Ani-Bot: A Modular Robotics System Supporting Creation, Tweaking, and Usage with Mixed-Reality Interactions

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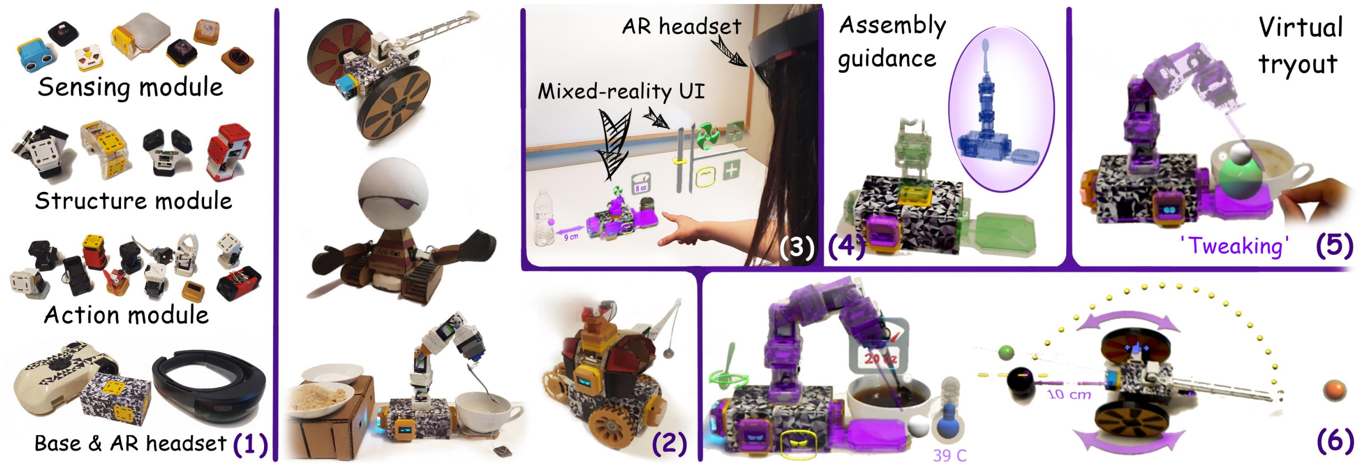

Figure 1. Ani-Bot system overview: Ani-Bot provides users with (1) a modular kit that allows them to (2) assemble and construct robots with crafted DIY objects, and (3) use mixed-reality interaction to perform direct manipulation, sensor driven programming, and animation authoring. (4) The system can assist users in the assembly process, and (5) help them tweak ineffective designs through virtual tryout. (6) Taking advantage of mixed-reality, users can easily program their robots to perform environmentally interactive tasks, such as adding sugar to a teacup or shooting objects into a bowl.

ABSTRACT

Ani-Bot is a modular robotics system that allows users to control their DIY robots using Mixed-Reality Interaction (MRI). This system takes advantage of MRI to enable users to visually program the robot through the augmented view of a Head-Mounted Display (HMD). In this paper, we first explain the design of the Mixed-Reality (MR) ready modular robotics system, which allows users to instantly perform MRI once they finish assembling the robot. Then, we elaborate the augmentations provided by the MR system in the three primary phases of a construction kit's lifecycle: Creation, Tweaking, and Usage. Finally, we demonstrate Ani-Bot with four application examples and evaluate the system with a two-session user study. The results of our evaluation indicate that Ani-Bot does successfully embed MRI into the lifecycle (Creation, Tweaking, Usage) of DIY robotics and that it does show strong potential for delivering an enhanced user experience.

ACM Classification Keywords

• **Information systems∼Multimedia content creation**

Author Keywords

Modular robotics; Mixed-reality; Human-robot interaction; DIY robotics; User interface.

INTRODUCTION

DIY modular robotics has a strong appeal to makers and designers since it can be used in quickly designing, building, and animating their own creation which opens the thrilling possibility of bringing imagination to life. The physical modular units inherently serve as tangible interactive interfaces within a DIY robotics process. Thus, developing a robotics kit with embedded Tangible User Interface (TUI) shows the potential to allow intuitive interaction in the DIY process [3, 37]. However, the versatility and malleability of such TUI's are limited when it comes to programming complex tasks involving a fine level of control [40]. To provide comprehensive controllability for the robotics kit, a Graphical User Interface (GUI) design has been adopted by commercial products such as Lego Mindstorms [5]. This separate digital interface, however, breaks the bridge between the physicality and the virtuality which are built through the TUIs [22]. To prevent inconsistent and fractured user experiences in the DIY robotics process, we

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seek for a seamlessly integrated workflow in which the intuitive tangible interactions are enhanced by a coherent spatially situated and contextually relevant digital interface.

