# Buoyancé:
# Reeling Helium-Inflated Balloons with Mobile Robots on the Ground for Mid-Air Tangible Display, Interaction, and Assembly


Alan Pham*
University of Chicago
Chicago, Illinois, USA
apham799@uchicago.edu

Yuxiao Li*
University of Chicago
Chicago, Illinois, USA
yuxiaoli@uchicago.edu

Miyu Fukuoka
The University of Electro-Communications
Chofu, Tokyo, Japan
University of Chicago
Chicago, Illinois, USA
fukuoka@media.lab.uec.ac.jp

Ken Nakagaki
University of Chicago
Chicago, Illinois, USA
knakagaki@uchicago.edu

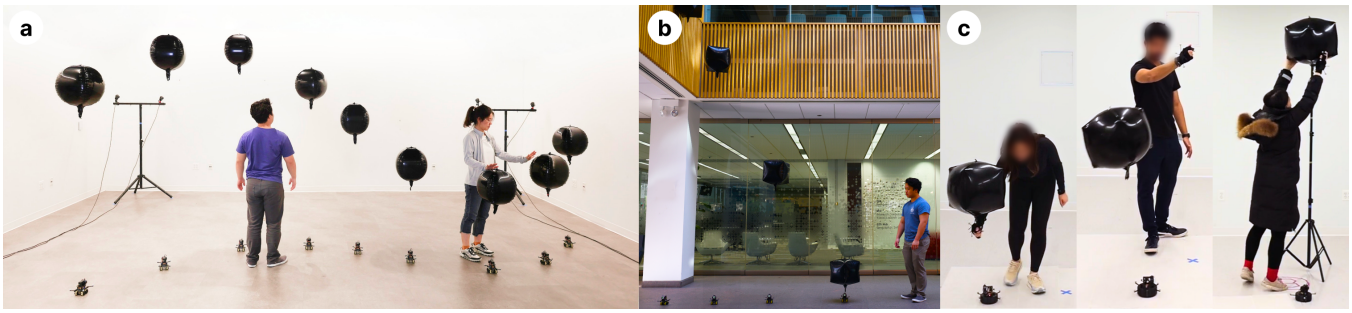




**Figure 1: Buoyancé. The integration of multi-robot systems with reeling helium-inflated balloon mechanisms can enable diverse interactive applications: (a) Information Display, (b) Height Representation, and (c) Tangible and Gesture-based Interactions.**


## Abstract

We introduce a novel approach to spatially actuated tangible UI by controlling helium-inflated balloons (HIBs) in mid-air using mobile reeling robots, named ReelBots. With a relatively compact device form factor, the robots can manipulate HIBs in an extensive vertical range, reaching relatively high altitudes (20m or more), thanks to its reeling mechanisms. The hardware offers diverse interactive functionalities and applications for representing abstract data in 3D space, reconfiguring lights and cameras in an everyday space, and assembling HIBs into diverse configurations. Our proof-of-concept implementation was developed based on omnidirectional mobile robots and a motion tracking system to demonstrate the novel approach of enriching 3D physical space. Our control software is designed to manipulate multiple robots to control the position of HIBs in real time via multiple options ranging from GUI control and tangible and gesture based controls.



## CCS Concepts

• **Human-centered computing** → **Interaction devices**.


*The first two authors contributed equally to this research.


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## Keywords

Actuated Tangible User Interface, Spatial User Interface Display, Human-Robot Interaction, Mid-air Assembly, Embodied Interaction

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## 1 Introduction

Helium-inflated balloons or bodies (HIBs) are uniquely familiar, magical, and joyful presences in our everyday lives. They play a special role in elevating human experiences—both literally and figuratively—by uplifting moments of celebration, from birthday parties and amusement park adventures to large-scale gatherings like Comic-Cons. Readily available in grocery stores and party shops, HIBs are accessible tools for adding delight and wonder to shared occasions with friends and family, across generations.

What makes HIBs uniquely enchanting are their core physical phenomenon: the levitating effect of helium, due to its lower density than the surrounding air. This allows balloon bodies to rise gracefully, defying gravity in a safe, affordable, and accessible way. Yet their magic is not only visual or scientific—it's also tactile. Often tied to strings, HIBs offer a delightful interaction: floating just above us, yet anchored, inviting people to grasp, guide, and engage with them. This dual nature—light and tethered, yet tangible and

controlled—gives HIBs a distinctive, embodied affordance unlike any other everyday object, blending whimsy with presence in a way that's uniquely resonant in human life.

The unique physical property of HIB, providing inflatable objects with buoyant forces, has gained attention in the field of robotics to improve the mobility of robotic hardware, such as terrestrial two-legged robots [19, 60], long-bodied robotic arms [55], or quiet & power-efficient drones [59]. The use of HIBs, in this manner, has advanced robots' abilities to attain 3D locomotion while utilizing soft, safe, and cheap materials, which is challenging with traditional 'rigid and heavy' robots.

In this paper, we investigate applying HIBs for Swarm UI [28], an active HCI research area for building tangible displays and interactions using multi-robot systems on tabletop or ground surfaces. By equipping individual robots with HIBs, which are controlled by a reeling-string mechanism, we enable 3D spatial, tangible display and mid-air interaction, while the robots remain on the ground (Figure 1a and 1b).

While diverse approaches have been proposed in prior HCI research for 3D spatial, mid-air, levitating tangible UIs (e.g., drones [4, 20], ceiling rigs [6, 12, 61], HIBs with embedded propulsion [36, 59], or acoustic levitation [14, 15],) our proposed approach, named Buoyancé, opens up unique opportunities for interactivity. Buoyancé's approach features several technical benefits, such as space instrumentation, safety for touch, scalability, or energy efficiency. These benefits allow for novel interactivity with unique affordances, anchored to how we interact with everyday HIBs (e.g., using strings to control).

