully build the robot, install the software, and enlist the help of volunteers to crochet new covers. The group has since implemented the robot in their own field studies. A third prototype was assembled by another university research group. Unlike the previous groups, we provided no components and gave only a link to the repository containing the laser cutting design files, software, and instructions [52]. Apart from troubleshooting some software-related issues, the research team was able to independently build and control the robot.

The gradual open-sourcing of Blossom, from shipping a completely assembled robot to only linking to a design repository, has supported the open-sourcing of the robot and provided growing evidence for the accessibility of the presented design and its potential to be used by a variety of users. The fact that external research groups were able to build the robot with little assistance and readily use it for their own research work has shown that the robot is easily reproducible and that an accessible open-source platform could be a useful model for social robotics research.

6.2 Public Exhibitions

Blossom has been exhibited at several public events, including two technology fairs, an academic conference, and a collegiate project team showcase. These events had diverse demographics of attendees, from lay-users to roboticists, and were opportunities to present Blossom to a wider audience and receive feedback on its design. During these events we showcased Blossom's movement and customizability and explained the motivation for the project. Participants responded positively to the robot's design, and several indicated that they would want to interact with it like a pet. At the project showcase, we showed different configurations and allowed participants to control Blossom with the phone. Though many found the controller to be somewhat difficult at the beginning, they found the interaction to be entertaining and would use Blossom to gesture to their friends, supporting to the robot's expressive capabilities.

²The silicone used is Smooth-On EcoFlex™50.

Along positive comments regarding the design, there were a few recurring questions and suggestions. A common question was whether Blossom could react to user input and whether it had sensors such as cameras or microphones. Attendees familiar with fabric-making expressed interest in creating covers and accessories and sharing the project with a broader craft-making community. Others suggested interfacing Blossom with voice-based assistants to provide them with a physical embodiment. Many also expressed interest in owning or building a Blossom robot.

Showcasing Blossom at these events was useful in demonstrating its expressiveness and receiving feedback from a diverse population of users. The largely positive comments regarding Blossom's appearance are encouraging and affirm that the design appeals to a wide audience. The difficulty that participants had with controlling the robot suggests that there is a learning curve to using the phone as a controller. That said, the ability for untrained users to use a phone to readily create gestures appeared to be more accessible than using traditional programmatic methods.

6.3 Children's Science Day



Fig. 14. Children interacting with Blossom at the science day event (top) and examples of accessories created by participants (bottom).

Blossom was exhibited at a children's science day event where young children, approximately 4-8 years of age, could visit stations with various activities (Figure 14). For our activity, we had craft materials available for children to create accessories for Blossom. Children would then affix

the accessories to Blossom and control the robot using a smartphone. Participants interacted with Blossom in different ways, with some staying at the booth for a long time crafting several accessories with others only interested in controlling the robot. There were some children who came in groups and took turns between crafting accessories and controlling; these groups sometimes collaborated by having the crafter ask the controller to move the robot to make it easier to attach an accessory. This might suggest that the Blossom platform can encourage collaborative design and interaction of several users with a single robot.

Although we initially suggested creating ears, we were positively surprised that children branched off to make a wide range of different accessories, from appendages to facial features to jewelry. Most creations were simple single-layer shapes, but some designs were more elaborate and featured multiple layers and adornments. The diversity of accessories made emphasizes the flexible design of the platform.

The ways that children controlled Blossom led to interesting observations regarding the smartphone as a controller. Users would often move the phone in exaggerated ways that Blossom would physically not be capable of achieving, such as turning completely upside down or twisting around over 360°. The children also had their own implicit feature requests, such as how to make Blossom locomote and jump. These were emphasized by that fact that several children chose to make appendages such as legs and wings.

Adults were also interested in Blossom, from the project's application to its technical implementation. Some parents participated by making their own accessories while others helped their children control the robot more effectively. They commented on the project as relating art and technology, fitting in with Science, Technology, Engineering, Arts, and Math (STEAM) education, and also noted Blossom's unconventional appearance compared to traditional robot aesthetics.

The children's science day was a valuable opportunity to demonstrate Blossom's aesthetic flexibility and the accessibility of its customization and control method, even to very young users. The positive responses to the activity from children and adults alike show that they enjoyed the interaction and further supports the platform's expressiveness. We especially noted that the flexible design of the robot supported users with diverging interests.