The newly emerging Mixed-Reality (MR) technology enables the embedding of a versatile and malleable digital interface in the DIY robotics process without impeding the inherent tangibility. Previous researches have attempted mainly in either assisting the assembling of passive building blocks [47, 31, 48] or controlling a pre-defined robot/machine [18, 24, 12, 20, 21]. Although we are inspired and motivated by these efforts, we focus on extending mixed-reality interaction to the whole lifecycle of modular robotics, namely **Creation**, **Tweaking**, and **Usage** [29]. Therefore, we propose Ani-Bot, a modular robotics system embedded with MRI. As demonstrated in Figure 1, while users are building their robots, the corresponding virtual model is automatically generated and superimposed with the robot from the view of HMD. Users can then visually control the physical robot by interacting with the virtual representation. With the Ani-Bot system, users can: (1) **Create** robot constructions with virtual guidance; (2) **Tweak** ineffective designs and perform virtual tryout; and (3) **Utilize** mixed-reality to make their DIY robots interact with the surrounding environment. To summarize, the main contributions of this paper are:

1. *System workflow*, which embeds MRI with modular robotics.
2. *Design of the Ani-Bot system*, including the mixed-reality ready ‘plug-and-play’ hardware and the incorporated MR features that promote a novel interaction experience.
3. *Evaluation results*, including the constructive feedback summary from our user studies that guides future endeavors.

RELATED WORK

Interacting with DIY Robots

Due to the inherent tangibility in the DIY robotics process, previous works have developed several TUI approaches. Topobo and VEX robotics adopted the Programming-by-Demonstration method with kinetic memory to play back user-defined motions and animate the robot [37, 8]. Since only actuation modules can be programmed, this approach has a limited level of controllability. On the other hand, the Programming-by-Assembly approach requires no further programming once the robot is constructed, thus encouraging users to try different assembly configurations [40]. Therefore, this highly engaging TUI approach has been widely used in the area of childhood robotics education by Cubelets, LittleBits, MakerWear, etc. [3, 11, 2, 35, 25]. However, because each module is pre-programmed for a specific function, complex robots require a large number of modules, which increases both the physical size and the difficulty of assembling. Furthermore, since the TUI robots are assembled and programmed for designated tasks, changing a task usually results in re-assembling a new robot architecture, which lowers the versatility and malleability.

Due to the limitations in TUI’s controllability, many commercial robotics kits have adopted an additional GUI to control the robot, such as Lego Mindstorms, Tinkerbots, VEX Robotics, etc [5, 7, 8, 1, 6]. However, most of these GUIs have been separated from the physical robot targets, thereby creating a gap which results in an inconsistent user experience. Alternatively, researchers have been exploring the merging of other interaction methods with DIY robotics. KIWI used scannable image-target-covered cubes to tangibly program the robot [43]. Handimate [39] and PuppetX [17] used hand and body gestures to control the crafted DIY robots, respectively.But although these control modalities show good interactivity, the lack of a fine level of controllability still remains an open issue. Mirror Puppeteering achieved user-defined playback animation with hands-on manipulation [41], yet it still required an external camera to track markers on the articulating parts. On the other hand, Ani-Bot’s MRUI is superimposed onto the physical target that bridges the gap by directly interacting with the target object. More importantly, a coherent MRUI design preserves the tangibility of DIY robotics and the consistency of the user experience. By exploiting the advantage of a digital user interface, our system is capable of achieving informative visualization and complex programming.

Assembly-Aware Construction

To effectively control modular robots, a virtual controller needs to be mapped with the physical target. Both GUI designs and controller-enabled interactions require manual correspondence for the mapping, which can be a tedious process for users. For example, when using Handimate [39], users need to manually set the gesture-actuator mapping configurations on a mobile application before controlling the robot. This problem can be solved if the modular kit can be made aware of its own assembly configuration and can therefore accomplish the mapping automatically. Such an assembly-aware concept already exists in many TUI construction kits, including Cubelets and MakerWear [3, 25]. However, they address only electronic communication logics without geometric information of the physical assembly. In our case, geometric assembly-awareness is essential for deploying a mixed-reality user interface. Prior works have explored the subject via hardware connection [26, 46, 10] and computer vision approaches [32]. But most of these works only applied assembly-awareness to passive building blocks that involved no motions. In comparison, the Ani-Bot system provides a virtual geometric model of robotic modules that update and coincide with the physical assembly, thus allowing responsive interactions and active visual feedback.

Assembly and Design Guidance with MRI

Utilizing MRI, different modalities of virtual guidance have been explored to assist users in the assembly process. Henderson et al. overlaid instructions from the view of users’ Augmented Reality (AR) headset [19], while Makris et al. displayed the corresponding virtual CAD model [31]. In terms of interaction media, some researchers used a virtual interactive tool [47], while others chose to directly manipulate the virtual model with bare hands for assembly guidance [44] and design simulation [45]. These works focused on providing assembly guidance for robotics/machines with pre-defined designs. Furthermore, without an external monitoring system on the assembly procedure, the guidance remained non-interactive. By embedding an RFID tag in each of the construction modules, Zhang et al. achieved real-time tracking and monitoring for non-mobile passive blocks that enabled interactive guidance [48]. Moreover, researchers have been coupling MRI with interactive design processes, including participatory design [33], decision making [36], and design evaluation [34]. Driven by the needs from the creation and tweaking phases, we focused on incorporating suggestive design guidance for functional robot design. By achieving assembly-awareness, Ani-Bot provides users with interactive mixed-reality assembly guidance for re-configurable modular robotics construction.