In our paper, we introduce the generalizable approach of Buoyancé, joining a multi-robot system with HIBs via a comprehensive design space, which overviews the capabilities of Buoyancé, including tangible display, interaction, and assembly. Our proof-of-concept prototype, based on off-the-shelf omnidirectional ground robots and an optical 3D tracking system, allows for closed-loop control of a multi-robot system controlling HIBs mid-air with reeling mechanisms. By tracking markers attached to hands and fingers, we have also developed hand-based gesture and tangible interactions, developing 'grasp and release'-based control methods. In turn, allowing three distinctive ways to control the HIB's position by navigating the robots (named *String Tangible Control, Direct Tangible Control, and Nearby Gesture Control*). The hardware system is tested through the technical evaluations, measured speeds of movement as well as assembly capabilities. With the implemented prototype, we demonstrate wide potential applications for such a system to be deployed in the future of physical environments, spanning across tangible information display, room reconfiguration, and mid-air constructive assembly. Additionally, a user study was conducted to evaluate and compare the three HIB control modalities based on 'grasp and release.' The study also extracted feedbacks regarding the unique perception, affordance and interaction of Buoyancé.

While midair 3D tangible interfaces have been explored in HCI in diverse technical methods, we wish Buoyancé will inspire this research realm by employing the unique property and affordance of HIBs to defy gravity, enriching or 'uplifting' tangible, bodily interaction within physical space and environments.

List of Contributions:

- Overall approach of Buoyancé and its design space presenting the actuation and interaction design through HIBs controlled by multi-robot systems with reeling mechanisms.
- Proof-of-concept implementation based on omnidirectional rover robots and HIBs, along with the software design that allows for a variety of control modes, including three embodied HIB control methods based on 'grasp and release.'
- Technical evaluations of the our proof of concept system.
- A range of potential applications, motivating the proposed approach to be applied for display, interaction, and assembly.
- A user study ($N = 12$), evaluating and comparing three bodily interaction methods for controlling the 3D positions of HIBs.

## 2 Related Work

The concept and design of Buoyancé build upon prior research in Spatial Actuated Tangible UIs, HIB-based Interactive, Robotic Systems, and Mid-Air Assembly.

### 2.1 Spatial Actuated TUIs — Levitation, Multi-Robot and Suspension Systems

Research into building actuated spatial tangible interaction has explored various methods to create dynamic, tangible interactions within a 3D space. For example, researchers have built interfaces that manipulate objects in mid-air through different techniques. One such approach, drones, is widely utilized to achieve spatial display and TUI in HCI [4, 20, 23]. Their ability to hover and maneuver in 3D space makes them ideal for creating interactive experiences where objects can be dynamically positioned and moved. However,42 drones have considerable practical limitations, such as constant loud noise, safety concerns (prohibiting users from comfortably touching and interacting), and high-energy-consuming levitation (resulting in short continuous levitation time). In addition, other approaches employ techniques such as magnetic levitation [27, 29], acoustic levitation [17, 18, 37, 41], or air jet [49, 62]. While these additional methods address some of the issues from the use of drones, none are currently suited to achieve room-scale actuation.

On the other hand, researchers have employed string or wire-based actuation methods to enrich the physical space. For example, ceiling-mounted reeling devices have been used to suspend and control physical objects in mid-air, such as kinetic sculptures [2, 57] and a shape display [9]. As demonstrated in STRAIDE [9], actuation has been explored for information display through actuated rigged elements and for enabling interaction with vertically actuated elements. To enhance the flexibility and control of the reeling mechanisms, AeroRigUI [61] introduced swarm robots to dynamically manage the position of the reeling mechanisms placed on the ceiling surfaces, improving the control of rigged or suspended objects. Building on top of the literature of Swarm UI to manipulate a cluster of wheeled robots [28, 32, 33], their approach allows for 3D control with a single string and can be extended to 6D control using multiple strings.

Buoyancé takes inspiration from these existing methods but introduces a unique approach by combining helium-inflated balloons (HIBs) with on-ground robots equipped with reeling mechanisms.

As prior research has largely investigated spatially actuated tangible UI that often requires extensive infrastructure (including ceiling instrumentation), our implementation offers vertically scalable mid-air spatial interaction through a ground-based setup that is relatively easier to install. This setup removes concerns of hardware falling from above the head while adding whimsical actuation throughout entire rooms.

The use of multi-robot systems to develop spatial tangible interaction is also an active research area in HCI. For example, RoomShift proposed a way to dynamically configure physical space to move around furniture with floor-locomotive robots for VR haptics [50]. InflatableBots was also developed to add haptics for VR, but by a shape-changing inflatable mechanism (< 2m) controlled by wheeled robots on the floor [21]. Onishi et. al's Waddle Walls explored controlling a vertically actuated partition system (< 1.8m), also controlled by robots on the floor [38]. The robots in these works are equipped with relatively large actuators to create human- or room-scale transformations. Therefore, the robots need to be relatively large (Roomba Vacuum robots or equivalent size - at least 300x300mm laterally). In our approach, we use a reeling mechanism (often observed for shape-changing mechanisms in HCI [52–54]), which can be compactly stored; Therefore, the base robot (ReelBot) can also be compact (approximately 90 x 80 x 110mm without marker attachments), YET the maximum height it can reach exceeds significantly beyond the robots in prior work – Figure 1c shows reaching approximately 4m, but we tested it can reach more than 20m as detailed in a later section.

