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Understanding Users' Perceptions and Expectations toward a Social Balloon Robot via an Exploratory Study

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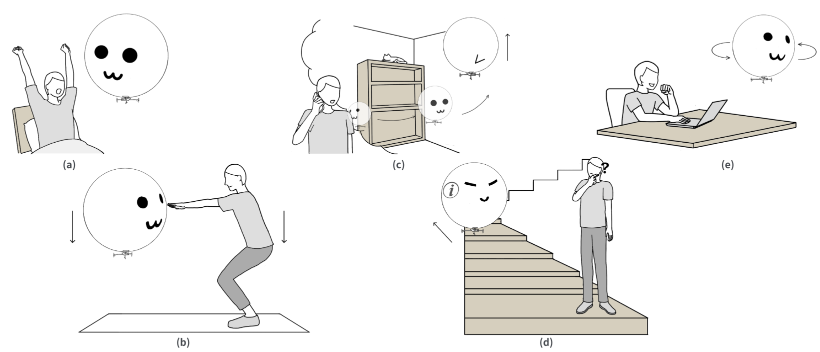

Figure 1: We collect participants' feedback toward presented social functions of a balloon robot, namely BalloonBot, with a storytelling demo: (a) At 8:00 a.m., BalloonBot flows over to wake up the user and provides a cheerful greeting. (b) One hour later, it becomes a fitness coach, guiding the user with touches. (c) At 1:00 p.m., BalloonBot is the housekeeper, helping locate a roaming cat at home. (d) By 3:00 p.m., BalloonBot in the library assists the user in book searching across different building levels. (e) Finally, BalloonBot provides relaxing and supportive companionship while the user works on their laptop.

Abstract

We are witnessing a new epoch in embodied social agents. Most of the work has focused on ground or desktop robots that enjoy technical maturity and rich social channels but are often limited by terrain. Drones, which enable spatial mobility, currently face issues with safety and proximity. This paper explores a social balloon robot as a viable alternative that combines these advantages and alleviates limitations. To this end, we developed a hardware prototype named BalloonBot that integrates various devices for social functioning and a helium balloon. We conducted an exploratory lab study on users' perceptions and expectations about its demonstrated interactions and functions. Our results show promise in using such a robot as another form of socially embodied agent. We highlight its unique mobile and approachable characteristics that harvest novel user experiences and outline factors that should be considered before its broad applications.

CCS Concepts

• **Human-centered computing** → **Interactive systems and tools**; • **Computer systems organization** → **Robotics**.

Keywords

human-robot interaction, social robots, flying robots

ACM Reference Format:

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1 INTRODUCTION

Social robots participate in our lives more than ever. They often act in certain social roles, e.g., providing companionship and entertainment to the child as a babysitter [44, 51], managing patients in the hospital as a nurse [6, 98], and delivering guidance to people with chronic disease as a doctor [62] or simply teaching people how to cook as a chief [52]. Given special designs, they also help extend the capacity of humans by acting as powerful tools, e.g., memory management and life sharing for people living alone [95], and interacting with dancers on the stage to create novel visual effects [34]. Particularly, the emergence of large language models (LLMs) has significantly enhanced these robots in their perceptive and cognitive abilities and enriched their interactions with humans and the physical world, enabling them to appear more frequently and carry out more diverse tasks in our society [6, 26, 29, 61, 63, 79, 93, 95, 98, 103, 112].

Among this surge of exploring social robots across various scenarios, a majority of existing works still focused on ground robots [6, 44, 49, 51, 63, 98, 112] or those placed on a desktop [52, 61, 93, 95, 98, 103] (both referred to as *surface robots* in the rest of this paper). This could be largely due to the technical maturity and market dominance of this kind of robot, where Pepper [4], NAO [3], and their follow-up products can be easily accessed. However, typical limitations of these robots include their restricted mobility given the static design (e.g., desktop robots) and/or obstacles on the ground and the lost opportunity to function in the aerial space. In this sense, drones appear to be a proper alternative option that enables spatial mobility while providing similar social functions [13, 48]. However, it is also highlighted that drones as social robots face several limitations, such as noise, proximity, safety, and endurance concerns, particularly due to their inherent mechanical structures and functionality designs [55]. We ask if there is another form of social robot that enjoys spatial mobility and enables a safe and approachable social experience.

In recent years, the robot with a balloon appeared as a potential platform that inherits the mobile capacity of drones but allows a quieter operation and longer duration in the air [11, 69, 70, 76, 89, 104, 105]. So far, many studies have focused on the implementation and design of such a *balloon robot*, e.g., its mechanical structure [104], balloon materials [36, 37], and flight control algorithms [82, 83] in a large aerial space. For the discussion about the use scenarios, it was mainly adopted as a non-social tool in the past, e.g., for the visual presence of attendees in a remote meeting [76, 89], and aerial and dynamic recording during a discussion [70]. Only the study seen in [35] has discussed participants' acceptance of such a balloon robot as a potential social robot. However, a gap exists: without demonstrating representative use examples, they were unable to reveal users' further perceptions and expectations about its social interactions and functions.

Thus, this paper aims to draw a clearer picture of using a balloon robot as an interactive, proximal, and friendly social agent. To the best of our knowledge, this paper is the first to integrate social channels into wireless balloon robotics and explore users' feedback on such a new social embodiment. By developing a hardware prototype named *BalloonBot* and its controlling web interface software, we first proposed a series of use cases that are grounded on the application topics demonstrated by the relevant literature and BalloonBot's characteristics. We then conducted an exploratory lab study, which comprised a *stimuli session* using a pre-recorded video showcasing these use cases and a *hands-on session* where participants were allowed to operate, check, and touch BalloonBot. In particular, the video was crafted using a Wizard-of-Oz (WoZ) design. Finally, each participant was invited to complete a questionnaire and an on-site semi-structured interview. Looking into the results, we provided novel and informative insights on how BalloonBot is perceived by users from different dimensions, their diverse expectations about the functions it may carry, and concerns it should address in the future.

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2 RELATED WORK

2.1 Social Robots on the Surface

To date, most studies and commercial products targeting human-robot interactions have used surface robots. Aside from the technical maturity that can largely reduce the developmental cost, we notice the following motivations that further contributed to their dominant uses. First, reliance on specific payloads: For certain use scenarios, surface robots are ideal for handling payloads, including i) manipulation-oriented payloads, e.g., robotic arms for door-opening and desktop cleaning in housekeeping [63, 94, 103]; and ii) visually-interactable payloads, e.g., touchscreens for cognitive training [20]. Second, alignment with contexts: Except for requiring certain payloads, the motivations behind some studies were yet to extend the design space of surface robots given specific contexts, for example: i) child-robot interaction studies prioritize safety and durability (e.g., interactive toys [44, 45, 101]), which surface robots inherently provide; and ii) mechanical innovation studies focus on integrating robots with existing infrastructure, as seen in library delivery systems [54]. While these factors drive the popularity of surface robots, their constraints in navigating complex terrains and confinement to 2D planes limit broader impact. This highlights opportunities for exploring alternatives, especially in contexts where essential social capacities—such as seeing, listening, speaking, and moving—are already sufficient to drive the application.

2.2 Social Drones

The use of drones as interactive agents has gained significant attention in recent years, with studies exploring the potential of drones for social interactions with humans. Therein, many studies have examined the effects of flying behaviors (e.g., the height, approach direction, interaction distance, speed, sound, flight path) [15, 16, 21], outer appearance (e.g., having an emotional face) [47, 55, 90, 111], and interaction modalities (e.g., voice and gesture) [71] of drones on user experiences. Specifically, some of them looked into users' preferences on drones' social roles in domestic settings, which yet concluded that participants consistently perceived drones as functional tools rather than interactive agents, e.g., to bringing them items over a companion or a friend [55], and a toy over a pet [99]. For the rationale, researchers generally attribute these findings to the operational challenges of drones, namely noise and safety concerns created by high-speed propellers and potential collisions [9, 23, 99, 108]. Consequently, social drone applications remain scarce in high-stakes areas concerning children, elderly care, and healthcare applications [71]. Some practices tend to fix the problems created by blades, e.g., by using propeller guards and enabling interactions with proximity, such as Tai chi coaching [59] and breathing exercises [41]. Whereas, the study by Abtahi et al. [5] revealed that such protectors' material and form factors could discourage users from touching the drone, as participants fear damaging them. Notably, drone noise was seen as disruptive and uncomfortable and remains unsolved [23, 27].

2.3 The Robot with a Balloon

For their persistence in the air, balloon-based systems have served meteorological observation for weather monitoring [19, 57] and planetary terrain and composition analysis [11, 69] since the 1960s. With contemporary drones' limitations, researchers are now repurposing buoyant platforms for prolonged, safe, and quiet aerial interaction. The robot with a balloon, as another *robot in the air* and the alternative to drones, is also referred to as blimps [35, 42, 83, 88, 109], blimp robots [100], the soft flying robot [84], and exactly the *safety drones* [104] in the past decades. A unique design of balloon robots is their reduced dependence on always-on high-speed blade propulsion systems, given buoyancy generated by lighter air like helium. Thus, they can achieve spatial mobility in a safer and quieter way, suitable for social interactions with proximity. Until recently, many works still focused on improving the hardware implementation of such a robot [36, 37, 74, 82, 83, 104], while the progress in exploring its social interaction and functions has been relatively sparse and slow. Therein, unique characteristics of the robot with a balloon have inspired the early explorations of its interactive functioning, with representative works including: i) telepresence systems integrating the camera and projector [76, 89]; ii) overhead recording tools for meeting analytics [70]; and iii) programmable entertainment platforms generating dynamic visual patterns [68, 81, 84].

Despite the surge of intelligent embodied agents, balloon robots' capacity for multimodal social signaling (i.e., listening, seeing, speaking, and moving) remains unexplored, particularly in driving social interactions and functions. Thereon, this paper presents an exploratory study to shed light on this. Specifically, we contribute by proposing a novel social balloon robot prototype (BalloonBot) and answering the following two questions: **RQ1: How do people perceive the mobile, multimodal, and intelligent interaction presented in BalloonBot's WoZ demo**, and **RQ2: What expectations do people have given BalloonBot's presented functions**.

3 METHOD

In this section, we first introduce the hardware design and implementation of BalloonBot, demonstrating its simple yet efficient structure that makes it an accessible social robot platform. Then, we report the evaluation results of BalloonBot's kinetic and noise performance. Finally, to move another step forward in demonstrating the potential of such a robot in social interactions and functions, we propose four use cases given BalloonBot's unique characteristics and emerging topics from relevant literature.

3.1 Designing and Implementing BalloonBot

Our primary design consideration for this robot is to seamlessly integrate the key social interaction channels[18, 106], namely seeing, listening, speaking, and moving onto a small panel. Thereon, another consideration is to enable a touchable structure and, consequently, the plug-and-play connection between this mechanical part and the balloon to account for endurance. We avoid context-relevant designs to present a more generalizable implementation and user feedback.

3.1.1 Mechanical Part. As shown in Figure 2 (a), the mechanical part of BalloonBot comprises two control boards hosting a bunch of devices, two orthogonal-connected plastic rods (with the longer horizontal one hanging a servo and a motor on each end, and the shorter vertical one hanging a motor), and the plastic Lego-like standing mount attached with a Velcro pad. The detailed model,

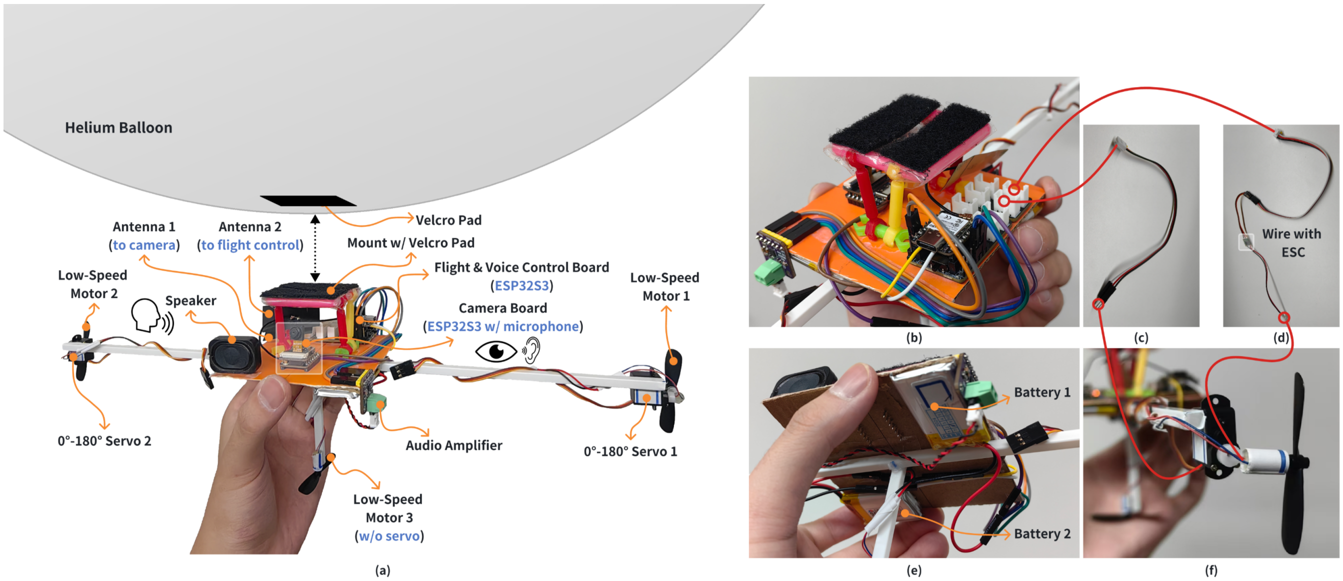

Figure 2: (a) An overview of BalloonBot. (b) The upside panel from the backside view, where the flight & voice control board is connected via the wires shown in (c) and (d) with the servo and the motor on each end, respectively. It is also connected via another ESC-equipped wire to the motor at the bottom. (e) Two batteries are attached to the underside panel. (f) The lateral view of a servo and a motor.

weight, and price of each hardware component are summarized in Table 1. As shown in this table, the weight and the cost of making such a robot are well balanced. Below, we report BalloonBot's basic social functioning details per control board with different devices.