Robot Operation with MRI

MRI has been investigated for interacting with robots. TouchMe and exTouch have demonstrated the process with mobile robots [18, 24]. Utilizing MRI with robotics, researchers have achieved human-robot collaboration for object manipulation [15], object delivery [23], and household sequential task instruction [16]. Besides being viewed through an AR tablet device [28, 20, 21], the control interface can also be projected directly onto [38] or near the physical target [42, 30] for ease of mixed-reality interaction. Furthermore, MRI is applied in industrial robotics for path planning [14, 12], spatial programming [27], and trajectory planning [13]. However, the above work utilized mixed-reality primarily for programming movements for robots with determined designs and configurations. Instead, we aim at investigating an MRUI with higher malleability for DIYing a re-configurable robot with both output and input modules. To the best of our knowledge, no prior work has attempted to or explored embedding MRI with DIY robotics; this, is our primary contribution of this paper.

DESIGN PROCESS AND GOALS

To design and fabricate the Ani-Bot system, we followed a user centered design process. We first developed a preliminary system with a few basic modules and MRI features. Then, by conducting a participatory design study with the preliminary system, we elicited critical design principles for our mixed-reality modular robotics system.

Participatory Design Activity

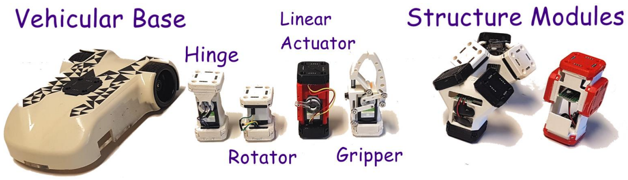

Figure 2. Preliminary modular kit for the Ani-Bot system.

Our preliminary system is demonstrated in Figure 2 with basic ‘on-target’ direct manipulating UI (Figure 6 (1)). We recruited 5 participants (3 male) who had substantial experience in DIY robotics and asked them to use the system. We encouraged the participants to think out loud. Also, a semi-structured post-study interview was conducted. We focused on investigating the design of a mixed-reality ready modular robotics kit, a coherent user interface, and appropriate interactions. After the study, we found that participants unanimously requested more modules with various structures and functionalities in order to fully support the element of DIY. In terms of the design of UI and the interaction methods, users suggested that we fully exploit the advantage of the digital interface by displaying more informative and visually dynamic user interfaces with appropriate operations to interact with them.

System Design Goals

Based on the feedback about our participatory design activity as well as our own experience in designing the preliminary prototype, we have synthesized the following key design goals:

- **Plug and play.** The system should be mixed-reality ready for users as they play with the modules, with no configuration/preparation time so as to ensure fluid user experiences.
- **Low floors and high ceilings.** The MR system should be intuitive and easy to start, but provide high a ceiling for the level of control capability.
- **Visually intuitive.** The system’s MRUI should be informative, provide active feedback, and be self-explanatory. Moreover, it should not be distractive and obstructive between users and their robots.
- **Support creative exploration** As a DIY platform, the system should support users’ creative interactive exploration via both hardware and software designs.

THE ANI-BOT SYSTEM DESIGN

System Workflow

Ani-Bot embeds MRI with DIY modular robotics; the workflow is illustrated in Figure 3. All modules in the system have processing power and can be physically connected with each other to establish network communication. By organizing the configuration data from each device, the robot is aware of its own assembly configuration and sends the data to the AR headset (Microsoft HoloLens [4]) to generate the corresponding virtual model. By detecting and tracking an image marker (Vuforia [9]) on the Base Module, the virtual model is superimposed onto its physical target for the mixed-reality interaction. The kinematics data of the virtual model are constantly transmitted to drive the physical robot. In this way, users interact with the physical robot by manipulating the virtual representation from the view of the AR headset.

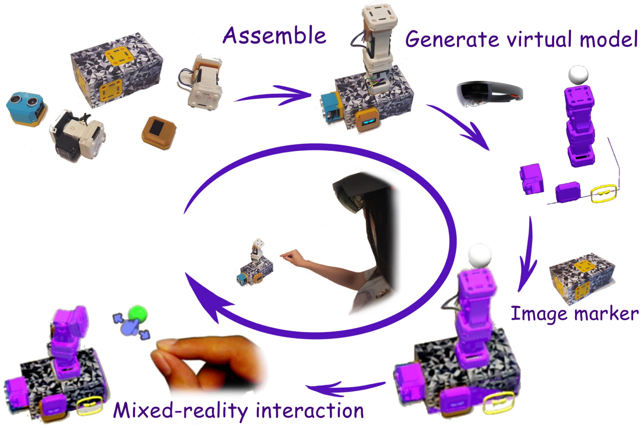

Figure 3. Ani-Bot system workflow.

Figure 4. Module library of the Ani-Bot system.