## 2.2 HIB-based Interactive, Robotic Systems

The buoyant force of Helium has provided a means of research into HIBs in numerous fields. In robotics, HIBs have been widely utilized to increase the general mobility, safety, robustness, and overall cost-effectiveness of mechanically built terrestrial robots [5, 19, 35, 55, 56, 60]. Having more versatile robots has increased the applications and scenarios of land-bound robots. For example, with the vast array of shapes HIBs can take on, past studies such as Giacometti Arm utilized skinnier HIBs in conjunction with artificial muscles and constant air feeding tubes to explore narrow pathways that conventional robots could not traverse through [55]. Additionally, Mami Nishida utilized fun and sociable shapes to aid in the social well-being of *"socially vulnerable people"* [35]. Alternatively, while add-ons to the HIBs may limit their ability to levitate, they still enable more robust upright positions and jumping abilities when combined with actuated reel mechanisms [5, 19, 60].

A few works in HCI have explored employing the buoyant properties of HIBs for facilitating novel interaction. DIRI and ZerONE proposed robotic systems that combine HIB and light actuators to build a safe indoor drone system without blades for human interaction and observation [36, 59]. More recently, Xu et al. have studied bodily, tangible interaction and affordance of HIB-based *"flapping-wind floating robots"* through a user study, revealing their unique interactivity and perception, including a highly perceived level of safety [58]. While these self-propelled HIBs tend to be slow for the movement control, with the Midair Balloon Interface, the rubber HIB was used in conjunction with surrounding multiple airborne ultrasound phased arrays (AUPAs) to develop a safe and soft tangible midair interface [14, 15]. Buoyancé instead aims to employ HIB in conjunction with on-ground robots to achieve multi-object levitation while expanding the scalability of the interactive area, and exploring the unique interactive affordance based on the configuration of HIB with a tethered string.

## 2.3 Mid-Air Assembly

Constructive assembly – the functionality to flexibly assemble primitive blocks to target arbitrary shapes – is one of the features we explore with Buoyancé, and it has been widely explored in the HCI domain. For example, DynaBlock [51] and Kinetic Blocks [47] explored approaches to assemble magnet-embedded passive blocks with an actuated base. Robotic assembly, employing tabletop wheeled robots, has been proposed by Zhao et al. for VR haptic proxy [63], as an extension of Zooids [28]. Although our work also employs wheeled robots for assembly, we explore *mid-air assembly*. To achieve mid-air assembly, the use of drones has been one of the major approaches commonly seen in robotics [16, 39, 40, 45]. Acoustic Levitation is another approach to achieve mid-air assembly, to make non-contact assembly of passive materials [10, 13], while scalability is often limited. HIB-based assembly has been explored for large-scale passive self-assembly by MIT's Self-Assembly Lab [26, 42], which doesn't provide controlled (dis)assembly. In contrast, our approach, by using computationally controlled rover robots on the ground to reel HIBs, achieves room-scale mid-air assembly and disassembly, creating shapes that are overall soft and potentially safer to touch and interact with, compared to ones using drones [16, 39, 40, 45].

# 3 Buoyancé

We introduce the design space of Buoyancé (illustrated in Figure 2) that aims to define its generalizable system architecture, interactivity, and application space.

## 3.1 Basic Architecture, Example Configurations, and HIB Control

The basic architecture of Buoyancé consists of (1) helium-inflated balloon (HIB), (2) strings attached to HIB, and (3) robots equipped with a reeling mechanism (referred to as ReelBot in our paper.) For HIBs, diverse sizes and geometries can be employed (Figure 3a). For string, threads with different visibility can be employed as an option depending on the use cases: transparent threads, like fishing line, to prioritize for aesthetics, while more visible strings, like yellow-colored thread, could be employed for users to be better aware of the string for interaction and safety. While the tethering string serves to reel HIB, controlling its vertical position, it can also serve as a medium for users to control the HIBs, following the affordance of everyday HIBs (further elaborated in section 3.2).

The HIBs and ReelBots can be configured in different numbers to achieve different functionalities, especially for HIB control. For example, a single HIB and single ReelBot (1 HIB + 1 ReelBot) can perform basic functionality of moving the HIB in 3-Dimensions (X, Y, and Z), though rotations (roll, pitch, and yaw) cannot be controlled. With 1 HIB and 2 ReelBots, the HIB's pitch and yaw can be controlled. Furthermore, with more than 2 ReelBots, pitch, roll, and yaw can all be controlled by synchronously controlling the reeling