- **Seeing and Listening** (Camera Board). Two control boards using XIAO ESP32S3 microcontrollers are used to manage all the devices. To reach a balance between the power supply, particularly when using batteries, and data processing efficiency, we assign one of the control boards (referred to as ESP32S3Sense) to have a camera (OV2640) and a microphone connected. This helps handle transmitting a comparably larger amount of visual and audio data, separating which from the flight control signals. The camera captures images at a resolution of 480×320 pixels, with a frame rate of 30 fps and a field of view of 52°, achieving a balance between image clarity and real-time efficiency. The microphone uses the I2S (Inter-IC Sound) interface with the mono mode of PDM (Pulse Density Modulation), 16000 Hz sample rate, and 16-bit resolution, suitable for precise audio data acquisition and processing. Via a 2.4GHz Wi-Fi connection with the computer, data is transferred in real-time using the HTTP protocol.
- **Speaking and Moving** (Flight & Voice Control Board). We adopt another control board (ESP32S3) with an extension board (as shown in Figure 2 (b)) to handle the voice output using a speaker and flight modules. The digital sound signal is converted into analog signals by the control board using the I2S interface, and then amplified by the audio amplifier and played by the speaker. To fulfill the mobility of BalloonBot in a 3D indoor environment, we designed a motion scheme with 3 motors (maximum speed of 30,000 RPM at 3.7V) and 2 servos (180° range). The motor speed is adjustable with the Electronic Speed Controllers (ESC). In Table 2, we provide a detailed report on the flight control strategy combining servos and motors. We assume the initial state of BalloonBot is when the balloon's buoyancy is balanced with the weight of the mechanical part below. That is, even as buoyancy decreases over time, Motor 3 can provide supplementary lift to keep the balloon aloft, ensuring that horizontal motions driven by Motors 1 and 2 remain unaffected.

Table 1: The detailed model, total weight, and unit price of each hardware component of BalloonBot.

Component	Overview	Num.	Weight (g)	Price (USD)
Balloon	32-inch balloon w/ valve	1	62.5	0.69+5 (Helium)
Control Board 1	XIAO ESP32S3	1	3.8	7.69
Control Board 2	XIAO ESP32S3Sense	1	5.3	10.72
Extension board	w/ 8 Grove connectors	1	10.0	5.36
Speaker	8Ω 3W	1	5.0	0.89
Audio amplifier	MAX98357	1	3.1	0.65
Motor	610 DC Core-less Motor	3	4.5	0.30
Servo	180 degree	2	6.6	3.71
Speed Controller	DM-ESC001	2	3.6	1.17
Battery	1S 900 mAh Li-Po	2	27.8	2.34
Others	Mount, DuPont lines, etc.	-	35.5	-
Total	-	-	**167.7**	**46.34**

We prepared a web interface for the wizard-end control of BalloonBot, comprising real-time audiovisual transmission, voice, text, and sound file input for audio playback, flight control, and system log. Please kindly refer to Appendix A for more details.

3.1.2 *Integrating with the Balloon.* Using a helium balloon first adds to BalloonBot's increased aloft duration and reduced noise. Given the total weight of the mechanical part to be 105.2 g, as illustrated in Table 1, the size of the balloon needs to balance such a payload against the capacity of moving across confined spaces

Table 2: The flight control strategy of BalloonBot. By default, servos are set to be 0° in moving forward, and we use the symbol ↑ to represent a respectively higher speed of the specific motor for differential turning control.

Motion state	Servo degree	Driven motor
Forward	1, 2: 0°	1, 2
Backward	1, 2: 180°	1, 2
Spinning Left	1: 180°, 2: 0°	1, 2
Spinning Right	1: 0°, 2: 180°	1, 2
Forward&left	1, 2: 0°	1, 2(↑)
Forward&right	1, 2: 0°	1(↑), 2
Down	1, 2: 90°	1, 2
Up	-	3

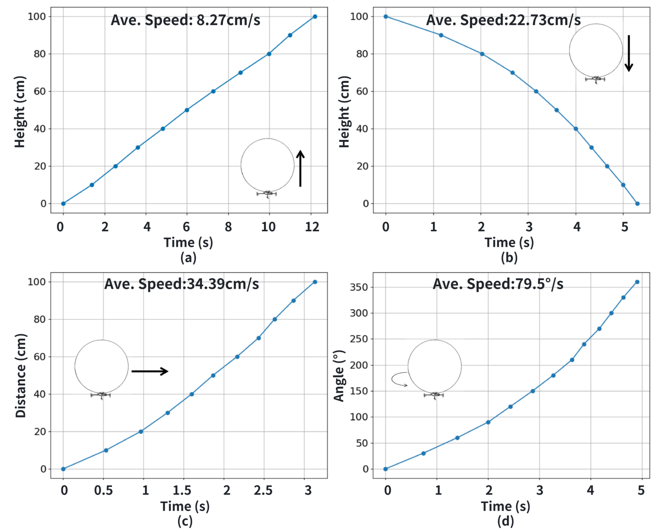

Figure 3: BalloonBot's speed profile during (a) ascent, (b) descent, (c) forward motion, and (d) yaw rotation.

(e.g., flying across the door or a narrow lobby). In this work, we compared latex with TPU as the balloon material. We managed to reduce the thickness of TPU to 0.06 mm under the current manufacturing conditions available in the local balloon factory. However, it is still heavier and more expensive than the latex. Although latex is vulnerable to oxidation, our experiment selects latex as the current material for BalloonBot. Specifically, we use a spherical latex balloon with a fully inflated diameter of 80 cm, which offers an additional lifting capacity of 130 g. As can be seen in our video figure, such a size also fits well with normal indoor structures. It should be noted that there are other materials commonly used for balloon manufacturing, such as PVC, PE, and aluminum film. However, a comparison between these materials is beyond the scope of this paper. In addition, we add emoji stickers to the balloon's front- and back-end surfaces to indicate its orientation. Finally, to integrate this balloon into the robot system, we implement the following design considerations:

- **Touchability-Oriented Structure Design**. Spreading propulsion devices around the balloon may enhance maneuverability and stability during flight [35–37, 104]. However, these devices also hinder interactions with proximity, as they obstruct direct contact with users. Therefore, we designed the current mechanical form and attached it underneath the balloon, a practice also seen in [84]. In our experiments, during close interactions like being hugged by a user, the balloon did not experience any damage or loss of control.
- **Plug-and-Play Functioning with Velcros**. The balloon itself is fragile and susceptible to oxidation and punctures. To enable quick replacement and adjustments, we attached the mechanical panel with a standing plastic mount and a Velcro pad, with another corresponding pad underneath the balloon. This allows for convenient connection and disconnection of the balloon.

3.2 Kinetic and Noise Evaluation

Within a room with no wind and a baseline environmental noise of 34 dBA, we evaluated the kinetic performance and noise level of BalloonBot with neutral buoyancy. Results are reported as follows.

- **Kinectic Performance**. We recorded the time spent per unit distance (i.e., 10cm for moving in a line and 30° for rotation) of BalloonBot in its major motion categories to demonstrate its speed and steadiness. It should be noted that the forward direction of BalloonBot is the facing direction of its camera. As shown in Figure 3, BalloonBot moves smoothly, which creates a sense of steadiness. Except for the ascent motion that almost has a constant speed of 8.27 cm/s, it can reach a maximum speed of 30cm/s, 50cm/s, and 128°/s after 5 seconds, 2 seconds, and 3 seconds, during descent, forward motion, and yaw rotation, respectively. Furthermore, we programmed the robot to leverage its servos to achieve rapid braking (normally within 1-2 seconds) through reverse thrust during motion.
- **Noise Level**. We set the motors responsible for forward/yaw rotation, ascent, and descent motions at maximum speed. We then collected the distribution of noise levels along different distances across three representative directions. The handheld decibel meter is positioned at the same horizontal height as the rotor. As is shown in Figure 4, BalloonBot by most generates negligible sounds (<50dBA) even at close distances (≥30cm), which is quieter and allows a closer interaction than the previous one made without propellers [104].

3.3 Designing Downstream Use Cases

Current practices on implementing and evaluating the social aspects of balloon robots in the real world are very limited, which include i) using LED lights and controlled motions for art and entertaining [14, 84, 109]; ii) supporting telepresence with cameras or projectors [76, 89]; and iii) visual meeting recording in the air [70]. To draw a clearer picture of the balloon robot in social functioning and shed light on its future usage, we designed four downstream use cases under different social roles as stimuli for participants in our experiment. We first consider two key characteristics of BalloonBot, namely *spatial maneuverability* and *proximity*. In addition, we deem BalloonBot a perfect platform for intelligent multimodal interactions, e.g., natural communication [25, 52, 95], target recognition

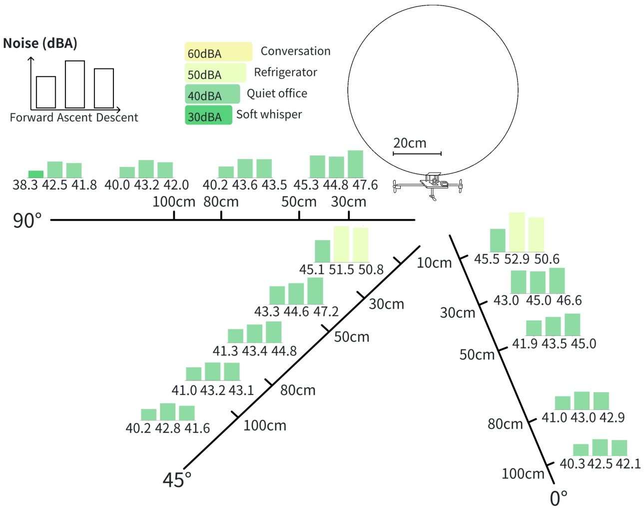

Figure 4: BalloonBot's maximum operational noise distribution along three directions when setting the corresponding motors at the maximum speed. The reference bars indicating the sounds from 30dBA to 60dBA are taken from [2]

[35, 46], and pose estimation [17, 97], thereby considering *multi-modal intelligence* as another characteristic in its social functioning. Thereon, we propose the following use cases:

- **A touchable fitness coach in the air**. The idea of using robots for proactive health has been attracting attention recently, where a typical usage adopts the robot as a fitness coach [97]. To move beyond this capacity demonstrated by surface robots, we design examples demonstrating BalloonBot's touch-oriented interaction and the non-verbal behaviors enabled by its spatial mobility. Specifically, we prepared BalloonBot to organize a fitness session with tactile guidance, real-time language instruction, and feedback. As shown in Figure 5 (a-c), we designed three exercises, namely squat with shoulder raise, shoulder flexion in a kneeling position, and neck stretching. For neck stretching, BalloonBot acts as an aerial target to guide users in exercising their necks.
- **A smart housekeeper that is quiet and moves across rooms**. Devices with balloons were originally designed for long-duration hovering observation [11, 19, 57, 69]. BalloonBot could, in a similar sense, enhance smart home systems by operating quietly and smartly and moving across rooms that may have ground obstacles. We highlight these aspects here, as surface robots and drones may fall short in such a comprehensive scenario. To showcase this skill, as illustrated in Figure 5 (d)(e), we let BalloonBot help a user locate and report the wandering cat in the house. More generally, the robot may function in a hybrid environment comprising both smart and non-smart facilities in the future.
- **An emotional companion that invites the user to hug**. In recent years, people have found robots suitable for providing emotional support [40, 75, 95, 98]. We aim to understand if a *prominent, soft, and touchable flying robot* may create novel emotional value for the user. As shown in Figure 5 (f)(g), when a user is feeling down, BalloonBot can play soothing music and/or invite the user to have a comforting hug. If the user is in a positive mood, it can create cheerful moves and speak actively to enhance their emotional well-being.