Module Design

As shown in Figure 4, we expanded our preliminary module library based on feedback from the participatory design activity. **Base Modules** are the starting point of users' DIY construction, and they have three purposes: 1) realize tracking and detection of the virtual model via the image marker; 2) organize and transfer data between devices and the AR headset as a communication hub; and 3) provide a power supply for the connected devices. **Action Modules** provide various types of actions for users to interact with the real world. **Structure Modules** increase the structural diversity of the modular robot's configuration. They help the Ani-Bot system to better support users' DIY creation process. **Sensing Modules** read the environmental data, which are visualized in the MRI and used to program the robot behaviors. Together, all these modules compose the hardware modular kit that works coherently with the corresponding software interface to constitute Ani-Bot's mixed-reality modular robotics system.

Hardware Implementations

The modular design is illustrated in Figure 5 (2), using the Hinge Module as an example. The physical connection of the Ani-Bot's module is a Male-Female surface connection setup (42mm * 42mm), which is positioned by four cylindrical pins and secured by two embedded magnets (K&J Magnetics: DC1-N52). Most of the modules in the system have one pair of Male-Female connection surfaces to pass the power supply as well as an electric signal via four pins. All modules in Ani-Bot have only one Male surface, containing a customized PCB and a Bluetooth Microcontroller (RFduino). By reading from the *Sequence pin* and *Orientation pin*, the MCU knows its current position and orientation in the whole robot's assembly. The Base Module, as shown in Figure 5 (1), contains a Bluetooth MCU that receives the configuration data from all the connected devices. By integrating the data from all the devices, the Base is aware of the whole robot's assembly configuration instantly. The assembly configuration data are then transmitted to the HMD via an on-board WIFI MCU (ESP8266) to generate the corresponding virtual representation of the physical robot. When receiving action data from the HMD, the Base Module organizes the incoming data and feeds them to the corresponding receiver device for action.

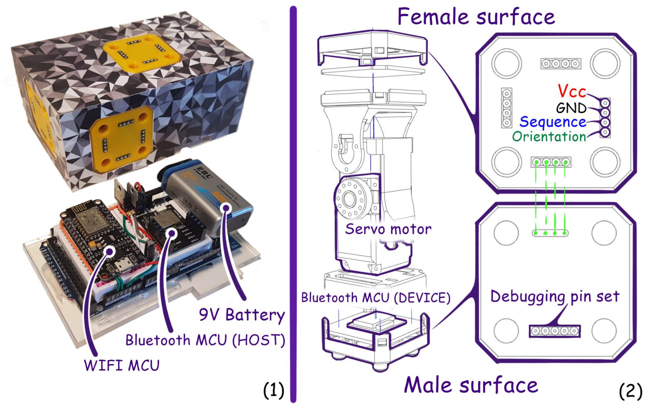

Figure 5. Hardware design of Ani-Bot's module. (1) Cuboid Base module design setup. (2) Exploded view of the Hinge Module.

Interface and Interaction Design

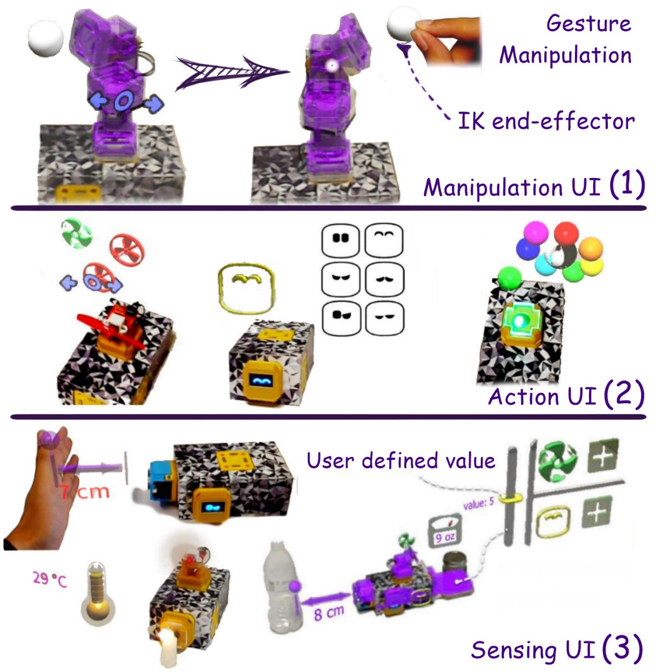

Figure 6. MRUI in the Ani-Bot system consists of (1) Manipulation UI for actuators, (2) Action UI for the other action modules, and (3) Sensing UI for visualizing and programming the sensing modules.

The Ani-Bot system utilizes gesture-based interactions for most of its control and programming. These interactions are supported by the HMD (Microsoft HoloLens) and they require an *air tap* with one finger for clicking and selecting, and a *drag and drop* with two fingers for continuous manipulation. The MRUI in the Ani-Bot system is superimposed or floating nearby the physical robot for a seamless interaction experience. Our UI is designed for three categories of interaction (Manipulation, Action, and Sensing) according to the property of the physical module. For actuators such as Hinge, Rotator, Linear Actuator, and Gripper, we superimpose the corresponding semi-transparent virtual model directly onto the physical module, as shown in Figure 6 (1). Users control these modules by manipulating the virtual models. They can achieve one DOF motion by manipulating each individual module or achieve multi-DOF motions by manipulating the auto-generated Inverse-Kinematics (IK) end-effector on top of the assembly tree. For the other action modules with discrete mode switching, a list-like UI is designed individually according to the module's function. As shown in Figure 6 (2), users can access these UIs to switch on/off the Fan module, change the facial expression on the Face module, and change the light color on the LED module, etc. In terms of the sensing modules, each environmental sensing value (distance, temperature, weight, etc.) is dynamically displayed as shown in Figure 6 (3). Moreover, users can program logic events by setting a user-defined threshold value and accessing the currently connected action modules. An example is illustrated in Figure 6 (3 right), where the user just programs the Fan module to turn ON when the weight sensing value is above 5 and the Face module to display ‘happy’ when the value is below 5.