6.4 Build-a-Blossom Workshop

Lastly, Blossom was used in educational workshops for middle school students to learn about the skills involved in robotics engineering. The students had varying levels of technical experience, ranging from good familiarity with technology to very little exposure to programming or mechanical construction. The activity was to build and customize a Blossom robot, program its gestures, and choreograph its movements to a video of the students' choosing. There were six workshop sessions; each was approximately 80 minutes long and had 16–20 students that were divided into four groups. The total was 107 students in 24 groups. Lab members familiar with the construction and programming processes were present to provide assistance, but intervention was kept to a minimum and mainly involved guided troubleshooting.

Each group was provided a partially-disassembled robot and the assembly instructions. The construction process included building the head platform and attaching the ears, connecting the tower to the base assembly, connecting the motors, and suspending the head by hanging it from the tower and attaching the cables from the motors. A crocheted cover was included with each robot. We observed that often some students were building the inner structure, while other group members customized the cover with craft accessories. Figure 15 shows examples of some of the appearances created by workshop participants.

Once the robot was assembled, students connected it to a computer and programmed its movements using the smartphone application. Often groups designated one member with the mobile



Fig. 15. Examples of the embodiments created by the students in the building workshop.

application to be the movement choreographer in charge of creating gestures. Students then imported the gestures into the web application and timed each movement, some with modulation, to the video chosen by the group. This resulted in a variety of choreographies with which the robot reacted to the student’s videos. The videos themselves ranged from music videos to which the robot was made to dance, often “dressed up” as the performing artist, to humorous videos with the robot reacting as an audience. Other examples included viral videos (“memes”) where the robot was fashioned like one of the characters in the video, imitating the action on screen.

All of the 24 groups were able to successfully build and control the robot by the end of their session. The structures were mostly assembled correctly, except for the ear assembly, which had sometimes to be bypassed due to its cable routing. The programming process was largely error-free and some groups were able to make fairly complex choreographies. Similar to our observation at the children’s science day event, many students tried to control the robot in impossible manners.

The vast majority of students were actively engaged throughout the sessions. We conducted brief informal question-and-answer sessions at the end of each meeting, where students were asked to say what their favorite and least favorite part of the workshop was. There was a wide variety of responses about the favorite part, with some students enjoying the craft more, and others preferring the mechanical construction or the gesture generation. This suggests that the Blossom platform allows students with different interest to be involved in some capacity. Others expressed satisfaction at being able to build and control a complete working robot in a short time. Several students who were admittedly disinterested or intimidated by robotics at the beginning found themselves enjoying it due to the engagement of the activity and the relation to personally meaningful video content.

The workshop was an opportunity to thoroughly evaluate all of Blossom’s major design objectives. The fact that untrained middle-school students were able to build and animate the robot within the duration of the sessions demonstrated the accessibility of the platform’s assembly and gesture

authoring workflow. The variety of embodiments and their relation to the personal content choice of the students emphasized Blossom's flexibility. The complexity of the resulting choreographies indicates the robot's expressiveness.

The difficulties in assembly highlighted weak points in the design that can be rectified in future iterations, most notably the appendage module. The interconnectivity between the robot's control computer and the phone controller can also be streamlined. Future evaluations on customizability should explore alternative embodiments by providing different appendages.

7 FUTURE WORK

The field deployments of Blossom, together with our own experience in manufacturing and using Blossom, indicate several points in which the current design can be improved upon.

Smartphone Control Mapping. Many users who attempted to control the robot tried to move it in ways that it was not capable of, such as turning all the way around and flipping. This reveals a problematic mapping between the unconstrained motion of the phone and the limited range of the robot. Possible solutions include better instructions or training to control the robot properly, a mechanical rig to place the phone into, enforcing the robot's movement constraints, or methods for better mapping from the raw orientation detected by the smartphone's IMU sensor to the robot's pose. Relatedly, many users attempted to control the height of the platform by raising and lowering the phone; while it would be difficult to get accurate height control due to the sensor used, usable height control should be explored, possibly by using filtering or predictive methods to alleviate drift.

Sensing Capabilities. Users often commented that they wished Blossom had sensing capabilities. Incorporating sensors for the robot to react to external inputs should thus be considered. Implementing sensors on the robot itself may compromise its accessibility and handcrafted aesthetic, but simple sensors could afford richer functionality without being obtrusive. Many have interacted with Blossom by petting its head or calling to it, and components such as touch sensors or microphones could be implemented to provide more functionality. Another approach is to leverage sensors built into smartphones [21], such as the microphone or camera to avoid adding complexity directly to the design of the robot itself.