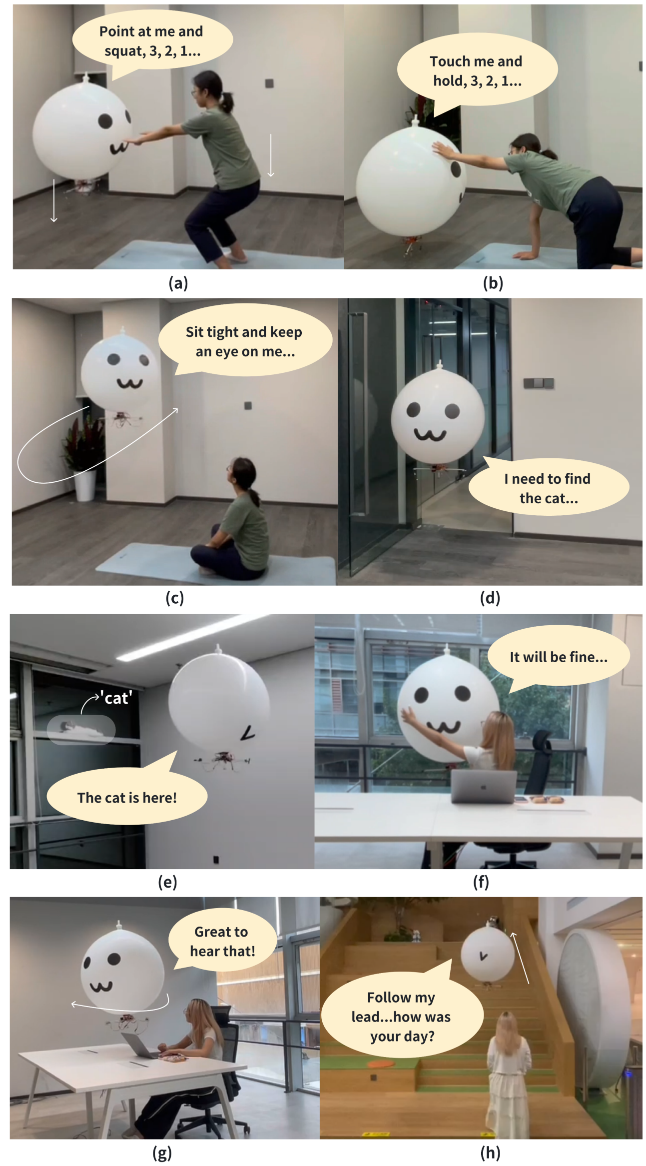

Figure 5: We prepared video stimuli with a Wizard-of-Oz design covering four use cases: (a-c) fitness coach, (d-e) housekeeper, (f-g) emotional companion, and (h) indoor navigator.

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More generally, the robot may function in a hybrid environment comprising both smart and non-smart facilities in the future.

4 The Exploratory Lab Study

We conducted an exploratory lab study to understand users' perceptions and expectations of BalloonBot's demonstrated use cases. This user study is formally reviewed and approved by the Institutional Review Board (IRB) of the University.

4.1 Video Stimuli with Wizard-of-Oz Designs

Due to the imperfect technical maturity of novel robot prototypes adopted for research touching futuristic topics, many studies conducted their user experiments using content made in virtual reality [55], 3D games [10, 64], and video demos [35]. Likewise, we made video stimuli for our lab experiment that showcase a wizard-of-oz implementation of the proposed four use cases. This helps: i) isolate evaluation of BalloonBot from current prototype limitations (as we will report later); and ii) maintain stimuli consistency across different participants as well as prevent potential technical artifacts (e.g., temporary flight instability and possible voice latency) from skewing feedback.

For each use case, the wizard (an experienced BalloonBot pilot) remotely controlled the flight and speech of the robot, given its real-time visual and audio playback provided by the web interface. At the same time, two volunteers acted as the user. The authors together prepared the scripts for BalloonBot's voice output per each use case, which was further refined by GPT-4o[1] to increase the sense of *machine capacity* [22, 52]. While the wizard *talked* with the user directly via our web interface, such scripts serve as a reference to remind the wizard about the process and help reduce the use of words that are too colloquial. BalloonBot pronounced the texts by using the TTS API[2].

4.2 Participant

We sent out social media flyers to recruit 33 participants, including 16 male participants (M) (mean age=37.38, std=13.50) and 17 female participants (F) (mean age=38.29, std=12.86). Given the focus of our experiment on living experiences, all participants were employed professionals having independent living spaces in the local area, either in rented or self-owned apartments. Regarding the experience of using robots, only 2/33 participants (1M, 1F) claimed to be frequent users, 9/33 participants (5M, 4F) reported to be moderate users and had some knowledge, 10/33 participants (5M, 5F) participants selected neutral, another 10/33 participants (5M, 5F) reported to have only a few experiences, and 2/33 participants never used robots before (2F). All the participants read the warm-up story describing the content of this study before the experiment, while each received a 15-dollar gift card as a reward after completion. Please refer to Table 3 for more information on each participant, including the gender and age group, respectively.

[1]The OpenAI ChatGPT 4o (https://chat.openai.com/) at its December 2024 version.
[2]The 'Nova' voice from OpenAI text-to-speech (TTS) API (https://platform.openai.com/docs/guides/text-to-speech).

(a) (b)

Figure 6: Illustrations of the hands-on session where (a) the experimenter would answer the participant's questions by directly presenting the prototype, and (b) the participant could also give a try on the robot.

4.3 Procedure

We conducted the study each time with one student experimenter and one participant in a room of 5m×5m square. The devices used include a 12.9-inch iPad Pro for showing the video demo, a laptop for taking notes, a mobile phone for voice recording, and a BalloonBot prototype. The experiment has a sequential design, including: i) first, the *Stimuli Session*, where each participant was invited to watch the pre-recorded video demo of BalloonBot's four use cases and allowed to pause for any possible questions or opinions; and ii) second, the *Hands-on Session*, where the participant could touch and check the robot by their own and control via the web interface, as shown in Figure 6; this helps them get a first-hand experience about BalloonBot's details, e.g., appearance, flight behavior, and operational noise. Particularly, during hands-on sessions, participants were prompted with a short description of the robot and how to operate it, and reflections on use cases. In this way, our experiment created a mixed experience for participants that also prevents first-exposure bias: they observed the use cases presented by BalloonBot and explored by hand the robot's technical details. In the end, each participant completed a questionnaire and a semi-structured interview. Therein, participants were informed of our WoZ designs during the interview. Before this, only one participant noticed some clues of the WoZ setting in the stimuli session: "*I heard from the video there are keyboard sounds in the background, wondering if someone was controlling the movement. I am not sure, actually, because I mostly took BalloonBot as a semi-automated machine, if not fully autonomous*".

4.4 Measures

We adopt a 5-Likert scale (from 1, very much disagreed, to 5, very much agreed) questionnaire covering four different sections. The first two refer to the prior experiences of participants, including generic aspects of $Q1$ *Familiarity*, i.e., use frequencies or knowledge of robots, and $Q2$ *Attitude* using Negative Attitudes toward Robots Scale (NARS) [87]. The remaining two touch the interaction experiences given our experiment, including $Q3$ *Perceptions about BalloonBot's Presented Interaction*, and $Q4$ *Expectations about BalloonBot's Functions*. For $Q3$, we collected participants' ratings across the following dimensions:

- **Safety**, a major concern in human-robot interactions [12], and is important to reveal whether participants may spot any safety issues after watching the demo of BalloonBot;
- **Noisiness**, a major drawback of social drones [13, 48], to which the effect of BalloonBot should be verified;
- **Empathic Alignment**, important to inform participants' perceived trust, acceptance, and interaction efficiency with BalloonBot [22, 39, 50, 85], and to judge whether participants can well perceive and find emotionally aligned with the demonstrated social behaviors of BalloonBot;
- **Ease**, another issue encountered by social drones given their constrained social presence and channels [15, 55], and is valuable for us to know whether the novel social functioning and appearance of BalloonBot improves the user's sense of ease against psychological burdens;
- **Privacy**, a prevalent problem that can be enlarged by a robot in the air [23], which would help understand participants' potential privacy concerns toward BalloonBot.

Particularly, to alleviate response biases, we phrased several survey questions negatively. Aside from NARS, for noisiness and privacy, we adopted questions: i) "BalloonBot produced noise that I found unpleasant"; and ii) "I'm concerned about my privacy given the use cases of BalloonBot", respectively.

For $Q4$, quantitative measures mainly include participants' ratings toward each of the proposed use cases. Following the questionnaire questions, we developed a follow-up semi-structured interview protocol to collect participants' detailed responses on their notable ratings and open comments on BalloonBot. Therein, some interview questions were rewritten from the questionnaires. For instance, for the question on *safety*, namely'*BalloonBot gives me a sense of safety*', asked in $Q3$ of the questionnaire, the interview questions include: i) *You found BalloonBot provides you with a sense of safety; could you share with us more about this* (for the rating > 3)? ii) *You did not find BalloonBot provides you with a sense of safety; could you tell us more about this* (for the rating < 3)? and iii) *How did you exactly perceive the presented safety of BalloonBot? And why* (for the rating = 3)? For $Q4$, especially for BalloonBot acting as *fitness coach* and *housekeeper*, which would already be prevalent in our society, we have participants actively compare BalloonBot with their previous experiences using robots or similar artificial systems. Please refer to Appendix B for the detailed Questionnaire and questions adopted. We transcribed the voice recordings with MacWhisper while all the authors independently verified the accuracy of the transcriptions.

4.5 Data Analysis

For qualitative analysis, we adopted content analysis to uncover insights by categorizing trends and patterns in the interview data [66, 77]. By doing so, we aim to understand participants' perceptions and expectations of BalloonBot at a conceptual level [33]. Since the interview was organized according to the sections in the questionnaire, we conducted inductive content analysis under each relevant topic concerning interaction perceptions and functional expectations, respectively. In this process, two experimenters who had conducted the entire study session, thus being familiar with the concept and values of this work, independently crafted the initial coding system using the same half of the transcriptions. Afterward, they conducted a coding meeting to align with each other and refine the codebook. They agreed on the final codebook by continuing the rest of the transcriptions. An additional author randomly selected pieces of transcriptions and their codings to help discover potential disagreements, which were further resolved to reach a consensus at another author meeting.

We also implemented quantitative analysis, mainly analyzing the potential correlation of participants' *familiarity* and *attitude* with their perceptions and expectations, respectively. This is particularly because there is a general prior hypothesis that users' *familiarity* and *attitude* may influence their user experiences with robots [15, 80]. With the Shapiro-Wilk test and Mauchly's sphericity test, we found the data did not meet the assumptions of normality and sphericity. Therefore, we adopted Spearman's correlation test for correlation analysis and reported the correlation coefficient r_s and associated type 1 error rate p.

5 RESULTS

We organize the analysis below for each research question. In particular, we aim to understand how participants perceive and expect the interaction and functions presented by BalloonBot, respectively, given their mixed experiences during the experiment, previous knowledge, or general attitudes toward using robots or dealing with technical products and even humans in general.

5.1 Participants' Perceptions about the Interaction Presented by BalloonBot (RQ1)

5.1.1 Safety Perceptions as a Combined Outcome of BalloonBot's Appearance, Material, and Functional Capacity. As shown in Figure 7 (a), 27/33 participants (selected 4 and 5 in the questionnaire) took BalloonBot as safe to be used in daily life, 5 selected neutral, and only 1 participant selected *2-disagreed* toward the safety of using BalloonBot. In general, many participants found BalloonBot's "*round and soft*" shape and "*light in weight*" material, as experienced during the hands-on session, as direct indicators of its safety. Some participants owe such a sense of safety to BalloonBot's "*friendly*" and "*intelligent*" capacity as witnessed in the video demo, e.g., "*the robot can help me find it (cat) quickly, which makes me feel the balloon is reliable*" (P15). In detail, we found:

- **Appearance and material as indicators of safety perceptions.** BalloonBot was perceived as non-threatening and cute due to its non-angular design (e.g., *"round, and harmless, no sense of danger"* (P1)) and the absence of hard edges (e.g., *"round and bulky, like Baymax"* (P26)). Interestingly, many participants compared BalloonBot and other robots, saying that: "*Robots made entirely of metal are uncomfortable and unfamiliar, but the balloon robot is light, with a smile, making it more relaxing and comfortable*" (P27). In this quote, P27 specifically compares the "metal" robot and highlights that our design provides emotional value (e.g., smile and relaxation). Additionally, "*The proximity of BalloonBot provides a sense of safety, while I may get hurt if a humanoid robot suddenly walks close to me, and also the propellers of drones are terrifying*" (P04); In this quote, P04 specified the physical and emotional proximity concerns that traditional robots caused, which might be potentially mitigated by BalloonBot. It could