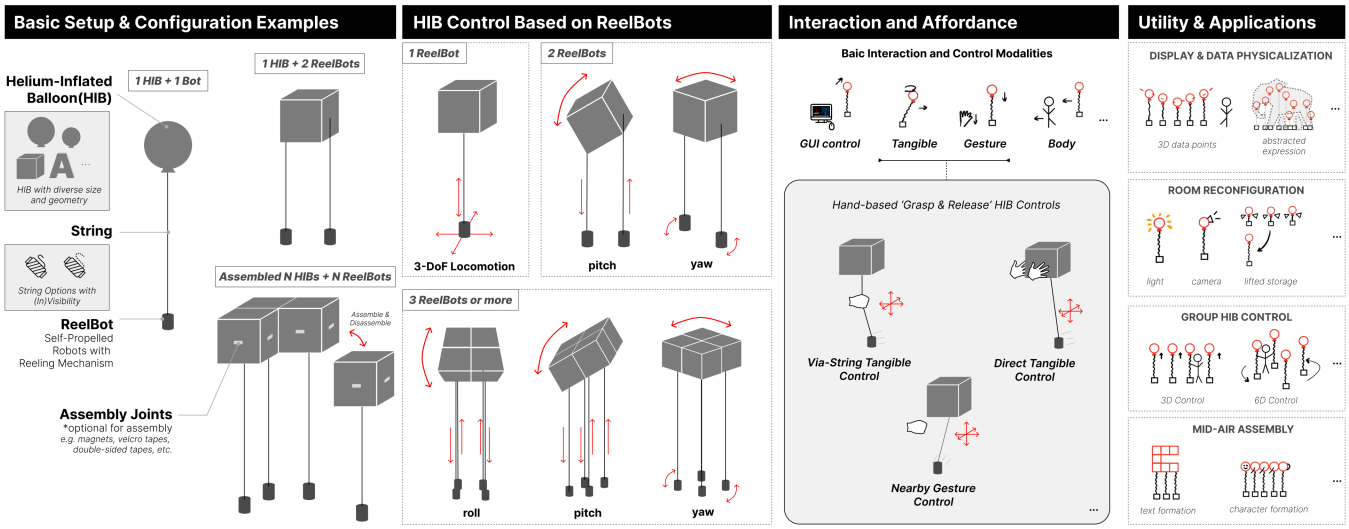



**Figure 2: Design space for the abilities of Buoyancé.**

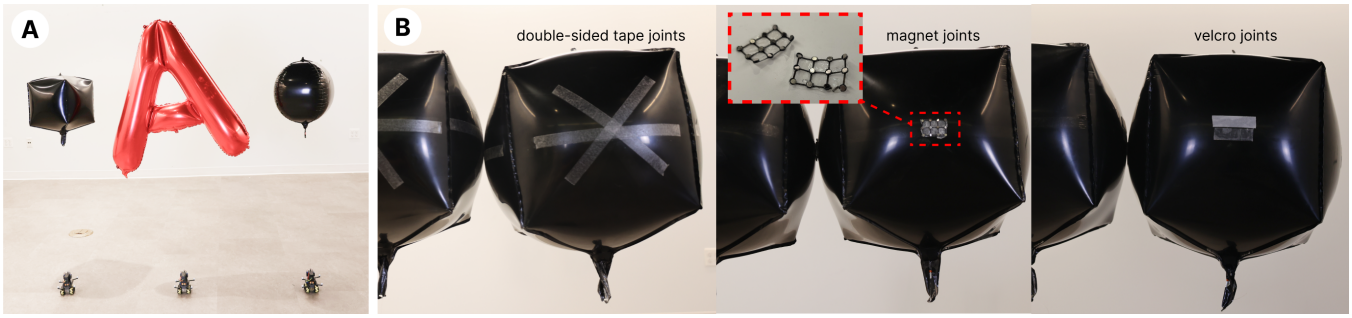



**Figure 3: Examples of (a) different types of HIBs, and (b) attachable accessories.**

mechanism of each ReelBot. Therefore, the HIBs' controllability can be changed dynamically according to the number of HIBs and ReelBots in the assembly.

While we explore a new design space and functionality enabled with HIB control, the basic control relationship of the number of reeling objects and the number of robots is built upon AeroRigUI[61].

## 3.2 Interaction

**Basic Interaction and Control Modalities** There are different ways users could control and interact with the Buoyancé system. This includes *GUI control*, using a 3D visualization tool on a computer, allowing people to control the 3D position using GUIs. For more bodily interaction with the HIBs, *Tangible*, *Gesture*, and *Body* inputs can each provide unique control methods for the users to touch, wave and move their body to control the HIBs, especially by combining with bodily tracking technology (e.g. computer vision).

While there are diverse possibilities for the interactive modalities with Buoyancé, this paper further explores *Hand-based 'Grasp & Release' HIB Controls*, for three distinct ways to use hands' grasping and releasing gestures, similar to how we can 'Drag & Drop' files on desktop GUIs. For example, as illustrated under Interaction and Affordance in Figure 2, *Via-String Tangible Control* (a method anchoring to the affordance of everyday tethered HIB) allows people to control the HIB by grasping the string and moving it in 3D, which results in navigating the robots to adjust the HIB position accordingly, then releasing the string to place the HIB in an arbitrary 3D position. Similarly, *Direct Tangible Control* enables users to grab the HIB with two hands, where robots adaptively move to adjust the HIB position. Lastly, *Nearby Gesture Control* lets users grasp near the HIB, without direct touch, to control the 3D position. While the hand gesture is used for users to explicitly specify the 3D input, users can walk around the space to navigate the HIBs and robots, making it a wholly embodied interactive method.

## 3.3 Utilities and Applications

As of the utility and application space for Buoyancé, **Display and Data Physicalization** is one of the primary utility areas. With the capability of placing multiple objects in mid-air, Buoyancé can display diverse 3D data physically, which is explored as data physicalization in HCI [25]. While representing 3D data using levitating tangible physical objects has been explored in past HCI research