Intermediate Programming Language. The Blockly interface is currently only used for triggering gestures to videos, but it could also be used as a mid-level programming method that is more versatile than the existing Wizard-of-Oz interfaces, while being still more accessible than a full programming language. Features such as motor control and conditional statements responding to external inputs could be useful to expand the current functionality.

Lower Cost. On the mechanical side, while wood is relatively inexpensive and is well-aligned with the handcrafted aesthetic of the robot, transitioning to an even cheaper material such as cardboard or paper could further improve its accessibility. The most expensive aspect of the current design are the high-end servo motors. They provide many advantages over standard servo motors, primarily velocity and acceleration control and daisy-chaining, but are relatively expensive. Transitioning to standard hobby servos would significantly reduce the overall cost of the platform at the potential cost of ease-of-control and movement quality.

Diverse Appendages. Finally, we would like to explore more kinds of appendages to illustrate the platform's customizability. Flexible arms and dinosaur-like spikes were briefly explored, but the ear design has proven to be the most easy-to-use and expressive. Given the inclusion of limbs and wings among the accessories created at the children's science event, such alternative configurations

should be explored in the future. Different appendages may also affect the robot's expressiveness by altering its DoFs and therefore its gesture capabilities.

8 CONCLUSION

This paper presented Blossom, an open-source social robotics platform for researchers and hobbyists that incorporates untraditional mechanisms and materials. Addressing gaps identified in prevalent robot designs, which often exhibit rigidity in structure, materials, appearance, and actuation, Blossom was conceived with the goals of accessibility, flexibility, and expressiveness in mind.

Blossom is *accessible* by several means. First, it is comprised of inexpensive components which are readily fabricated using low-cost materials and a laser cutter. The mechanical setup relies heavily on snap and press fits without the need to use fasteners, but still provides mechanical robustness. The robot's ease of construction was evaluated by providing external research groups with the assembly instructions and software, which they used to successfully build replicas of the robot and implement them in their own applications. The accessibility was further evaluated in a workshop for middle-school students to build a Blossom and program its behaviors. All 24 student teams were able to build and control the robot in a single 80-minute session.

A smartphone-based puppeteering controller is presented as a novel approach to gesture authoring with an easier learning curve compared to traditional programmatic or computer animation methods. This feature also supports the accessibility design goal. It was evaluated at the above-mentioned middle-school student workshop, as well as at a children's science day exhibit, where participants and visitors were able to create a wide range of behaviors for the robot without prior training.

Blossom's *flexibility* is achieved through its open-ended design that allows users to customize its appearance, DoFs, and behaviors. Allowing end-users to personalize their own robot is a largely unexplored space in HRI and could invite a broader demographic to robotics. It also works in support of the so-called IKEA effect, which predicts that self-made creations are favorably valued over comparable mass-manufactured objects [38, 53].

Blossom's *expressiveness* is owed in large part to the use of compliant materials in the internal actuation mechanism. This provides the design with physical flexibility and results in smooth motion without requiring complicated control through software. The use of soft exteriors that flow freely over the mechanism creates an organic skin-like effect, which further accentuates the looseness and lifelike nature of the robot. Incorporating alternative materials such as woven fabric exteriors and wood supports the robot's aesthetic expressiveness, and offers an alternative for social robots, which may fit the domestic space better than existing choices of plastics and metals.

In our field evaluations, we repeatedly noted that different participants chose to engage with – and commented on their enjoyment of – diverging aspects of the Blossom platform. Some preferred the mechanical construction, others liked creating new exterior covers, or adorning those with craft materials. Yet others were interested in generating precise movements for the robot or stringing them together to create behaviors. We can thus identify a fourth design outcome of the proposed system, namely that it supports *diversity* in the robot user population. This notion is anecdotal and post-hoc, and should be separately evaluated in future research. We are currently working with a number of partners to test Blossom in additional settings, including high schools and maker spaces.

The detailed design description provided here can hopefully inspire the designers of other social robots to adopt flexible actuation schemes such as the one presented. We also hope that the handcrafted aspect of this robot can invite a broader community to participate in robot-building, and that the accessible gesture authoring system will be used in social robotics applications where there is a need to quickly generate robot behaviors by lay-users. As embodied technologies become

more ubiquitous in daily life, a family of soft handcrafted robots that are easy to build and control may pave a new design path for social human-robot interaction.