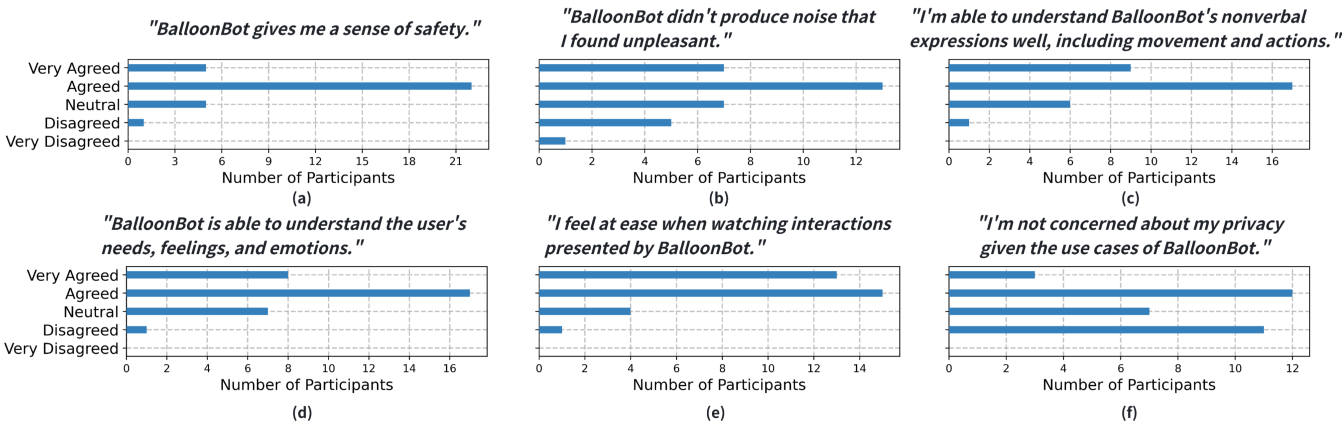

Figure 7: Questionnaire questions and results about participants' perceptions about BalloonBot's presented interaction. The original questionnaire questions of (b) and (f) were reversed here for analysis.

be noted that these responses on BalloonBot's appearance and material align well with recent progress on so-called soft robotics [56, 107], where researchers found that robots using soft materials add to better acceptance and novel expressivity. A number of participants also pointed to a better fit with domestic environments of Balloon in comparison with drones, as the latter "*moves drastically in the air*"(P23) and "*may damage the indoor facilities*" (P12). Other participants mentioned that robots on the ground may also get into obstacles and people (P15). All these quotes highlight the improved sense of safety of BalloonBot for close indoor interactions.

- **The user-centric functions contribute to the sense of safety.** While we explained to participants the use of WoZ designs during the interview, several users felt a sense of safety due to the robot's demonstrated functions, especially for those presented by BalloonBot as housekeeper, companion, and navigator. They saw it as a helpful tool for "*caring for the elderly, and on behalf of their children*" (P21). Although safety is not explicitly mentioned in similar quotes, such an acceptance of BalloonBot is an important indicator since safety is one of the priorities for robots dealing with people of special groups, e.g., the elderly [7, 65, 67]. More specifically, the flying behavior presented by BalloonBot during its functioning helped express "*a sense of kindness*" (P09), another indicator of their perceived safety. Moreover, one participant implied that they value the less demanding social attributes of BalloonBot in comparison with humans, saying, "*When I'm lonely, the robot won't mind if I repeat myself; it always answers clearly, which helps me relax.*" (P28).

By running the Spearman correlation test, we find no correlation between reported safety scores and robot familiarity ($p = 0.2604$). We only find a moderate negative correlation between safety and the second question in NARS, namely $Q2.2$ ("*I find it difficult to communicate with the robot.*"), with $p = 0.002$ and $r_s = -0.5175$, implying that the communication is important for building a sense of safety. Indeed, we noticed that most participants here thought they could communicate well with the robot.

5.1.2 BalloonBot's Hardware Implementation Helped Reduce Perceived Noise Levels. As shown in Figure 7 (b), the majority of participants (27/33 participants) did not find BalloonBot's operational noise to be annoying, with only a small proportion (6/33 participants) expressing annoyance. As our participants directly experienced the noise levels of BalloonBot during the hands-on session, many of them compared such performances with those of other robot types, especially because the issue of noise has been a common concern [23, 53, 91]. Therein, a participant who has rich experiences using drones commented that "*drones always make noise during use, and the balloon robot is more tolerable for me in a domestic setting*" (P24). Furthermore, one participant described the "*walking noise*" by humanoid robots and "*rolling noise*" by typical surface robots as "*uncomfortable*," and by contrast, commented that "*the balloon robot is a bit better because it floats to me*" (P16).

The quantitative analysis shows no significant correlation between perceived noisiness and robot familiarity, with p-values of 0.9656. We find a negative correlation between perceived noisiness and $Q2.2$ of the NARS, with a Spearman's correlation coefficient $r_s = -0.3983$ and $p = 0.0217$, which implies that participants who found it more difficult to communicate with the robot were more likely to be disturbed by the noise of BalloonBot.

5.1.3 BalloonBot's Presented Non-Verbal Behaviors and Intelligence Enhanced Participants' Sense of Empathic Alignment. We included two questions in the questionnaire to understand the possible empathic alignment perceived by participants toward BalloonBot, i.e., $Q3.3$: "I'm able to understand the nonverbal expressions of BalloonBot well, including its movement and actions" (*human* ⟵ *robot*) and $Q3.4$: "BalloonBot is able to understand the user's needs, feelings, and emotions" (*human* ⟶ *robot*). As shown in Figure 7 (c) and (d), 21/33 participants found a sense of mutual understanding and selected 4 or 5 for both two questions. Another 5 participants found it easier to understand the robot (selecting 4, agreed) than having the robot understand humans (selecting 3, neutral). Generally, participants found BalloonBot's abundant uses of non-verbal behaviors, e.g., "*ascent and descent during fitness support*," "*moving close slowly to comfort the user*," and "*approaching for touch*," as "*supportive*," "*warm*," and "*emotional*." In addition, the WoZ implementation of BalloonBot's multimodal intelligence also helped participants perceive BalloonBot's keen sensitivity to human states. Specifically, we found:

- **Non-Verbal Behaviors as the Unique Interactive Channel of BalloonBot**. The spatial maneuverability of aerial robots, a distinction against surface robots, has inspired many studies to look at how the flying paths [15, 31, 38] and even physical interactions of drones [59, 102] can be understood by users. Following up on this route, BalloonBot's soft and touchable design further allowed us to design more diverse non-verbal behaviors and trigger novel user perceptions. P06 liked BalloonBot's "*circling around the user, posture, and moves*" as if it were "*alive*." P14 thought that they could "*feel it was approaching as emotional companionship when you are sad*." Even more, P19 commented that "*BalloonBot seemed to ask for petting*," because it would "*actively approach you and gently bump into you*." Moreover, one participant made a comparison with ChatGPT, highlighting that "*I do have experiences with ChatGPT, but the embodied version demonstrated by BalloonBot is even better...language becomes even less important since this robot can act and touch you like an animal*."
- **Natural Interactions enabled by WoZ Intelligence Created a Sense of Responsiveness**. We implemented BalloonBot's multimodal intelligence in our WoZ demos to deliver smooth communications and reactions to users' needs. Our participants received these designs well, giving them a strong feeling of being understood. For instance, P11, P26, and P32 found BalloonBot's "*actively coming over and comforting actions upon user's sadness*" as strong indicators of its sensing capacities. In addition, participants also valued BalloonBot's demonstrated role of a fitness coach since it can "*actively prompt the user to move, like reaching up or down to touch it*" (P21) and "*remind me, for example, not to arch my back*" (P22) during the exercise. While LLMs are creating a surge of machine intelligence that can better understand users' intentions and needs [24, 96], these findings showcase how BalloonBot could become a suitable platform.

With Spearman's correlation test, we find no correlation between reported ratings about the "*human* ← *robot*" alignment against familiarity ($p = 0.7757$). Whereas, we find a moderate negative correlation between such ratings and the attitude $Q2.3$: "*I find it uncomfortable to communicate with a robot in front of others*," with $p = 0.014$ and $r_s = -0.422$; and also for the "*human* → *robot*" alignment, with $p = 0.017$ and $r_s = -0.5248$. Such correlations may imply that people willing to communicate openly with a robot may be better prepared to align with BalloonBot.

5.1.4 Perceived Ease As an Outcome of BalloonBot's Appealing Presence and Practical but Less-demanding Social Functions. As Figure 7 (e) shows, the majority of participants (28/33 participants) reported feeling relaxed and comfortable after watching the demo and directly interacting with BalloonBot, selecting 4 or 5 on the scale. Many of them explained such perceptions as they found BalloonBot in the demo and the real world "*novel*," "*interesting*," "*adorable*," and "*agile*," and some proactively asked to touch or even hug the balloon during the hands-on session. Besides, 4/33 participants expressed neutrality, while only 1 participant (P23) disagreed and found the "*moving speed of BalloonBot a bit slow*" and preferred "*a smaller size*." In detail, we found:

- **Participants felt relaxed given BalloonBot's attractive and friendly presence**. BalloonBot's "*Baymax*"-like appearance contributed not only to participants' sense of safety but also relaxation. They again made comparisons with other robots, saying, "*interacting with BalloonBot is more relaxing than humanoid robots due to its cute appearance*" (P28). One participant also found the presence of BalloonBot "*part of the whole scene*" and thus "*doesn't seem to have much of an effect on me*" (P19), proposing a promising integration of such a robot into the various use cases.
- **BalloonBot's less-demanding design contributes to participants' sense of ease**. Aside from its fresh presence, participants found BalloonBot less demanding in terms of social attributes compared with humans and dependence on environments compared with other robots. For the former one, a representative comment is that "*interactions between people are more complex because the others may have their own emotions and attitudes for me to care about*" (P28). This is especially for introverted persons who find it overwhelming dealing with other people but not robots [97]. For the latter, one participant was well triggered by the use case of fitness coaching and commented that "*I don't want a bulky robot standing next to me while I'm panting during exercise in a small room...a balloon floating in the air would provide a much more relaxing experience*" (P14).

The Spearman test demonstrates that there is no correlation between the sense of ease and familiarity $p = 0.6924$. Additionally, we find a negative relation between the perceived ease and two metrics of NARS questions, namely $Q2.2$ and $Q2.3$, with $p = 0.0498$ and $r_s = -0.3443$, $p = 0.0067$ and $r_s = -0.4624$ respectively. These imply that participants who feel discomfort or have difficulty communicating with the robot tend to rate the experiences they perceived from BalloonBot lower.

5.1.5 Perceived Privacy as an Independent Topic is Affected by Multiple Factors. As shown in Figure 7 (f), 15/33 participants expressed little to no concern about privacy issues related to their experiences with BalloonBot, selecting 4 or 5 on the questionnaire. Therein, except for 6 participants who did not find the use of BalloonBot associated with any potential privacy issues, some participants found the debate on privacy is tricky nowadays since "*mobile phone*" and "*wireless sensing, like Wi-Fi*" that have a higher risk of privacy leakage are everywhere. At the same time, some chose "*to trust the technician behind this product shall manage users' privacy well*" (P8). Moreover, the non-anthropomorphic form of BalloonBot helped lower the concern of one participant, as "the robot does not look like a human and seems not interested in my data" (P29). Nearly another half of the participants stayed neutral (n=7) or showed certain concerns about their privacy (n=11); notably, none of them found such discussions raised by the specific use of BalloonBot. Various reasons exist behind these concerns:

- **Privacy concerns about information leakage to malicious third parties**. Among the 18 participants who stayed neutral or showed concerns, 9 of them described their concerns as "*I am afraid of the illegal use of my data by intended persons and*

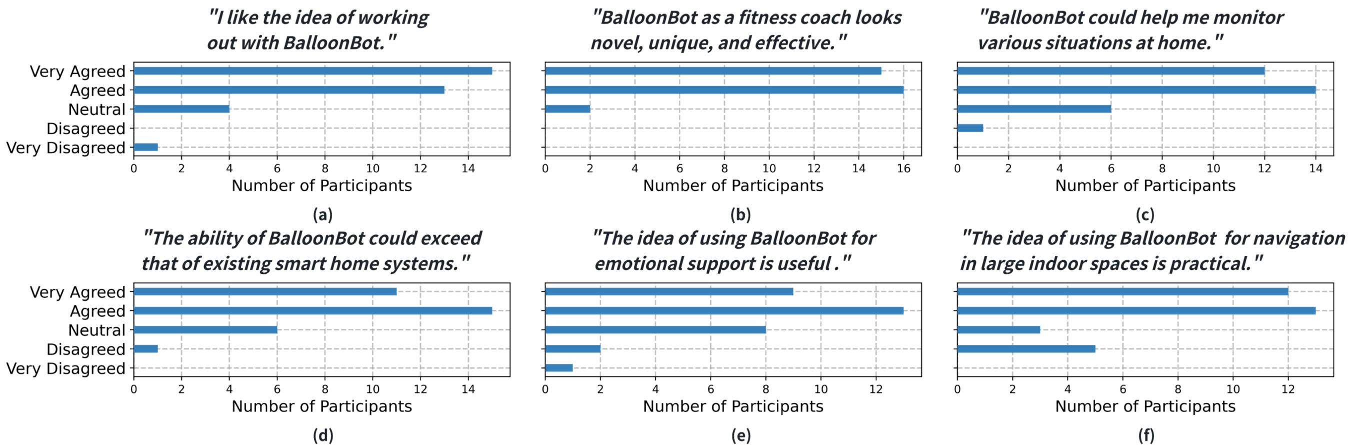

Figure 8: Questionnaire results on participants' expectations about BalloonBot's functions.

organizations" (P17) and "*I am fine with BalloonBot's own processing of my data but do not wish such data get transmitted back to unknown places*" (P02). In reaction, most participants reduced their concerns after describing successful techniques like visual abstraction and target removal [72]. This will inform BalloonBot of the importance of actively applying privacy protection techniques in its future deployments.