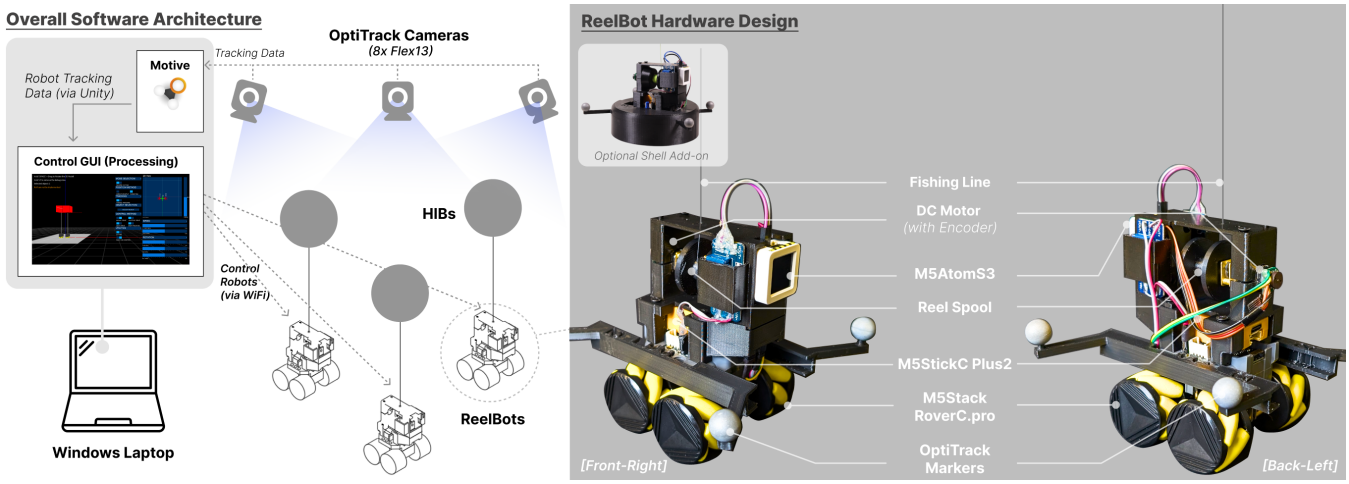



**Figure 4: System Overview of Implementation of Buoyancé.**

[20, 37, 61, 62], Buoyancé's approach features scalability with lateral and vertical directions for the information to be presented. Quiet and energy-efficient levitation are other advantages that may suit, for example, a 3D display for public usage, such as a public advertisement.

As robots are emerging in our everyday environments (e.g. vacuum robots, pet robots), **Room Reconfiguration** is another application area, we consider that Buoyancé can be extended to. As floor-locomoting robots are pervasive, our approach to extend them with reeling HIBs easily enables them to fully cover 3D space in everyday rooms, either for *lighting*, or monitoring with *a camera*.

By extending the hand-based HIB control capability, Buoyancé can be used for **Group HIB Control**, allowing users to move multiple HIBs together (Figure 9). This could be combined with display or data physicalization applications, but allowing users to move and control a group of HIB flexibly freely, either in 3D (x,y,z) or 6D (3D + roll, pitch, and yaw).

**Mid-Air Assembly** is a utility that expands many application areas, as it can enrich displaying information via assembled objects (e.g. representing texts or animated characters), or, can potentially function as robotic mechanisms to handle specifically shaped objects. By dynamically assembling and disassembling, shapes that could not be represented with a single balloon can now be dynamically configured.

# 4 Implementation

This section introduces the implementation of Buoyancé's proof-of-concept system. To facilitate future research and development, we have made both the software and hardware designs of Buoyancé publicly available. [1]

## 4.1 Overall System Setup

The overall system consists of ReelBots, HIBs, an optical tracking system (OptiTrack), and a computer to control the system (Figure 4). ReelBots are wirelessly controlled by a Processing-based graphical user interface (GUI) software via WiFi for visualizing and controlling the lateral movement of each robot and the vertical position of the HIBs.

To build closed-loop control for the robots, we incorporated the OptiTrack motion capture system (8 x Flex 13 cameras). OptiTrack's Motive software interfaces with Unity via the Open Sound Control (OSC) protocol which further processes the data and relays it back to the Processing GUI. With this overall set-up, the GUI centralizes control of the robots, managed with a position tracking system.

## 4.2 Hardware Implementation

*4.2.1 ReelBot Hardware.* The core physical component of Buoyancé, ReelBot, can be broken down into two major components: (a) a rover mechanism – allowing omnidirectional traversal over the X-Y plane, and (b) a reeling mechanism, controlling the height of the HIB. All of these come in a relatively compact and lightweight package of 87.1 x 76.5 x 109.4 cm and 255.4 grams. The rover mechanism consists of the publicly available M5Stack RoverC.pro (RoverC) and M5StickC Plus2 (StickC).The reeling mechanism is enabled through the use of an N20 Gear motor (with encoder) controlled by the M5AtomS3 (Atom, for short) connected by the M5Atomic H-Bridge driver unit. The motor is controlled through a fine-tuned closed-loop PID control and slew rate controller. This tuning helped match the acceleration of the motor with the natural levitation of the HIB, mitigating undesired line entanglements and thus minimizing inaccuracies in height.

For the reeling string, 0.27 mm diameter fishing lines or a 0.25 mm diameter 100% polyester thread are employed based on the user's desired needs for string visibility. This line is threaded through a 2mm hole on top of the ReelBot body, acting as a filter to prevent tangling on the spool — ensuring only a single thread of the reeling string is reeled in or out. Both StickC and Atom individually communicated with the central computer via WiFi, while the motor to drive the reeling mechanism was powered from the battery of RoverC - we employed a 3.7V 2800maH rechargeable Lithium Ion battery, which in total lasted around 2-3 hours with basic operations during our prototyping.

[1] https://github.com/AxLab-UofC/Buoyance_UIST2025

Overall, the rover and reeling mechanisms were coupled through 3D-printed shells utilizing screws. The rover also included an optional Shell Add-on which was used to protect the wheels as well as change the aesthetics of the ReelBot (Illustrated in Figure 4).OptiTrack Markers were attached to the optional add-on shell of the robots which measured around 128.56 mm. This addition increased the size and weight of the ReelBot, with its length becoming anywhere in the range of 91-150 mm, width of 101-106mm, and weight of about 271 grams with its height remaining the same.