Besides gesture-based interactions, the Ani-Bot system also exploits the HMD’s multimedia capabilities to create immersive user experiences with active feedback. To avoid being overwhelming and distracting, we utilize voice commands and audio feedback for functions which have no explicit need to visualize, such as mode transition and menu navigation.

MODULAR ROBOTICS WITH MRI

In this section, we demonstrate and discuss the augmentation offered by MRI in the Ani-Bot system. Specifically, we illustrate the system’s designated features for the three phases of a construction kit’s lifecycle: **Creation**, **Tweaking**, and **Usage**, respectively. We showcase how these embedded MR features can enhance the user experience for DIY robotics.

Creation

The process of playing with a modular robotics kit begins with the assembly. Ani-Bot encourages users to freely explore different assembly configurations by providing a rich module library. In addition, the system can also fully or partially assist users in the assembly process. Utilizing MRI, Ani-Bot provides users with *mixed-reality assembly guidance* for existing designs (Figure 7 (1)). The virtual guidance is interactive and gives real-time assembly feedback. For example, the color of the virtual model will change when the corresponding physical module is correctly assembled. Besides the full assembly manual, the system can also provide partial functional structure suggestions according to the key input module. For example, in Figure 7 (2), upon detecting the ‘Distance Sensor,’ users can activate the *functional suggestion guidance* by voice command, and the system will display a 2-DOF thrower setup with default adjustable structure parameters.

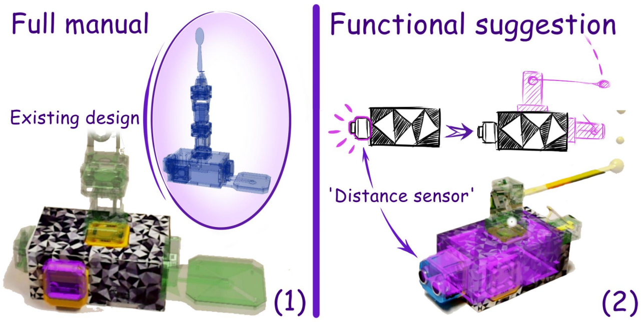

Figure 7. Creation with MRI: mixed-reality assembly guidance. (1) Full MR assembly manual for existing design. (2) Suggestive guidance based on key input device.

Tweaking

When encountering ineffective designs, users will start the iterative process in order to explore and find a working solution, namely Tweaking. Instead of physical tweaking, which requires effort for iterations with real robots, Ani-Bot provides a virtual tryout feature for users to tweak the ineffective designs into a working configuration. As demonstrated in Figure 8, upon removing the end-effector, users can activate the ‘*Tweaking Mode*’ through a voice command. The system will then display a series of suggested derivative configurations based on the current physical setup. Users can try different virtual assemblies and compare their performance in the mixed-reality simulation to find better solutions.

Figure 8. Tweaking with MRI: virtual tryout for functional improvement. Tweaking a robot manipulator setup so that the spoon tip can reach inside the bowl.

Usage

One of the main advantages of mixed-reality is its ability to the merge of a virtual interface with its corresponding physical target. By exploiting this property, Ani-Bot allows users to easily control their robots to effectively interact with the surrounding environment. For instance, Ani-Bot’s sensing modules expressively visualize the input data (temperature, distance, force, etc.) from the surrounding environment (Figure 1 (3,6)). In addition, each sensing module offers the ability to program sensor-driven logic events with the programming UI (Figure 1 (3)). In this case, the user just programs the ‘Fan Module’ to turn on when the weight exceeds the set value, otherwise the ‘Face Module’ displays a smiling expression.

Besides the sensing programming, Ani-Bot allows users to create and manage keyframe animations that enable their robots to execute automatic actions. As illustrated in Figure 9, after activating the ‘*Animation Mode*,’ users can manipulate the virtual model to set the keyframes (the physical robot will not move in ‘*Animation Mode*’). Upon playing the animation, the robot will automatically transit through the defined keyframe positions and complete the action. Each animation can then be saved as an interactive ‘*Action Sphere*,’ which floats near the physical robot and plays back the animation when tapped. Users can create multiple animations and intuitively manage them. By dragging an ‘*Action Sphere*’ into another one, users can merge them together and create a new ‘*Action Sphere*’ which has the combined animation. In this way, users can easily achieve complex animation authoring to create environmentally interactive and storytelling like animations.