- **The call for user autonomy in privacy protection**. Several participants highlighted the importance of having full control over the robot's behaviors and data, such as "*adding a wake-sleep mode and noticeable indicator on whether it is watching*" (P23) and "*I prefer the data to be stored locally, making it difficult for others to access*" (P25). These opinions align well with design guidelines that advocate for users' full data control, e.g., the user autonomy over website cookies advocated by GDPR [1]. For BalloonBot, future versions could add lights to its balloon to indicate whether and what kinds of sensors are functioning, as seen in the practice for indicating air qualities [58], and allow users to switch on and off via language commands conveniently.

5.2 Participant's Expectations given the Functions Presented By BalloonBot (RQ2)

As shown in Figure 8, participants generally found the demonstrated use cases of BalloonBot suitable, useful, and practical. Notably, regarding BalloonBot's roles as "*fitness coach*" and "*housekeeper*," their positive ratings become even more aligned. Upon such ratings, we provide some informative insights from our follow-up interview about their exact expectations toward BalloonBot.

5.2.1 BalloonBot as the Fitness Coach Could Improve by Providing Richer Contents. Participants liked the idea of using such a touchable flying robot as a fitness coach (n=28), and nearly all the participants found such a use case novel, unique, and effective (n=31). The only participant (P25) who expressed negative opinions therein explained that "*not very interested, as I don't usually enjoy fitness activities*." In specific, they commented that "*it can judge your posture accuracy from multiple angles*" (P18), "*You can get immediate exercise guidance regardless of time and location*" (P11), "*the touch and language provide a sense of supervision and engagement*" (P33), and "*I think personal trainers are expensive, and sometimes they don't fully meet personal needs*" (P24). Additionally, the current demo has raised many insightful comments from participants on its future improvements. Some expected more professional and expert-like feedback, such as "*whether the knees go over the toes during squats*" (P23), and "*I hope the robot's feedback can be emotionally rich, as this would maximize my motivation*" (P22). There is already a trend, as researchers are improving machines to understand people's movements and respond with knowledge-enhanced languages [96]. There are also expectations about having more diverse BalloonBot-engaged exercises, e.g., "*I feel like I could play table tennis with BalloonBot*" (P21), and "*BalloonBot could organize indoor games or simply walks, as a form of aerobic exercise*" (P07).

5.2.2 Integrating BalloonBot with Smart Home Systems Could Enhance Its Functions as a More Comprehensive Housekeeper. Most participants found BalloonBot's role as a housekeeper helpful in managing situations in their homes (n=26) and appeared to have obvious advantages over existing smart home systems (n=26). They were well motivated by the "*challenging*," "*interesting*," and "*useful*" case of finding a wandering cat, thus expected the robot to help "*locate other stuff when they are busy*" (P20), "*find a moving child and return timely feedback to the parents*" (P17), and necessarily "*check the gas and other fatal signals*" (P17). Still, one participant was concerned, as the task could be demanding for the robot since "cats tend to hide…it will be tough for the robot to pull off" (P22). For the comparison against smart home systems, participants felt that BalloonBot's spatial mobility is the key advantage since it could "*reduce the number of cameras installed at home while allowing flexible switching of monitored areas*" (P24). Thereon, many participants further reported an integration of BalloonBot into the smart home system, expected that "*the BalloonBot could interact with, e.g., smart curtains, to automate their opening and closing, rather than simply informing me of their status*" (P25, P33).

5.2.3 BalloonBot as a Promising Emotional Companion Requires Certain Expertise. More diverted ratings were received for the use case of BalloonBot as an emotional companion. More than half of the participants found such a use case helpful (n=22), while the rest stayed neutral (n=8) or expressed negative feelings about it (n=3). Participants who liked this idea generally found the presence and physical interactions demonstrated by BalloonBot "*comforting*" and forming "*a tactile sensation of warmth*," similar to "*pets*." However, the rest of the participants pointed to the fact that a robot like BalloonBot "*inherently lacks human-like vitality and is unable to provide emotional guidance through more expressive facial expressions and movements*" (P07, P02), and "*even humans can't always console someone who's upset*" (P18). Participants expressed the expectation that a robot should provide professional feedback to better gain people's acceptance. As one participant noted, "*Psychologists use certain strategies during conversations to achieve better intervention results*" (P21). Specifically, the robot should "*spend more time rather than quickly jumping to solutions*" (P22). This could involve "adopting micro-expression detection and body language analysis to better understand the user's needs" (P33). Actually, this echoes well with the practice of leveraging robots as emotional companions that explore techniques inspired by domain experts, such as storytelling [8, 86] or directly using expert knowledge for special groups [28].

5.2.4 Contexts Matter for BalloonBot's Unique Role as the Navigator. Participants shared varied opinions on the BalloonBot's demonstrated use case as an indoor navigator. Therein, 25/33 participants found BalloonBot a good fit for large-scale indoor navigation, and 5/33 participants showed opposite opinions. For the former, participants generally valued BalloonBot's "*flexible mobility in guiding users without being obstructed*" (P32), and thus "*suitable for large public spaces*" (P16, P25, P27, P33). For the latter, participants were concerned about BalloonBot's potential technical limitations, e.g., "*blocking the user's path in a small lobby*" (P7), and "*struggling with precise navigation due to insufficient indoor positioning*" (P9). While drones in this sense may provide similar functioning [13, 48], many participants shared their expectations that BalloonBot, as a unique navigator, shall merge well with the suitable context. Specifically, such a role could be necessarily valued better in the "*museum*," "*library*," and even "*hospital*," where "*a quiet and safe navigator*" (P25) is much needed. This participant especially illustrated such an expectation with a vivid diagram, as shown in Figure 9. In addition, similar to the proposal seen in [104], it can be well motivated to have such a navigator in the "*mall*," to fully leverage its "*prominent appearance for attracting guests*" (P27), and "*stand out to guide directions through the crowd*" (P33).

5.2.5 Some Common Expectations about BalloonBot: Personalization and Visual Effects. Aside from the expectations participants provided according to our presented use cases, two pieces of common feedback emerged that could also inform BalloonBot's future development. The first comes to the great interest expressed by our participants in making the robot customized. On the one hand, this stands for a customizable appearance, similar to the feedback seen in [35], concerning balloons "*colors*," "*paintings*," and even "*shapes*." On the other hand, several participants talked about personalized behavior, e.g., "*to learn my habits and act on my behalf*" (P18), and "*wakes up upon hearing specific commands*" (P17). Following the motivation behind projector-installed balloons for telepresence [89], and adding "eyes" to drones [55], many participants also mentioned their preference for visual effects for BalloonBot. This can be the

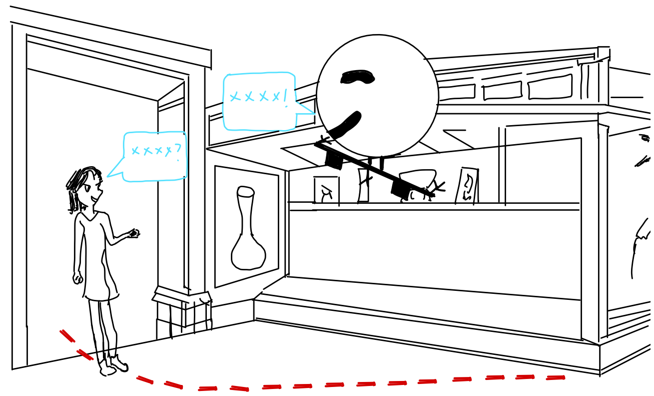

Figure 9: An illustration of using BalloonBot as a museum guide for interactive navigation by P25.

projection "*to display simple emotional expressions*" (P18), or just "*turn on the equipped lights when navigating at night*" (P12). Here, we call for the participation of industry partners in such development, since our current design choices were constrained by: i) payload limitations, i.e., 130g net buoyancy, given the balloon size and material, excluded conventional LED matrices and displays; and ii) cost barriers created by the latest practical techniques, i.e., the too-expensive micro-projectors [30].

6 DISCUSSION

Here, we first discuss the novel understanding acquired via our exploration of a social balloon robot in relation to the previous works. Then, we outline the major challenges that should be addressed in developing such a robot. Finally, we discuss the limitations of this study and envision the next step.

6.1 A Promising Platform that Balances Spatial Mobility, Safety, and Proximity

Interactive payloads (e.g., robot arms [63, 73, 94, 103], touchscreens [20]) and the fit with specific use scenarios (e.g., the integration with toys for children [44, 45, 101]) are the fundamental motivations aside from technical maturity behind the dominant use of surface robots for the domestic context. However, surface robots face persistent criticism about their lack of tolerance to terrain and, most importantly, the missing opportunity in aerial space. Researchers continue developing terrain-adaptive systems, exemplified by: i) legged robots overcoming obstacles [32, 92]; and ii) self-reconfigurable climbers for vertical surfaces [43, 60]. Accordingly, drones are still popular, given their agile and swift mobility in the air. To alleviate people's concerns about its high-speed propellers, efforts are seen in building protectors [5, 59, 102] that allow physical interactions with drones. In such a sense, the robot with a balloon, namely BalloonBot in this study, may not stand out by merely overcoming these disadvantages. Instead, this study focuses on a buoyancy-driven platform balancing spatial mobility, safety, and proximity to understand people's perceptions and expectations of such a new social robot.

We then contributed by implementing the first social balloon robot prototype (BalloonBot). Meanwhile, we analyzed participants' (n=33) feedback upon observing a series of downstream use cases prepared with WoZ designs and hands-on explorations of the robot. Our participants found an improved sense of safety and ease given BalloonBot's appearance and material. Some further made comparisons with their previous experiences with "*metal*" robots and drones that have "*terrifying propellers*," highlighting the proximity achieved by an improved sense of safety toward BalloonBot. Although the ratings from most participants, together with our quantitative evaluations, pointed to the acceptance of the operational noise of BalloonBot as a major concern of social drones [23, 53, 91, 108], participants who are very sensitive to the sound could yet "*hear the mechanical noise inside, which might be a bit annoying*" (P18), and for certain cases, such noise may also distract the user when they are "*trying to focus*" (P13). In general, we believe that such issues could be rapidly addressed as hardware technology advances. Notably, the latest low-speed rotors we used in this work already produce significantly less noise than those employed in previous studies [70, 82]. Additionally, participants found BalloonBot's demonstrated non-verbal behaviors (i.e., touch and moves) informative, which provided them with a sense of empathic alignment, an outcome that is less seen in previous work on social drones [13, 48]. Nevertheless, our experiment does not provide new insights into people's sense of privacy but aligns with existing practices about using data anonymization strategies and securing users' autonomy regarding their data. In short, findings from this work may open opportunities for such a new flying social robot in the near future.

6.2 The Next Step: Toward an Interactive and Practical Companion

Based on feedback from participants and our experiences collected in developing the prototype, we identified three key challenges hindering BalloonBot's broader applications as a practical social robot. The first is about adding extra interactive channels, including i) visual elements, from displaying colors as seen in [58], to projections similar to telepresence systems demonstrated in balloon interfaces [89]; and ii) natural interactions, e.g., tactile feedback, gesture recognition, and natural communication. Nevertheless, including extra devices poses a challenge to the balloon's buoyancy, implying the need to develop lighter balloon materials and highly integrated electronics. The second is finding capable algorithms or software to fulfill the potential functions, as showcased by our WoZ use cases. While existing tools like PoseFormerV2 [110] for real-time human pose estimation, Segment Anything Model 2 (SAM2)[3] for scene understanding, and Imentive AI[4] for facial expression classification can be well adapted for enhancing BalloonBot's capability, developing techniques for more stable flying control and multimodal sensing remains crucial for achieving full autonomy. Finally, infrastructure requirements present significant hurdles, such as i) sustainable helium supplies and ii) automated charging solutions like those implemented in commercial vacuum robots [78]. Specifically, for BalloonBot's autonomous operation, the necessary additional hardware includes a motion sensor (e.g., MPU6050) and positioning modules (VL53L01+PMW3901), with a total extra weight of nearly 20g.

[3]SAM2 by META AI, https://ai.meta.com/sam2/

[4]Imentive AI APIs, https://imentiv.ai/apis/

6.3 Limitations and Future Work

Future works may look into resolving the following two limitations of the current study. First, our study was conducted in a controlled laboratory setting rather than in realistic environments like homes or public spaces. While simulation-based methods using VR [55], 3D game engines [10, 64], and video prototypes [35] provide initial understanding given current technical constraints, longitudinal studies in the real world may create extra user experiences to understand sustained interaction patterns. Additionally, the current hardware prototype, with exposed electronics and unshielded propellers (identified as discomfort sources in the qualitative analysis above), necessitates iterative refinement. Though perfect hardware integration remains elusive, prioritizing safety-critical enhancements like component encapsulation and airflow optimization could significantly improve user acceptance.