*4.2.2 HIB types and Attachable Accessories.* Regarding HIBs, we mainly employed black mylar HIBs of either a cubic or spherical shape for most of our implementation and demonstration [2]. We chose mylar as it is known to leak helium at a much slower rate than its rubber counterpart to minimize helium usage.

The cubic HIB measured about 24 inches in length, width, and height and contained about one cubic foot of helium-air mixture (containing at least 80% of helium) from a commercially available helium tank [3], whereas the spherical HIB measured about 22 inches in diameter and held roughly 0.6 cubic feet of the helium-air mixture. The black color limited the reflections and thus was a more compatible option for the marker tracking system.

Different HIBs can be employed for different scenarios, as demonstrated in our application section, providing great customizability and versatility. The selection of HIBs can be based on aesthetics (e.g., sphere HIB for a consistent geometrical appearance from any angle, Figure 13), semantic representation (e.g. caterpillar-like character with spherical HIBs, Figure 15b) or mechanical properties (e.g., cubic HIBs to use flat-face for ease of assembly, Figure 15a). As an exception, rubber HIBs were employed for the illuminating light application (Figure 14), which required embedded LED lights to pass through the material.

With the HIB providing enough buoyant force to lift itself, there is also enough force to attach or embed accessories to the HIBs (payloads of ~5g for spherical HIB, and ~5.5g for cubic HIB ), including a small camera, LED lights, or a thin paper sheet (See Figure 14). Assembly joint mechanisms can be added, as long as they are under the weight limit (a comparative study is discussed in section 5.3.)

*4.2.3 Lifting Body Capability (motor choice + hook design).* The implementation of the reeling mechanism is meant to shorten the distance between the ReelBot and HIB. When we constrain the height of the HIB, the reeling mechanism reels the ReelBot up into the air towards the HIB, rather than the HIB down towards the ReelBot (See Figure 14c). Thus, the capability of lifting the body up for neat storage or movements across levels that the wheels cannot overcome is enabled through the constraint. Because the motor must provide sufficient torque to lift the ReelBot without stalling in different contexts, the motor can be swapped for one with a larger ratio, which as mentioned previously is easily done through the design of its encasing shell. The 210:1 geared motor provides 2.8 kg*cm of torque while also rotating at 160 RPM which moves the ReelBot up at a comparable speed to the natural levitation of the non-constrained HIB while also providing enough torque to bear the weight of the ReelBot midair.

[2]Product for the cubic balloons https://www.amazon.com/dp/B099ZMH6XL/ and spherical balloons https://www.amazon.com/gp/product/B0B517TD6Z
[3]Product Link https://www.amazon.com/dp/B000RHMWBQ/

Because the material of the HIB is naturally thin, the hook that constrains the vertical movement of the HIB needs to be designed so that pressure on the HIB is distributed evenly to prevent punctures. Thus, the hook is designed to mesh well with the underside of the HIB sustaining its levitation post-lifting.

## 4.3 Software Implementation

The software control includes (1) a real-time position tracking system powered by OptiTrack cameras, and (2) a Processing-based GUI that facilitates control over both the ReelBots and the reeling mechanism with HIBs. Our tracking system software operates at a frame rate of 120 fps, while the GUI functions at 60 fps, and the communication with the robots occurs at 10 fps. We measured the latency of the RoverC movement and reeling mechanism from the timing GUI sends comment as 67 ms and 62 ms, respectively.

*4.3.1 Room Setup and Tracking System.* Position tracking for each ReelBot is achieved using 8 OptiTrack Flex13. The cameras were positioned from various angles to cover a wide area at various angles to capture the ReelBots and users' hand gestures, which can be varied to match the dimensions of different rooms. One example of a room we used for the system (See Figure 5) measured approximately 6 x 6 m with 3.14 m height, and the cameras were positioned in the corner of the room, enabling a tracking area of approximately 4.8 x 4.8m.

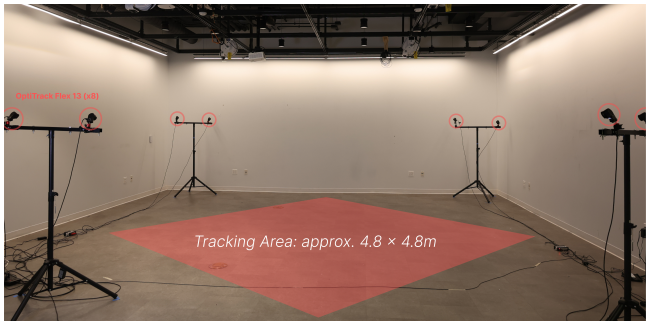



**Figure 5: An example of a room used for a Buoyancé prototype setup and OptiTrack Cameras.**

*4.3.2 Robot and Reel Control.* For the robot control, the HIB is guided to its target position using PID control for both the RoverC (x, y) and reel mechanisms (z). The RoverC is controlled by the calculated movement speeds based on the target position (specified in the control tool), and tracked position (detected by the OptiTrack). The speeds are defined as the speed of X and Y separately, to be compatible with RoverC's control API. Hence, the combination of X and Y speeds results in the omnidirectional, velocity-variable motion of RoverC. The speed data is sent from Processing to each ReelBot. With our custom-built PID controller, we set the deadzone offset to 5 cm, so the robots won't oscillate near the target.

The motor for the reel mechanism, controlling HIB's height, is actuated based on the target rotation angle calculated from the target height set in the GUI. This is transmitted over WiFi at 10Hz.