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A BLOSSOM KINEMATICS

The novel design of Blossom's internal mechanism requires custom kinematics for gesture generation and simulation. In this appendix we detail the forward and inverse kinematics derivation for the robot.

A.1 Forward Kinematics

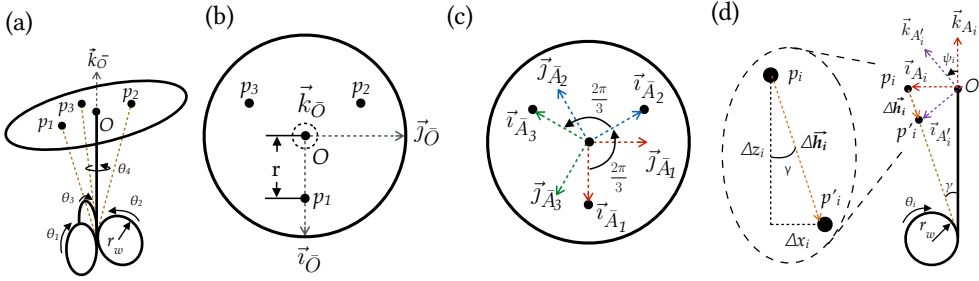


Fig. 16. Kinematic diagrams of the robot's inner mechanism. As shown in (a), the inertial reference frame $\bar{O} = \langle \vec{i}_{\bar{O}}, \vec{j}_{\bar{O}}, \vec{k}_{\bar{O}} \rangle$ is defined with the origin O at the center of the platform when at rest. The lines from the base of the tower to the attachment points p_{1-3} represent the cable. The tower motors that actuate the platform are at the base of the tower and rotate the motor wheels of radius r_w by angle θ_{1-3} . The base motor located below the tower motors (not depicted) rotates the tower about the vertical axis by θ_4 . Top view diagrams in (b) show the locations of the attachment points. The frames \bar{A}_1 , \bar{A}_2 , and \bar{A}_3 depicted in (c) are aligned with the attachment points and rotate about the vertical $\vec{k}_{\bar{O}}$ axis shown in (b). The side view (d) shows the actuation mechanics of a single attachment point. The frame \bar{A}' is aligned with \bar{A} as it rotates about the vertical $\vec{k}_{\bar{O}}$ axis, but additionally rotates about the shared $\vec{j}_{\bar{A}} = \vec{j}_{\bar{A}'}$ axis out of the page. This results in the rotation from \bar{A} to \bar{A}' by the angle ψ_i . The displacement is approximated by $\Delta \vec{h}_i$ with components Δx_i and Δz_i in the $-\vec{i}_{\bar{A}}$ and $-\vec{k}_{\bar{A}}$ axes, respectively. The angle γ is the angle between the vertical axis and the line formed by the cable when the platform is at rest.

Figure 16 shows an approximation of the inner mechanism. For simplification, the elastic bands are neglected and cables are assumed to be rigid links of variable length capable of both pushing and pulling the platform. The attachment points of the cables are denoted p_{1-3} . As shown in Figure 16(a), the tower motor wheels of radii r_w rotate by θ_{1-3} and the base motor rotation about the vertical axis is denoted by θ_4 .

Top views in Figures 16(b) and (c) depict the locations of the attachment points and define the intermediate frames ($\bar{A}_1, \bar{A}_2, \bar{A}_3$). These intermediate frames are aligned with the attachment points p_{1-3} respectively and rotate about the vertical inertial axis, with all \vec{k} axes shared: $\vec{k}_{\bar{O}} = \vec{k}_{\bar{A}_1} = \vec{k}_{\bar{A}_2} = \vec{k}_{\bar{A}_3}$, and shown as $\vec{k}_{\bar{O}}$ in Figure 16(b).