7 CONCLUSION

This paper presents our exploratory investigations of people's perceptions and expectations toward a novel social balloon robot, which provides safe and approachable interactions with spatial mobility. To this end, we implemented a balloon robot prototype, referred to as BalloonBot, which integrates essential interactive channels comprising seeing, listening, speaking, and aerial moving. Targeting the deployment of BalloonBot for daily uses, we proposed a series of downstream use cases, i.e., fitness coach, housekeeper, emotional companion, and indoor navigator, given its unique characteristics and relevant topics in the literature, and created a video demo with a Wizard-of-Oz setup. We further conducted an exploratory lab study involving 33 diverse participants. By having the participants watch the demo and give a hand on the prototype, we collected informative feedback with questionnaires and semi-structured interviews. Our analysis showed participants' novel perceptions and expectations about BalloonBot; we additionally discussed the limitations and future development of the robot in terms of its hardware, software, and auxiliary infrastructures needed for its real-world deployments. All these findings generally contribute to the recognition of such a safe and approachable flying robot as a promising alternative for social functioning.

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References

[1] 2024. A guide to GDPR data privacy requirements. https://gdpr.eu/data-privacy/

[2] 2024. International Noise Awareness Day. https://noiseawareness.org/info-center/common-noise-levels/

[3] 2024. NAO. https://www.aldebaran.com/en/nao

[4] 2024. Pepper. https://us.softbankrobotics.com/pepper

[5] Parastoo Abtahi, David Y. Zhao, Jane L. E., and James A. Landay. 2017. Drone Near Me: Exploring Touch-Based Human-Drone Interaction. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3, Article 34 (sep 2017), 8 pages. doi:10.1145/3130899

[6] Angus Addlesee, Neeraj Cherakara, Nivan Nelson, Daniel Hernández García, Nancie Gunson, Weronika Sieińska, Marta Romeo, Christian Dondrup, and

Oliver Lemon. 2024. A Multi-party Conversational Social Robot Using LLMs. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. Association for Computing Machinery, New York, NY, USA, 1273–1275. doi:10.1145/3610978.3641112
[7] Victor Nikhil Antony, Sue Min Cho, and Chien-Ming Huang. 2023. Co-designing with older adults, for older adults: robots to promote physical activity. In *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*. 506–515.
[8] Cristiana Antunes, Isabel Neto, Filipa Correia, Ana Paiva, and Hugo Nicolau. 2022. Inclusive'r'stories: An inclusive storytelling activity with an emotional robot. In *2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 90–100.
[9] Jonas Auda, Nils Verheyen, Sven Mayer, and Stefan Schneegass. 2021. Flyables: Haptic Input Devices for Virtual Reality using Quadcopters. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology* (Osaka, Japan) *(VRST '21)*. Association for Computing Machinery, New York, NY, USA, Article 40, 11 pages. doi:10.1145/3489849.3489855
[10] Franziska Babel, Robin Welsch, Linda Miller, Philipp Hock, Sam Thellman, and Tom Ziemke. 2024. A Robot Jumping the Queue: Expectations About Politeness and Power During Conflicts in Everyday Human-Robot Encounters. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–13.
[11] Dave Barnes, Phil Summers, and Andy Shaw. 2000. An Investigation Into Aerobot Technologies For Planetary Exploration. (11 2000).
[12] Christoph Bartneck, Dana Kulić, Elizabeth A. Croft, and Susana Zoghbi. 2009. Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. *International Journal of Social Robotics* 1 (2009), 71–81. https://api.semanticscholar.org/CorpusID:17967380
[13] Mehmet Aydin Baytas, Damla Çay, Yuchong Zhang, Mohammad Obaid, Asim Evren Yantaç, and Morten Fjeld. 2019. The design of social drones: A review of studies on autonomous flyers in inhabited environments. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13.
[14] Jed Berk and Nikhil Mitter. 2006. Autonomous light air vessels (ALAVs). In *Proceedings of the 14th ACM international conference on Multimedia*. 1029–1030.
[15] Alisha Bevins and Brittany A. Duncan. 2021. Aerial Flight Paths for Communication: How Participants Perceive and Intend to Respond to Drone Movements. In *Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '21)*. Association for Computing Machinery, New York, NY, USA, 16–23. doi:10.1145/3434073.3444645
[16] Alisha Bevins, Siya Kunde, and Brittany A Duncan. 2024. User-designed human-UAV interaction in a social indoor environment. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 23–31.
[17] Julien Blanchet and Sixuan Han. 2023. Integrating a LLM into an Automatic Dance Practice Support System: Breathing Life Into The Virtual Coach. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 1–2.
[18] Andrea Bonarini. 2020. Communication in Human-Robot Interaction. *Current Robotics Reports* 1 (12 2020). doi:10.1007/s43154-020-00026-1
[19] D Ray Booker and Lynn W Cooper. 1965. Superpressure balloons for weather research. *Journal of Applied Meteorology and Climatology* 4, 1 (1965), 122–129.
[20] Anya Bouzida, Alyssa Kubota, Dagoberto Cruz-Sandoval, Elizabeth W Twamley, and Laurel D Riek. 2024. CARMEN: A Cognitively Assistive Robot for Personalized Neurorehabilitation at Home. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 55–64.
[21] Robin Bretin, Emily S. Cross, and Mohamed Khamis. 2022. Co-existing With a Drone: Using Virtual Reality to Investigate the Effect of the Drone's Height and Cover Story on Proxemic Behaviours. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 377, 9 pages. doi:10.1145/3491101.3519750
[22] Elizabeth Cha, Anca Dragan, Jodi Forlizzi, and Siddhartha Srinivasa. 2014. Effects of speech on perceived capability. In *Proceedings of the 2014 ACM/IEEE international conference on Human-robot interaction*. 134–135.
[23] Victoria Chang, Pramod Chundury, and Marshini Chetty. 2017. Spiders in the Sky: User Perceptions of Drones, Privacy, and Security. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6765–6776. doi:10.1145/3025453.3025632
[24] Weihao Chen, Chun Yu, Huadong Wang, Zheng Wang, Lichen Yang, Yukun Wang, Weinan Shi, and Yuanchun Shi. 2023. From Gap to Synergy: Enhancing Contextual Understanding through Human-Machine Collaboration in Personalized Systems. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 1–15.
[25] Dasom Choi, Sunok Lee, Sung-In Kim, Kyungah Lee, Hee Jeong Yoo, Sangsu Lee, and Hwajung Hong. 2024. Unlock Life with a Chat (GPT): Integrating Conversational AI with Large Language Models into Everyday Lives of Autistic Individuals. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–17.
[26] Kheireddine Choutri, Mohand Lagha, Souham Meshoul, Mohamed Batouche, Yasmine Kacel, and Nihad Mebarkia. 2022. A Multi-Lingual Speech Recognition-Based Framework to Human-Drone Interaction. *Electronics* 11, 12 (2022). doi:10.3390/electronics11121829
[27] Ashley Colley, Lasse Virtanen, Pascal Knierim, and Jonna Häkkilä. 2017. Investigating drone motion as pedestrian guidance. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia* (Stuttgart, Germany) *(MUM '17)*. Association for Computing Machinery, New York, NY, USA, 143–150. doi:10.1145/3152832.3152837
[28] Sawyer Collins, Kenna Baugus Henkel, Zachary Henkel, Casey C Bennett, Cedomir Stanojevic, Jennifer A Piatt, Cindy L Bethel, and Selma Sabanović. 2024. " An Emotional Support Animal, Without the Animal": Design Guidelines for a Social Robot to Address Symptoms of Depression. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 147–156.
[29] Nikos Dimitropoulos, Pantelis Papalexis, George Michalos, and Sotiris Makris. 2024. Advancing Human-Robot Interaction Using AI – A Large Language Model (LLM) Approach. In *Advances in Artificial Intelligence in Manufacturing*, Achim Wagner, Kosmas Alexopoulos, and Sotiris Makris (Eds.). Springer Nature Switzerland, Cham, 116–125.
[30] JB Display. 2024. The Micro-Projector by JB Display. https://www.jb-display.com/product/2.html
[31] Kaixu Dong, Zhiyuan Zhang, Xiaoyu Chang, Pakpong Chirarattananon, and RAY LC. 2024. Dances with Drones: Spatial Matching and Perceived Agency in Improvised Movements with Drone and Human Partners. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–16.
[32] Boston Dynamics. 2024. The Agile Mobile Robot. https://bostondynamics.com/products/spot/
[33] Satu Elo and Helvi Kyngäs. 2008. The qualitative content analysis process. *Journal of advanced nursing* 62, 1 (2008), 107–115.
[34] Sara Eriksson, Kristina Höök, Richard Shusterman, Dag Svanes, Carl Unander-Scharin, and Åsa Unander-Scharin. 2020. Ethics in movement: Shaping and being shaped in human-drone interaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.
[35] Erfan Etesami, Alireza Nemati, Ali F. Meghdari, Shuzhi Sam Ge, and Alireza Taheri. 2021. Design and Fabrication of a Floating Social Robot: CeB the Social Blimp. In *Social Robotics: 13th International Conference, ICSR 2021, Singapore, Singapore, November 10–13, 2021, Proceedings* (Singapore, Singapore). Springer-Verlag, Berlin, Heidelberg, 660–670. doi:10.1007/978-3-030-90525-5_58
[36] Festo. 2014. eMotionSpheres - Collision-free motion of autonomous systems in a space. https://www.festo.com/PDF_Flip/corp/Festo_eMotionSpheres/en/
[37] Festo. 2016. FreeMotionHandling - Autonomous flying gripping sphere. https://www.festo.com/PDF_Flip/corp/Festo_FreeMotionHandling/en/
[38] Paul Fletcher, Angeline Luther, Carrick Detweiler, and Brittany Duncan. 2022. Predicting Visual Differentiability for Unmanned Aerial Vehicle Gestures. *IEEE Robotics and Automation Letters* 7, 4 (2022), 11799–11806.
[39] Yusuke Fujioka, Yuyi Liu, and Takayuki Kanda. 2024. I Need to Pass Through! Understandable Robot Behavior for Passing Interaction in Narrow Environment. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 213–221.
[40] Pascale Fung, Dario Bertero, Yan Wan, Anik Dey, Ricky Ho Yin Chan, Farhad Bin Siddique, Yang Yang, Chien-Sheng Wu, and Ruixi Lin. 2018. Towards Empathetic Human-Robot Interactions. In *Computational Linguistics and Intelligent Text Processing*, Alexander Gelbukh (Ed.). Springer International Publishing, Cham, 173–193.
[41] Mafalda Gamboa, Mehmet Aydın Baytaş, Sjoerd Hendriks, and Sara Ljungblad. 2023. Wisp: Drones as Companions for Breathing. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 9, 16 pages. doi:10.1145/3569009.3572740
[42] Marina González-Álvarez, Julien Dupeyroux, Federico Corradi, and Guido CHE De Croon. 2022. Evolved neuromorphic radar-based altitude controller for an autonomous open-source blimp. In *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, 85–90.
[43] Guoying Gu, Jiang Zou, Ruike Zhao, Xuanhe Zhao, and Xiangyang Zhu. 2018. Soft wall-climbing robots. *Science Robotics* 3, 25 (2018), eaat2874.
[44] Yijie Guo, Zhenhan Huang, Ruhan Wang, Chih-Heng Li, Ruoyu Wu, Qirui Sun, Zhihao Yao, Haipeng Mi, and Yu Peng. 2023. Sparkybot:An Embodied AI Agent-Powered Robot with Customizable Characters andInteraction Behavior for Children. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 90, 3 pages. doi:10.1145/3586182.3615804
[45] Omer Gvirsman and Goren Gordon. 2024. Effect of Social Robot's Role and Behavior on Parent-Toddler Interaction. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 222–230.

[46] Xiaoxuan Hei, Chuang Yu, Heng Zhang, and Adriana Tapus. 2024. A Bilingual Social Robot with Sign Language and Natural Language. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 526–529.

[47] Viviane Herdel, Anastasia Kuzminykh, Andrea Hildebrandt, and Jessica R. Cauchard. 2021. Drone in Love: Emotional Perception of Facial Expressions on Flying Robots. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 716, 20 pages. doi:10.1145/3411764.3445495

[48] Viviane Herdel, Lee J. Yamin, and Jessica R. Cauchard. 2022. Above and Beyond: A Scoping Review of Domains and Applications for Human-Drone Interaction. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 463, 22 pages. doi:10.1145/3491102.3501881

[49] Zichao Hu, Francesca Lucchetti, Claire Schlesinger, Yash Saxena, Anders Freeman, Sadanand Modak, Arjun Guha, and Joydeep Biswas. 2024. Deploying and Evaluating LLMs to Program Service Mobile Robots. *IEEE Robotics and Automation Letters* 9, 3 (2024), 2853–2860. doi:10.1109/LRA.2024.3360020

[50] Hochul Hwang, Hee-Tae Jung, Nicholas A Giudice, Joydeep Biswas, Sunghoon Ivan Lee, and Donghyun Kim. 2024. Towards Robotic Companions: Understanding Handler-Guide Dog Interactions for Informed Guide Dog Robot Design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–20.