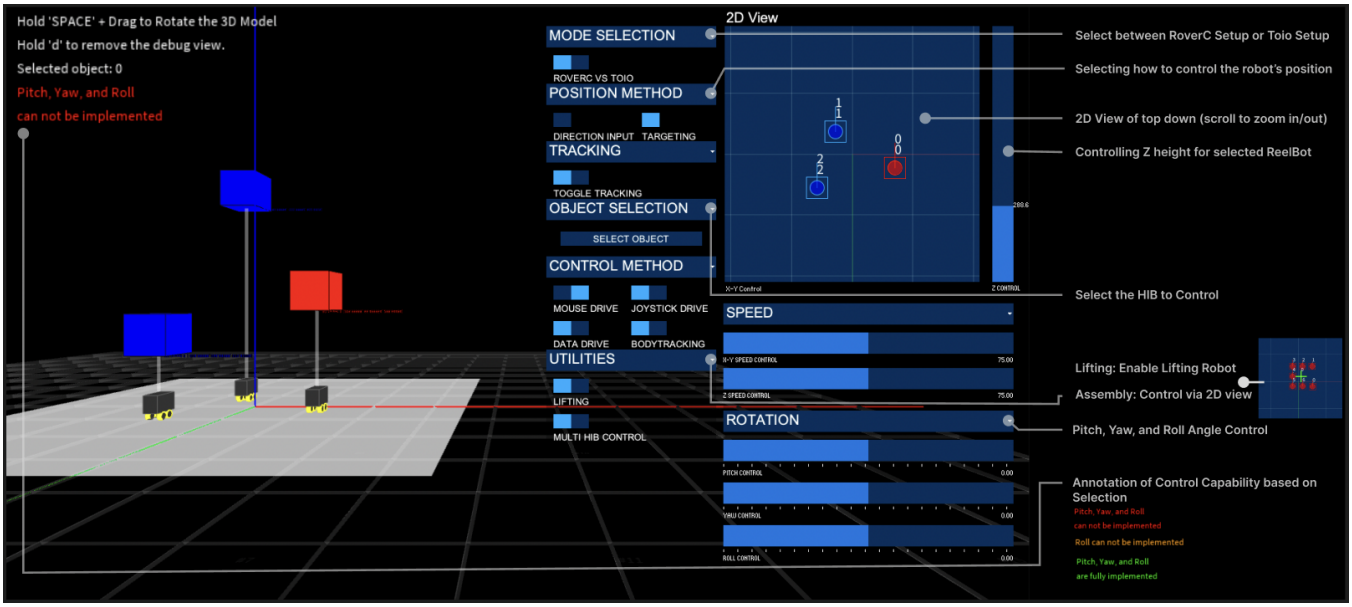



**Figure 6: Control GUI of Buoyancé.**

*4.3.3 GUI Control.* We developed the GUI control tool using Processing, based on the one for AeroRigUI [61], which is open-sourced on GitHub. While some of the GUIs, basic visualization, and the abstracted robot control for managing rigging/reeling objects were built upon theirs, a number of custom functionality was added, including multi-robot control, tracker position visualizations, robot speed control, etc.

**Overall GUI layout and functionalities:** The overall GUI is shown in Figure 6. We have implemented a GUI system that enables users to flexibly manage the XY movements of ReelBots and the Z-height adjustments of HIBs under various conditions. The left side of the GUI presents a 3D visualization that aids users in simulating the interaction between HIBs and ReelBots, while the right side contains detailed control functions, including different control methods and multi-robot control. The GUI uses red and blue colors to indicate the status of each HIB, representing which HIB is currently selected to be controlled (red) or not (blue) in the software (see Figure 6). Though this GUI is primarily purposed to control custom-built ReelBots, our GUI also supports using toios, based on the hardware of [61], providing users the flexibility to control different robot types.

**Robot Control:** We have developed an abstracted control system for managing one or multiple HIBs using multiple ReelBots, similar to [61]. For a single HIB setup, users can control one or more ReelBots, allowing the system to offer XYZ adjustments along with yaw and pitch control when multiple ReelBots are used. Moreover, our system includes an assembly feature: once HIBs are assembled, the GUI facilitates multi-robot control, enabling adjustments of the entire structure in XYZ, roll, pitch, and yaw directions. This is achieved through the synchronized movement of the ReelBots and adjustments to the HIBs' string lengths.

**Different Control Methods based on GUI:** Our GUI offers a range of control methods. With **mouse control**, users can adjust the XYZ positions and rotation angles (yaw, pitch, roll) via the GUI. These modifications directly correspond to the XY positions and reel length of the ReelBots, facilitated by the closed-loop control system. **Joystick controller mode** was also implemented to easily navigate each robot using a commercial game controller. **Data input control** feature allows precise steering of ReelBots based on a series of target 3D coordinate points. Users can define these discrete coordinates directly in the code, either as a dynamic script to continuously assign the 3D coordinates (e.g. sine wave animation; Figure 13a) or as a set of pre-defined coordinate point arrays (e.g. animal geometries; Figure 13d). The system interprets these inputs and autonomously guides each ReelBot to its assigned position. Transitions between shapes are computed using nearest-neighbor reassignment to ensure smooth and continuous motion.

*4.3.4 Hand and Body based Control.* We developed two methods for **body tracking**. The first method involves attaching OptiTrack markers directly onto wearable gloves (Figure 7a), enabling tracking of the user's hand movements. We defined two primary hand-based gestures: "grasp", identified by a closed hand that fully obscures the marker inside, and "release", characterized by an open hand revealing all markers. In such a way, users can intuitively control the ReelBots and HIBs, where grasping initiates ReelBots movement aligned with the hand's direction in all XYZ directions, and releasing halts the motion. Furthermore, we implemented three distinct interaction methods (Figure 7b): (1) Via-String Tangible control, in which users grasp and drag the string to direct the robot and HIB; (2) Direct Tangible control, allowing users to directly hold and reposition the HIB; and (3) Nearby Gesture control, allowing gesture-based manipulation.