EXAMPLE APPLICATIONS

Figure 10 demonstrates the four use cases we have created to showcase the diversity and controllability of our system, including two service robots (1,3) assisting environmentally interactive daily practice and two storytelling robots (2,4) with expressive emotions and stylish actions. The **Robot Thrower**

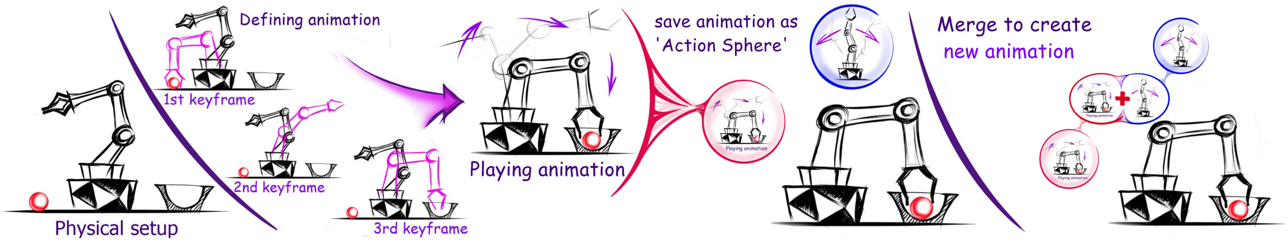

Figure 9. Mixed-reality animation authoring and management.

(1) is able to display the predicted shooting projectile to guide users to manually hit the targets with pinpoint accuracy. The thrower can also utilize the distance sensor to automatically adjust the shooting angle based on the distance reading from the target. The **Emotional Fire Fighter (2)** is a fully equipped vehicular robot with a front temperature sensor for detecting candle fire. He is never too shy to show his emotions via the face modules and he shows no hesitation in using his head-mounted fan and hanging hammer to put out a fire. The **Tea Maker (3)** is a smart service robot with an arm. By visualizing the temperature and weight of the teacup, users can customize their favorite beverage by programming the Tea Maker to automatically add sugar and keep stirring until the tea is ready to serve, which is detected by the temperature sensor and indicated by the blinking LED and the smiling face. The **Dancing Robot (4)** is a DIY character with a big head and gloomy expression. Users can program him to make numerous amazing dance moves.

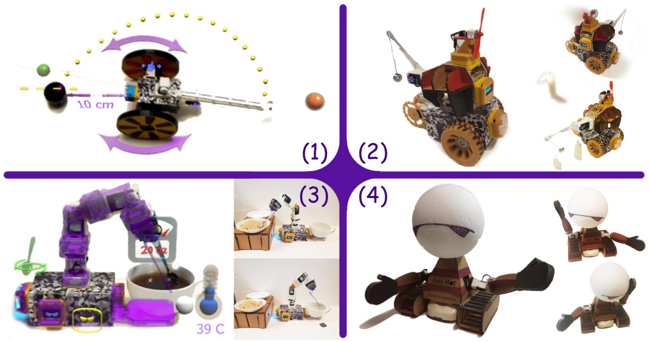

Figure 10. Use cases demonstration of the Ani-Bot system. (1) The Robot Thrower. (2) The Emotional Fire Fighter. (3) The Smart Tea Maker. (4) The Dancing Robot.

SYSTEM EVALUATION

To evaluate the Ani-Bot system, we invited 20 users to participate in our two-session user study (10 for each).

Session 1: System Usability Evaluation

We designed four tasks for the first study session featuring the key functions of the system. We invited 10 users (7 male), 7 of them in the 20-25 age range and 3 in the 25-30 age range, with varies backgrounds. The goal of this study session was to evaluate the usability of the Ani-Bot system and explore the user experience of DIY robotics with MRI.

Procedure. Session 1 took about 1.5 hours for each user, including a tutorial to introduce the HMD device and the Ani-Bot system (20 mins). We adopted one of our use cases ('Tea Maker') as the evaluation prototype due to the comprehensiveness of its functionality and the complexity of its physical structure. We dissected the prototype into four manageable tasks focusing on the three phases: **Creation**, **Tweaking**, and **Usage**. Users were given a questionnaire with Likert-type items and subjective questions after each task. Some of the more representative results are intuitively displayed as a colored scale bar for each task. Each Likert-type item is graded by users from 1 to 5, where 1 means strongly disagree and is colored in red, while 5 means strongly agree and is colored in green. The scale bars are aligned with positive answers (yellow, yellowgreen, green) on the right and negative answers on the left (red, orange). (N = number, U = user)

Task 1: Assembly Guidance, Paper Manual vs MR Manual

For a design configuration with seven modules (Figure 11), we asked users to complete the assembly using both a paper manual and an MR manual as a guidance (random order).

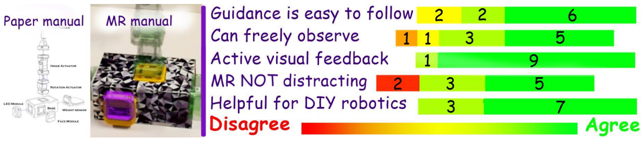

Figure 11. Task 1: Assembly guidance. Paper manual vs MR manual.