We are interested in the pose of the head platform given a set of motor angles θ_{1-4} . Consider the movement of one of the attachment points, p_i as depicted in Figure 16(d). The rotation of the motor wheel of radius r_w by angle θ_i causes the cable to be pulled in by length $r_w \theta_i$. Denoting the angle between the vertical axis and the cable as γ , this shortening of the cable results in the displacement $\Delta \vec{h}_i$ of point p_i from its resting position to the actuated point p'_i :

$$\Delta \vec{h}_i = -\Delta x_i \vec{i}_j - \Delta z_i \vec{k}_j = -r_w \theta_i \sin \gamma \vec{i}_j - r_w \theta_i \cos \gamma \vec{k}_j \quad (1)$$

A simplifying assumption is made that the attachment point moves along this line and that γ remains constant. The resulting actuated reference frame \bar{A}'_i is a rotation of the original \bar{A}_i about

the shared $\vec{J}_{\bar{A}_1} = \vec{J}_{\bar{A}_1'}$ axis out of the page. If we denote the vectors from O to the resting position of the attachment point p_i as \vec{r}_i , we get $\vec{r}_i = r_i \vec{A}_i$. After actuating motor i , we get the new vector from O to p_i , \vec{r}_i' :

$$\vec{r}_i' = \vec{r}_i + \Delta \vec{h}_i = r_i \vec{A}_i + \Delta \vec{h}_i \quad (2)$$

These vectors need to further be transformed to the inertial frame by the planar rotation matrices of θ_4 for \bar{A}_1 and of $\theta_4 + \frac{2\pi}{3}$ and $\theta_4 + \frac{4\pi}{3}$ for \bar{A}_2 and \bar{A}_3 , respectively. The calculated positions of the attachment points can then be used to determine the resulting orientation of the platform.

To do so, we define unit normal vectors for the idle and transformed orientations as \vec{N} and \vec{N}' respectively. We take $\vec{N} = \vec{k}_O$ to be simply pointing upwards from O . The transformed vector \vec{k}_O can be calculated from a normalized cross product of the transformed attachment point vectors in the plane of the actuated platform.

$$\vec{N}' = \frac{(\vec{r}_1' - \vec{r}_2') \times (\vec{r}_1' - \vec{r}_3')}{|(\vec{r}_1' - \vec{r}_2') \times (\vec{r}_1' - \vec{r}_3')|} \quad (3)$$

The normal vector to the rotation plane \vec{M} can be calculated and used to determine the quaternion rotation angle α and frame defined in \vec{v} .

$$\vec{M} = \frac{\vec{N} + \vec{N}'}{|\vec{N} + \vec{N}'|} \quad (4)$$

$$\alpha = \vec{M} \cdot \vec{N} \quad \vec{v} = \vec{M} \times \vec{N} \quad (5)$$

$$\vec{q} = \begin{bmatrix} \alpha \\ \vec{v} \end{bmatrix} \quad (6)$$

This quaternion is then used to determine the change in orientation and the downward displacement is approximated using Horn's method. The resulting changes in position and orientation are superimposed to determine the final pose.

A.2 Inverse Kinematics

Given the above forward kinematics solution, we can compute the head platform orientation given known motor positions. The same model can also be used to derive the inverse kinematics to calculate the required motor positions to achieve a desired final orientation of the platform. First, the Euler angles (ψ, θ , and ϕ about the body \vec{i}_B -, \vec{j}_B -, and \vec{k}_B -axes, respectively) of the desired orientation are used to derive the rotation matrix ${}^O R^{\bar{B}}$ from the \bar{B} frame in the final orientation to the inertial frame \bar{O} :

$${}^O R^{\bar{B}} = \begin{bmatrix} c\psi c\theta & c\psi s\theta s\phi - c\phi s\psi & s\psi s\phi + c\psi c\phi s\theta \\ c\theta s\psi & c\psi c\phi + s\psi s\theta s\phi & c\phi s\psi s\theta - c\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (7)$$

The rotation matrix is used to transform the representations of the positions of the attachment points \vec{r}_{p_i} from the body frame \bar{B} to the inertial frame \bar{O} :

$$\{\vec{r}_{p_i}\}_{\bar{O}} = {}^O R^{\bar{B}} \{\vec{r}_{p_i}\}_{\bar{B}} \quad (8)$$

From the initial (\vec{r}_{p_i}) and transformed (\vec{r}_{p_i}') positions of the attachment points, the displacements $\Delta \vec{h}_i$ can be calculated by:

$$\Delta \vec{h}_i = \vec{r}_{p'_i} - \vec{r}_{p_i} \quad (9)$$

Given the known size of the motor wheel r_w we can then calculate the angular motor displacement θ_i :

$$|\Delta \vec{h}_i| = r_w \theta_i \rightarrow \theta_i = \frac{|\Delta \vec{h}_i|}{r_w} \quad (10)$$