[51] Toma Itagaki and Richard Li. 2023. Smart-Pikachu: Extending Interactivity of Stuffed Animals with Large Language Models. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. 1–2.

[52] Razan Jaber, Sabrina Zhong, Sanna Kuoppamäki, Aida Hosseini, Iona Gessinger, Duncan P Brumby, Benjamin R. Cowan, and Donald Mcmillan. 2024. Cooking With Agents: Designing Context-aware Voice Interaction. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 551, 13 pages. doi:10.1145/3613904.3642183

[53] Michiel Joosse, Manja Lohse, Niels van Berkel, Aziez Sardar, and Vanessa Evers. 2021. Making Appearances: How Robots Should Approach People. *J. Hum.-Robot Interact.* 10, 1, Article 7 (feb 2021), 24 pages. doi:10.1145/3385121

[54] Dahyun Kang, Haeri Hwang, and Sonya S Kwak. 2024. Collabot: A Robotic System That Assists Library Users Through Collaboration Between Robots. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 352–360.

[55] Kari Daniel Karjalainen, Anna Elisabeth Sofia Romell, Photchara Ratsamee, Asim Evren Yantac, Morten Fjeld, and Mohammad Obaid. 2017. Social Drone Companion for the Home Environment: a User-Centric Exploration. In *Proceedings of the 5th International Conference on Human Agent Interaction* (Bielefeld, Germany) *(HAI '17)*. Association for Computing Machinery, New York, NY, USA, 89–96. doi:10.1145/3125739.3125774

[56] Amy Koike, Michael Wehner, and Bilge Mutlu. 2024. Sprout: Designing expressivity for robots using fiber-embedded actuator. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 403–412.

[57] Andreas Kräuchi, Rolf Philipona, Gonzague Romanens, Dale F Hurst, Emrys G Hall, and Allen F Jordan. 2016. Controlled weather balloon ascents and descents for atmospheric research and climate monitoring. *Atmospheric measurement techniques* 9, 3 (2016), 929–938.

[58] Stacey Kuznetsov, George Noel Davis, Eric Paulos, Mark D Gross, and Jian Chiu Cheung. 2011. Red balloon, green balloon, sensors in the sky. In *Proceedings of the 13th international conference on Ubiquitous computing*. 237–246.

[59] Joseph La Delfa, Mehmet Aydin Baytas, Rakesh Patibanda, Hazel Ngari, Rohit Ashok Khot, and Florian 'Floyd' Mueller. 2020. Drone Chi: Somaesthetic Human-Drone Interaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376786

[60] Tin Lun Lam and Yangsheng Xu. 2011. A flexible tree climbing robot: Treebot-design and implementation. In *2011 IEEE International Conference on Robotics and Automation*. IEEE, 5849–5854.

[61] JongYoon Lim, Inkyu Sa, Bruce A MacDonald, and Ho Seok Ahn. 2024. Enhancing Human-Robot Interaction: Integrating ASL Recognition and LLM-Driven Co-Speech Gestures in Pepper Robot with a Compact Neural Network. In *2024 21st International Conference on Ubiquitous Robots (UR)* (New York, NY, USA). IEEE, 663–668. doi:10.1109/UR61395.2024.10597463

[62] Maria R Lima. 2024. Home Integration of Conversational Robots to Enhance Ageing and Dementia Care. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 115–117.

[63] Haokun Liu, Yaonan Zhu, Kenji Kato, Atsushi Tsukahara, Izumi Kondo, Tadayoshi Aoyama, and Yasuhisa Hasegawa. 2024. Enhancing the LLM-Based Robot Manipulation Through Human-Robot Collaboration. *IEEE Robotics and Automation Letters* 9, 8 (2024), 6904–6911. doi:10.1109/LRA.2024.3415931

[64] Yiming Luo, Shihao Liu, Di Wu, Hao Wang, and Yushan Pan. 2024. " Please Be Nice": Robot Responses to User Bullying-Measuring Performance Across Aggression Levels. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–15.

[65] Marcus Mast, Michael Burmester, Eva Berner, David Facal, Lucia Pigini, and Lorenzo Blasi. 2010. Semi-autonomous teleoperated learning in-home service robots for elderly care: A qualitative study on needs and perceptions of elderly people, family caregivers, and professional caregivers. In *20th International Conference on Robotics and Mechatronics, Varna, Bulgaria, October 1-6*.

[66] P Mayring. 2000. Qualitative Content Anlysis [28 paragraphs]. Forum Qualitative Sozialforshung. In *Forum: Qualitative Social Research [On-line Journal]*, Vol. 1.

[67] Oli Mival, Steward Cringean, and David Benyon. 2004. Personification technologies: Developing artificial companions for older people. *CHI Fringe, Austria* (2004).

[68] Hiroya Nagata, Stefan Walke, Soichiro Yokoyama, Tomohisa Yamashita, Hiroyuki Iizuka, Masahito Yamamoto, Keiji Suzuki, and Hidenori Kawamura. 2018. Development of entertainment balloon robot system for an indoor event venue. *Artif. Life Robot.* 23, 2 (jun 2018), 192–199. doi:10.1007/s10015-017-0419-5

[69] Kerry T. Nock, Jack A. Jones, and Guillermo Rodriguez. 1996. Planetary Aerobots: A Program for Robotic Balloon Exploration. doi:2014/23827

[70] Diana Nowacka, Nils Y. Hammerla, Chris Elsden, Thomas Plötz, and David Kirk. 2015. Diri - the actuated helium balloon: a study of autonomous behaviour in interfaces. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Osaka, Japan) *(UbiComp '15)*. Association for Computing Machinery, New York, NY, USA, 349–360. doi:10.1145/2750858.2805825

[71] Mohammad Obaid, Wafa Johal, and Omar Mubin. 2020. Domestic Drones: Context of Use in Research Literature. In *Proceedings of the 8th International Conference on Human-Agent Interaction* (Virtual Event, USA) *(HAI '20)*. Association for Computing Machinery, New York, NY, USA, 196–203. doi:10.1145/3406499.3415076

[72] José Ramón Padilla-López, Alexandros Andre Chaaraoui, and Francisco Flórez-Revuelta. 2015. Visual privacy protection methods: A survey. *Expert Systems with Applications* 42, 9 (2015), 4177–4195.

[73] Akhil Padmanabha, Janavi Gupta, Chen Chen, Jehan Yang, Vy Nguyen, Douglas J Weber, Carmel Majidi, and Zackory Erickson. 2024. Independence in the Home: A Wearable Interface for a Person with Quadriplegia to Teleoperate a Mobile Manipulator. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 542–551.

[74] Daniele Palossi, Andres Gomez, Stefan Draskovic, Andrea Marongiu, Lothar Thiele, and Luca Benini. 2019. Extending the lifetime of nano-blimps via dynamic motor control. *Journal of Signal Processing Systems* 91 (2019), 339–361.

[75] Sung Park and Mincheol Whang. 2022. Empathy in Human–Robot Interaction: Designing for Social Robots. *International Journal of Environmental Research and Public Health* 19, 3 (2022). doi:10.3390/ijerph19031889

[76] Eric Paulos and John Canny. 1998. PRoP: personal roving presence. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Los Angeles, California, USA) *(CHI '98)*. ACM Press/Addison-Wesley Publishing Co., USA, 296–303. doi:10.1145/274644.274686

[77] Catherine Pope, Sue Ziebland, and Nicholas Mays. 2000. Analysing qualitative data. *Bmj* 320, 7227 (2000), 114–116.

[78] HA Shakhawat Hossen Prayash, Md Ragib Shaharear, Md Farhanul Islam, Saiful Islam, Noushad Hossain, and Shamik Datta. 2019. Designing and optimization of an autonomous vacuum floor cleaning robot. In *2019 IEEE International Conference on Robotics, Automation, Artificial-intelligence and Internet-of-Things (RAAICON)*. IEEE, 25–30.

[79] Jingtao Qu, Mateusz Jarosz, and Bartlomiej Sniezynski. 2024. Robot Control Platform for Multimodal Interactions with Humans Based on ChatGPT. *Applied Sciences* 14, 17 (2024). doi:10.3390/app14178011

[80] Shane P Saunderson and Goldie Nejat. 2021. Persuasive robots should avoid authority: The effects of formal and real authority on persuasion in human-robot interaction. *Science robotics* 6, 58 (2021), eabd5186.

[81] Inna Sharf, M. S. Persson, David St-Onge, and Nicolas Reeves. 2013. *Development of Aerobots for Satellite Emulation, Architecture and Art.* Springer International Publishing, Heidelberg, 167–181. doi:10.1007/978-3-319-00065-7_13

[82] Suryansh Sharma, Ashutosh Simha, Venkatesha Prasad, Shubham Deshmukh, Kavin Balaji Saravanan, Ravi Ramesh, and Luca Mottola. 2023. *BEAVIS: Balloon Enabled Aerial Vehicle for IoT and Sensing*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3570361.3592498

[83] Suryansh Sharma, Mike Verhoeff, Floor Joosen, RR. Venkatesha Prasad, and Salua Hamaza. 2024. A Morphing Quadrotor-Blimp With Balloon Failure Resilience for Mobile Ecological Sensing. *IEEE Robotics and Automation Letters* 9, 7 (2024), 6408–6415. doi:10.1109/LRA.2024.3406061

[84] Hiroki Shido, Hiroko Nishi, and Hiroyuki Ishii. 2023. Proposal of a New Performance Partner: 'Soft Flying Robot'. In *2023 32nd IEEE International Conference on Robot and Human Interactive Communication, RO-MAN 2023 (IEEE International Workshop on Robot and Human Communication, RO-MAN)*. IEEE Computer Society, 153–158. doi:10.1109/RO-MAN57019.2023.10309393 Publisher Copyright: © 2023 IEEE.; 32nd IEEE International Conference on Robot and Human Interactive Communication, RO-MAN 2023 ; Conference date: 28-08-2023 Through 31-08-2023.

[85] Sonja Stange and Stefan Kopp. 2020. Effects of a social robot's self-explanations on how humans understand and evaluate its behavior. In *Proceedings of the 2020 ACM/IEEE international conference on human-robot interaction*. 619–627.

[86] Sophia C Steinhaeusser, Ramona Piller, and Birgit Lugrin. 2024. Combining Emotional Gestures, Sound Effects, and Background Music for Robotic Storytelling-Effects on Storytelling Experience, Emotion Induction, and Robot Perception. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 687–696.

[87] Dag Sverre Syrdal, Kerstin Dautenhahn, Kheng Koay, and Michael Walters. 2009. The Negative Attitudes towards Robots Scale and Reactions to Robot Behaviour in a Live Human-Robot Interaction Study.

[88] Qiuyang Tao, Tun Jian Tan, Jaeseok Cha, Ye Yuan, and Fumin Zhang. 2021. Modeling and control of swing oscillation of underactuated indoor miniature autonomous blimps. *Unmanned Systems* 9, 01 (2021), 73–86.

[89] Hiroaki Tobita, Shigeaki Maruyama, and Takuya Kuzi. 2011. Floating avatar: telepresence system using blimps for communication and entertainment. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI EA '11)*. Association for Computing Machinery, New York, NY, USA, 541–550. doi:10.1145/1979742.1979625

[90] Tim Treurniet, Lang Bai, Simon À Campo, Xintong Wang, Jun Hu, and Emilia Barakova. 2019. Drones with eyes: expressive Human-Drone Interaction. In *1st International Workshop on Human-Drone Interaction*. Ecole Nationale de l'Aviation Civile [ENAC], Glasgow, United Kingdom. https://hal.science/hal-02128380

[91] Gabriele Trovato, Renato Paredes, Javier Balvin, Francisco Cuellar, Nicolai Bæk Thomsen, Soren Bech, and Zheng–Hua Tan. 2018. The Sound or Silence: Investigating the Influence of Robot Noise on Proxemics. In *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. 713–718. doi:10.1109/ROMAN.2018.8525795

[92] Unitree. 2024. A Robot Dog with Excellent Sportiness. https://www.unitree.com/cn/aliengo

[93] Eva Verhelst, Ruben Janssens, Thomas Demeester, and Tony Belpaeme. 2024. Adaptive Second Language Tutoring Using Generative AI and a Social Robot. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. Association for Computing Machinery, New York, NY, USA, 1080–1084. doi:10.1145/3610978.3640559

[94] Mudit Verma, Siddhant Bhambri, and Subbarao Kambhampati. 2024. Theory of Mind Abilities of Large Language Models in Human-Robot Interaction: An Illusion?. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 36–45.