Feedback and Discussion. Due to the simplicity of this design, users were able to complete the assembly almost equally rapidly (less than 30 s) and accurately with both manuals. It is noted that the point of this task was not to systematically study the time efficiency and accuracy between the two approaches. Rather, we tried to focus on exploring the user experience of MR assembly guidance and compare it with the most commonly used paper manual method. From the post-study survey, most users (N=8) preferred the MR manual over the paper manual for assembly guidance. The two users who disagreed felt that the overlaying virtual model was distracting and they suggested a switch function to toggle the MR interface. *"I am having some trouble differentiating the virtual model from the real one (U2)."* However, they still admitted that the MR guidance for the DIY robot was useful (reporting 5 and 4). The assembly process included identifying the right module and putting it in the right location. Ani-Bot's MR system allows users to freely observe the guidance virtual model from different perspectives for module identification. One user disagreed with this because of the limited field-of-view of the HMD device. *"It is hard for me to see the whole guidance model without moving my head (U7)."* We found that the virtual feedback for confirming the assembly correctness was particularly appreciated by the users. *"The color* *change feedback really assures me about my assembly and makes me confident."* Overall, we found that the expressive visual feature as well as the interactivity of the MR guidance provided an engaging and entertaining assembly experience. *"I really like it, it's fun and makes me want to try more. (U5)"*

Task 2: Design Tweaking, Physical vs Virtual Tryout

In this task, users were asked to improve the performance of the initially ineffective robot design by changing its assembly configuration. The goal was for the robot arm's end-effector (spoon) to get inside the bowl (Figure 12). Users were asked to perform tweaking in both ways with a randomized sequence.

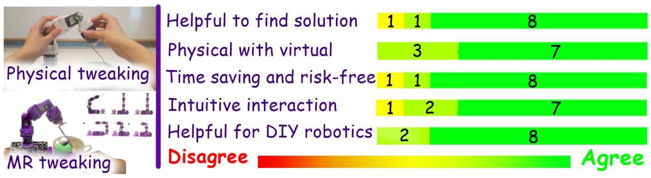

Figure 12. Task 2: Hands-on tweaking vs virtual tryout.

Feedback and Discussion. After this task, most users reported that they preferred MR tweaking over the physical tweaking (N=8). They particularly liked the grafting of the virtual model on the physical modules, while both moved together corresponding to users' simulating manipulation. *"I think the virtual/reality simulation really helps me to understand the dynamics of the robot (U7)."*. According to the survey and our observation, users generally enjoyed the MR tweaking due to its time-saving effectiveness and risk-free characteristics. *"MR is fast and easy to try. I enjoy testing different options (U4)."*. *"The MR tweaking reduces the cost and risk for revising physical robots (U1)."*. As for the two users who preferred hands-on tweaking, they believed the added complexity of the MR tweaking was unnecessary, but they still appreciated the visualization and simulation ability offered by the MR tweaking. To summarize, the system's virtual tryout feature effectively helped users to identify the configuration for performance improvement. *"With MR, I know it works and I do not need to finish assembling something to test (U8)."*

Task 3: Programming Sensor Driven Events

During this task (Figure 13), users were given a simple setup with two action modules (Fan, Face) and two sensing modules (distance, weight). They were asked to interact with the sensing modules and define the logic events triggered by the environmental data to drive the action modules. Users were first given a brief demonstration and then asked to freely explore the feature and define the logic events by themselves.

Figure 13. Task 3: Programming sensor driven events.

Feedback and Discussion. All the users found it easy to program a logic event except for U4, who answered 1 in this question. She initially struggled to understand the working mechanism and suggested adding more text or audio instructions to guide users. Despite this, she still agreed that the feature was useful for DIY robotics (score=5). Users generally enjoyed the sensing visualization, which presented the environmental information in a tangible and interactive way. *"This feature makes reading from a sensor so intuitive and entertaining (U3)!"* From the survey results as well as the subjective comments, we found users particularly appreciated the system's fast and easy approach to programming fairly complex events (N=9), which could even elicit and promote interest in DIY robotics. (*"I like this instant programming. It is easy and can make people more interested in DIY robots (U8)."*)

Task 4: Creating Environmentally Interactive Animations

In this task, users evaluated the animation authoring feature in the system. They were asked to define the keyframe animations that facilitated the 3-DOF robot arm with a spoon end-effector to automatically add sugar to the teacup (Figure 14). The average time cost for this task was about 15 min.

Figure 14. Task 4: Creating mixed-reality keyframe animations.