[95] Chenghao Wang, Changdan Cao, Xiangyu Sun, Yunqi Jiang, and Tianhao Liu. 2024. An Advanced Desktop Humanoid Robot for Emotional Support with Flexible Motion and Artificial Intelligence. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. Association for Computing Machinery, New York, NY, USA, 1095–1099. doi:10.1145/3610978.3640564

[96] Chongyang Wang, Yuan Feng, Lingxiao Zhong, Siyi Zhu, Chi Zhang, Siqi Zheng, Chen Liang, Yuntao Wang, Chengqi He, Chun Yu, et al. 2024. UbiPhysio: Support Daily Functioning, Fitness, and Rehabilitation with Action Understanding and Feedback in Natural Language. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 8, 1 (2024), 1–27.

[97] Chongyang Wang, Siqi Zheng, Lingxiao Zhong, Chun Yu, Chen Liang, Yuntao Wang, Yuan Gao, Tin Lun Lam, and Yuanchun Shi. 2024. PepperPose: Full-Body Pose Estimation with a Companion Robot. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 586, 16 pages. doi:10.1145/3613904.3642231

[98] Zining Wang, Paul Reisert, Eric Nichols, and Randy Gomez. 2024. Ain't Misbehavin' - Using LLMs to Generate Expressive Robot Behavior in Conversations with the Tabletop Robot Haru. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. Association for Computing Machinery, New York, NY, USA, 1105–1109. doi:10.1145/3610978.3640562

[99] Ziming Wang, Yiqian Wu, Shiwei Yang, Xiaowei Chen, Björn Rohles, and Morten Fjeld. 2024. Exploring Intended Functions of Indoor Flying Robots Interacting With Humans in Proximity. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 264, 16 pages. doi:10.1145/3613904.3642791

[100] Keigo Watanabe, Naoto Okamura, and Isakau Nagai. 2015. Closed-loop control experiments for a blimp robot consisting of four-divided envelopes. In *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 002568–002573.

[101] Randi Williams, Safinah Ali, Raúl Alcantara, Tasneem Burghleh, Sharifa Alghowinem, and Cynthia Breazeal. 2024. Doodlebot: An Educational Robot for Creativity and AI Literacy. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction*. 772–780.

[102] Nialah Jenae Wilson-Small, David Goedicke, Kirstin Petersen, and Shiri Azenkot. 2023. A Drone Teacher: Designing Physical Human-Drone Interactions for Movement Instruction. In *Proceedings of the 2023 ACM/IEEE International Conference on Human-Robot Interaction*. 311–320.

[103] Wenke Xia, Dong Wang, Xincheng Pang, Zhigang Wang, Bin Zhao, Di Hu, and Xuelong Li. 2024. Kinematic-aware Prompting for Generalizable Articulated Object Manipulation with LLMs. In *2024 IEEE International Conference on Robotics and Automation (ICRA)*. 2073–2080. doi:10.1109/ICRA57147.2024.10610744

[104] Wataru Yamada, Hiroyuki Manabe, and Daizo Ikeda. 2019. ZeRONE: Safety Drone with Blade-Free Propulsion. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–8. doi:10.1145/3290605.3300595

[105] Yasuyuki Yamada and Taro Nakamura. 2018. GerWalk: Lightweight Mobile Robot with Buoyant Balloon Body and Bamboo Rimless Wheel. In *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, Kuala Lumpur, Malaysia, 1814–1821. doi:10.1109/ROBIO.2018.8664749

[106] Haibin Yan, Marcelo Jr, and Aun-Neow Poo. 2014. A Survey on Perception Methods for Human–Robot Interaction in Social Robots. *International Journal of Social Robotics* 6 (01 2014). doi:10.1007/s12369-013-0199-6

[107] Oncay Yasa, Yasunori Toshimitsu, Mike Y Michelis, Lewis S Jones, Miriam Filippi, Thomas Buchner, and Robert K Katzschmann. 2023. An overview of soft robotics. *Annual Review of Control, Robotics, and Autonomous Systems* 6, 1 (2023), 1–29.

[108] Alexander Yeh, Photchara Ratsamee, Kiyoshi Kiyokawa, Yuki Uranishi, Tomohiro Mashita, Haruo Takemura, Morten Fjeld, and Mohammad Obaid. 2017. Exploring Proxemics for Human-Drone Interaction. In *Proceedings of the 5th International Conference on Human Agent Interaction* (Bielefeld, Germany) *(HAI '17)*. Association for Computing Machinery, New York, NY, USA, 81–88. doi:10.1145/3125739.3125773

[109] Hideki Yoshimoto, Kazuhiro Jo, and Koichi Hori. 2009. Designing interactive blimps as puppets. In *Entertainment Computing–ICEC 2009: 8th International Conference, Paris, France, September 3-5, 2009. Proceedings 8*. Springer, 204–209.

[110] Qitao Zhao, Ce Zheng, Mengyuan Liu, Pichao Wang, and Chen Chen. 2023. Poseformerv2: Exploring frequency domain for efficient and robust 3d human pose estimation. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*. 8877–8886.

[111] Xinyu Zhu, Xingguo Zhang, Zinan Chen, Zhanxun Dong, Zhenyu Gu, and Danni Chang. 2022. The Trusted Listener: The Influence of Anthropomorphic Eye Design of Social Robots on User's Perception of Trustworthiness. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 571, 13 pages. doi:10.1145/3491102.3517670

[112] Weiqin Zu, Wenbin Song, Ruiqing Chen, Ze Guo, Fanglei Sun, Zheng Tian, Wei Pan, and Jun Wang. 2024. Language and Sketching: An LLM-driven Interactive Multimodal Multitask Robot Navigation Framework. In *2024 IEEE International Conference on Robotics and Automation (ICRA)*. 1019–1025. doi:10.1109/ICRA57147.2024.10611462

A The Web Interface

As demonstrated in Figure 10, we built a web interface to enable a natural control of the robot as part of our Wizard-of-Oz experiment, which contains all the essential APIs that LLM-enabled agents could leverage in the future. Two control boards operating as servers continuously listen for commands sent from the computer client. The servers are designed to handle real-time commands by establishing a connection through the IP address and interpreting the data sent from the client to control the movement of BalloonBot. Firstly, we offered toggles to open or close the camera and microphone manually, as needed. Then, we utilized the keyboard for directional control, incorporating several operation methods. To better align with the user's natural operation, we implemented a long press for acceleration and release to stop. For the ascent operation, we utilized two buttons to discretely control acceleration and deceleration, allowing for more precise control of thrust requirements. We also reserved one button for braking. Moreover, the user can send speech either by typing or speaking directly. Additionally, the interface offers real-time feedback on the robot's status, including velocity and battery level, and provides a real-time first-person view and sounds, ensuring smooth interaction between the user and the system.

B Questionnaire and Interview Questions

The questionnaire is designed to assess key factors that influence participants' perceptions and expectations toward BalloonBot, including familiarity with robots, attitudes toward robots, perceptions of interaction, and expectations of its functions. Each section contains specific questions measured on a 5-point Likert scale, allowing participants to rate their experiences and opinions, ranging from strongly disagreed to strongly agreed. After completing the questionnaire, we asked interview questions to gain deeper insight into their ratings. Follow-up questions were added when necessary to have their further thoughts and open comments on what they found important or interesting. For their perceptions of the interaction presented by BalloonBot, i.e., the third section in Table 4, the interview questions include:

- **Safety, Empathic Alignment, Ease**: i) You found BalloonBot provides you with a sense of {*safety, empathic alignment, ease*}; could you share with us more about this (for the rating > 3)? ii) You did not find BalloonBot provides you with a sense of {*safety, empathic alignment, ease*}; could you tell us more about this (for the rating < 3)? iii) How did you exactly preceive the presented {*safety, empathic alignment, ease*} of BalloonBot? And why (for the rating = 3)?
- **Noise** (reversed for analysis): i) You found BalloonBot's operational noise acceptable; could you share with us more about this (for the rating > 3)? ii) You found BalloonBot's operational noise unpleasant; could you tell us more about this (for the rating < 3)? iii) How did you exactly find the operational noise of BalloonBot? And why (for the rating = 3)?
- **Privacy** (reversed for analysis): i) You are not concerned about privacy issues given the presented use of BalloonBot; could you share with us more about this (for the rating > 3)? ii) You are concerned about privacy issues given the presented use of BalloonBot; could you tell us more about this (for the rating < 3)? iii) How did you exactly find the privacy issue given the presented use of BalloonBot? And why (for the rating = 3)?

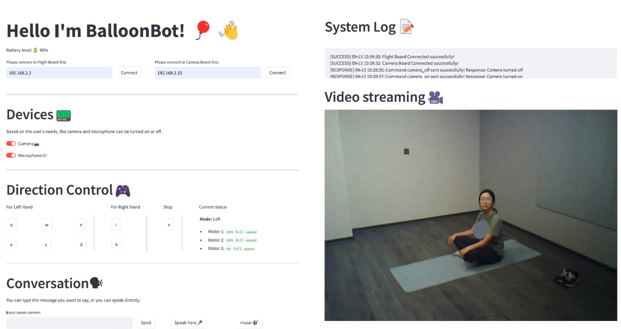

Figure 10: We prepared a web user interface for the wizard's real-time control of all the interactive channels of BalloonBot, e.g., the video and sound captured by the robot are streamed back here.

For their expectations about the functions that could be offered by BalloonBot, following the fourth section in Table 4, the interview questions include the following. Please note that for '*housekeeper*,' we asked slightly different questions for its second *questionnaire question* about the comparison against smart home systems.

- **Fitness Coach, Housekeeper, Emotional Companion, Indoor Navigator**: i) You found the presented use of BalloonBot as {*fitness coach, housekeeper, emotional companion, indoor navigator*} practical; could you share with us more about this (for the rating > 3)? ii) You did not find the presented use of BalloonBot as {*fitness coach, housekeeper, emotional companion, indoor navigator*} practical; could you tell us more about this (for the rating < 3)? iii) How did you exactly find the presented use of BalloonBot as {*fitness coach, housekeeper, emotional companion, indoor navigator*}? And why (for the rating = 3)?
- **Housekeeper**: For the comparison against smart home systems, we asked: i) You found the presented use of BalloonBot as *housekeeper* seemed better than smart home systems; could you share with us more about this (for the rating > 3)? ii) You found the presented use of BalloonBot as *housekeeper* seemed worse than smart home systems; could you tell us more about this (for the rating < 3)? iii) How did you exactly find the presented use of BalloonBot as *housekeeper* in comparison with smart home systems? And why (for the rating = 3)?

Table 3: Table of Participants. The Age Group is Reported instead of Exact Numbers to Protect Participants' Privacy.

ID	Gende	Age	ID	Gende	Age	ID	Gende	Age
P1	Female	50-59	P2	Female	50-59	P3	Male	30-39
P4	Male	30-39	P5	Female	20-29	P6	Male	20-29
P7	Male	50-59	P8	Female	30-39	P9	Male	20-29
P10	Male	50-59	P11	Male	50-59	P12	Female	20-29
P13	Female	30-39	P14	Female	40-49	P15	Male	30-39
P16	Female	50-59	P17	Female	50-59	P18	Male	30-39
P19	Male	20-29	P20	Male	50-59	P21	Male	50-59
P22	Female	30-39	P23	Male	20-29	P24	Male	30-39
P25	Female	20-29	P26	Male	20-29	P27	Female	30-39
P28	Female	50-59	P29	Female	30-39	P30	Male	50-59
P31	Female	50-59	P32	Female	30-39	P33	Female	20-29

Table 4: Questionnaire Questions for Evaluating Participants' Perceptions and Expectations about BalloonBot's Presented Interaction and Functions

Section	Measurement	Questionnaire Questions
Familiarity	`5-likert scale` unknown ⟶ knowledgeable $N \in \{1, 2, 3, 4, 5\}$	1. How familiar are you with using robots and your mastery of their functions?
Attitudes toward Robots	`5-likert scale` disagree ⟶ agree $N \in \{1, 2, 3, 4, 5\}$	1. I don't like robots with an intelligence level that is too high. 2. I can communicate easily with robots (reversed for analysis). 3. Communicating with robots in front of others makes me uncomfortable. 4. I am worried that robots will control society in the future.
Perceptions about the Presented Interaction of BalloonBot	`5-likert scale` disagree ⟶ agree $N \in \{1, 2, 3, 4, 5\}$	1. BalloonBot gives me a sense of safety. 2. BalloonBot produced noise that I found unpleasant. (reversed for analysis) 3. I'm able to understand BalloonBot's nonverbal expressions well, including movement and actions. 4. BalloonBot is able to understand the user's needs, feelings, and emotions. 5. I feel at ease when watching interactions presented by BalloonBot. 6. I'm concerned about my privacy given the use cases of BalloonBot. (reversed for analysis)
Expectations about the Functions of BalloonBot	`5-likert scale` disagree ⟶ agree $N \in \{1, 2, 3, 4, 5\}$	1. I like the idea of working out with BalloonBot. 2. BalloonBot as a fitness coach looks novel, unique, and effective. 3. BalloonBot could help me monitor various situations at home. 4. The ability of BalloonBot could exceed that of existing smart home systems. 5. The idea of using BalloonBot for emotional support is useful. 6. The idea of using BalloonBot for navigation in large indoor spaces is practical.