Feedback and Discussion. Considering the difficulty of task 4, we were surprised to find that most users (7/10) successfully accomplished the task with just one shot. We observed great excitement from the users when they have achieved this complex animation with just a few operations. *"I have never programmed a robotic arm so quickly and easily (U10)!"*. Based on the survey results, we found that users were highly satisfied with the MR animation authoring feature in the system. They appreciated the system's ability to create automatic actions *"Animation is useful to do repetitive work (U1)"* that enabled them to quickly explore their ideas with physical robotic movements. *"I like to set several actions at one time and make it keep doing what I want it to do (U9)."* Furthermore, they found the system to be very helpful for programming environmentally interactive tasks due to the active visual feedback from the mixed-reality view. *"I can use the surrounding objects as references when I define the animations; this makes it so easy for me to program my robot around them (U1)."*

Summary. After this session, users generally agreed that the interaction of the system was intuitive and effective (avg=4.6) with well integrated functions that help to provide elevated user experiences in DIY modular robotics (avg=4.56). The System Usability Scale (SUS) survey was also deployed after the study session to evaluate the system with an average score of 83.25 and a standard deviation of 6.8, which indicated high usability of the proposed system.

Session 2: Creating and Animating DIY Robots

The element of DIY is significant to Ani-Bot as the system is designed to support add-on DIY creativity by providing a modular platform and an effective method for controlling and programming. To evaluate this, we invited 10 users from diverse backgrounds for the second session of the study (7 male), with 8 of which in the 20-25 age range and 2 in the 25-30 age range.

Figure 15. Results from the open creation study session showcasing users' DIY robot. (1) Mr. Destroyer (2) Box Porter (3) Peru Totem (4) 3-head Nezha (5) Robot Bandit (6) The Whomping Willow (7) Sun-eye Monster (8) Cheerleader (9) Robo-Cop (10) The Hulk

Process. Session 2 lasted about 80 min including a 20 min system tutorial. Users had full access to the system's modular kit, as well as various DIY crafting tools and materials to create their own robot. During the session, they were asked to design, craft, assemble, and animate their own DIY robot.

Results. Figure 15 showcases all the DIY robots created by the users during the open creation session. We observed a large variety from the end results, ranging from humanoid characters (4,8,10), to mechanical characters (1,2,5,9), to object-based characters (3,6,7). Each user's DIY robot consisted of 7-9 modules, which indicated high complexity involving multiple degree-of-freedom movements. All animations were created by the users uniquely for their characters which truly brought the robots to life. For example, Mr. Destroyer (1) does not hesitate for one bit to shred anything he sees (detected by the distance sensor) with his blade, claw, and drill bit. The Box Porter (2) is a diligent fellow that specializes in moving anything delivered to him (activated by the weight sensor) to the designated area. The Cheerleader (8) is a lovely girl waving 'De-Fence' for her team, while the Whomping Willow (6) furiously bashes the 'flying car' trapped on its trunk.

Feedback and Discussion. From the post-study survey, we found that most users appreciated the system's coherent workflow to create and animate the DIY robots. *"It was especially fun to make the cheerleader and then see her actually move and do things."* From our observation, we found that the idea of combining DIY with robotics really promotes users' interest in exploring more features and functionalities of the system. *"Just being able to add skin for a better appearance on my robots also encourages me to explore more designs and shapes."* During the ideation process, many users liked to test-play with multiple modules and put on the HMD to quickly test the animation performance. *"It responded well to what I wanted it to do."* The plug-and-play seamless user experience as well as the real-time responsive mechanism was highly appreciated by the users. *"You don't need to worry how you are going to articulate your model for creating the control code. You just plug and play."*

LIMITATION AND DISCUSSION

During our user study, the most common complaints we received were about the HMD device, specifically, its form factor and interaction modality. *"It is too heavy and makes me feel dizzy after some time." "The display view is too small that I have to move my head to see the whole scene." "I don't like the mid-air gesture interaction; it feels awkward and is not very accurate."* Because our system was built on the HMD device (Microsoft Hololens), the limitation of the device became the limitation of our system. Furthermore, the device confined the mixed-reality experience exclusively to the headset wearers, which inevitably impeded the distribution and social impact of the system. This suggests that we need a better MR platform with a user-friendly form factor, intuitive interaction, and most importantly, public viewing and/or accessibility.

Another limitation of the system is caused by the MR tracking mechanism. The Ani-Bot system is currently implemented with an image marker on the Base Module. This requires an initializing detection and tracking process each time users start a new assembly. Moreover, the tracking results can be corrupted by occlusion from other connected modules. *"The virtual model is sometimes mis-aligned with the robot."* The tracking mechanism is the key reason for requiring the Base Module, which constrains the physical structure design of the modular system. This limitation can potentially be addressed by incorporating markerless tracking in the future.

It is interesting to note from the evaluation that users were always asking for more feedback (audio, visual, tactile) and natural control methods (gesture, voice). Future endeavors should therefore focus more on the modality of the interaction approaches to achieve comprehensive control with minimum cognitive load. Furthermore, the system should better understand its users and execute low level operations automatically. With the rapid development of AI technology, a new balance can be established and constantly adjusted between robot intelligence and user-involved controllability.

CONCLUSION

In this paper, we present a novel mixed-reality modular robotics system, called Ani-Bot. We explore and investigate embedding a coherent MRI for DIYing a modular robot. Our use cases as well as the system usability study have evaluated and verified the augmentations for modular robotics by embedding the mixed-reality interaction. The results from the open creation study have demonstrated the Ani-Bot system's capability to support both creating and animating DIY robotics. To this end, our system has shown a strong potential for delivering in-situ and novel user experiences for DIY robotics.

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