The second method of body tracking uses the MediaPipe library. Through a web camera from a USB camera, it can track either hands or body landmarks to map users' gestures to HIBs (Figure 8). While

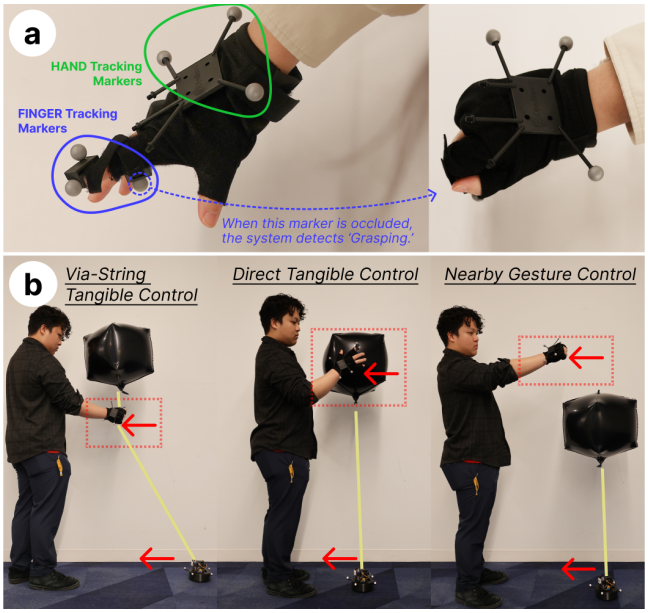



**Figure 7: Control enabled by tracking hand grasp and release movements: (a) gloves with attached markers, (b) three distinct interaction modalities.**

this method doesn't allow the system to track users' hands or bodies in relation to robots, it allows for marker-less sensing, which may be suited for non-collocated user interaction with robots.

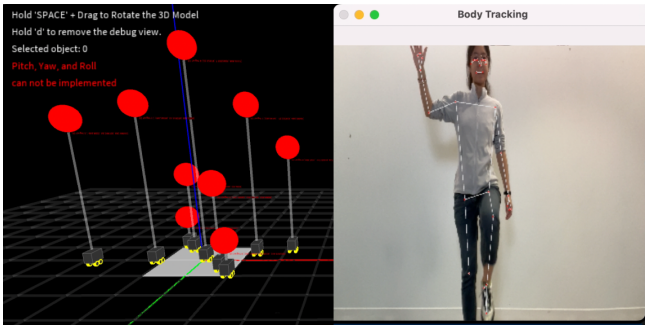



**Figure 8: Control using remote camera capturing (Media Pipe).**

*4.3.5 Group HIB Control.* The hand and body based control can be extended to develop Group HIB control. Leveraging the three 'grasp-and-release' based tangible control methods, as previously mentioned, we developed Group HIB control for users to control multiple HIBS collectively as a compound structure, inspired by [4]. Once the user begins to interact with a certain HIB, the other non-controlled HIBs are programmed to be repositioned to maintain the spatial configuration relative to the controlled HIB as the user moves the HIB around (as seen in Figure 9a). Additionally, if the user were to grab two HIBs, the other HIBs will automatically adjust their position and height based on the user's movement of the first two controlled HIBs (shown in Figure 9b).

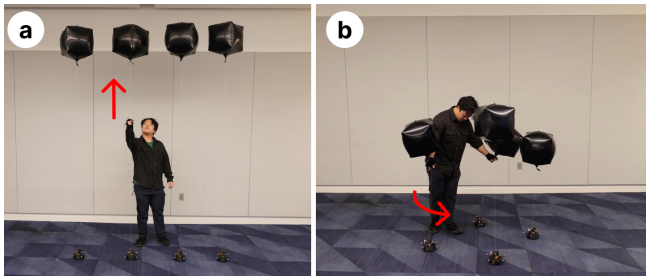



**Figure 9: Group HIB Control: (a) reposition the entire group of HIBs, (b) rotate them collectively.**

*4.3.6 Optional Collision Avoidance Functionality.* To mitigate the potential collision risks of on-ground robots with environmental objects and people, we implemented an optional collision avoidance functionality that is further integrated into our GUI and control system. For this functionality, each obstacle (objects or humans) needs to be mounted with an OptiTrack marker, which is manually specified with a custom-defined diameter boundary in the software based on the lateral size of the obstacles. With this setup, the collision avoidance functionality, appended to the robot targeting control (as in section 4.3.2), steers the ReelBots to keep a specific distance from these obstacles when navigating to the target destination to avoid collision, visualized within the GUI (Figure 10). While advanced swarm/3D collision detection approaches [3, 31], could be implemented, this approach is a preliminary step towards mitigating collisions.

## 5 Technical Evaluation

In this section, we performed a technical evaluation of Buoyancé to assess its functional capabilities. The evaluation focused on the following criteria: (1) robot control performance, (2) reeling motor functionality, (3) ease of assembly and disassembly, and (4) multi-robot control capability. This assessment aims to inform and optimize both the hardware configuration and software architecture, providing valuable insights for users seeking to advance system development. Specifically, these insights include the influence of HIB shape, material, and assembly choices on performance metrics (e.g. carrying capacity, height, and assembly time). The trade-offs in motor selection are another overall insight that underscores the importance of balancing speed, torque, and system demands.

### 5.1 Robot Control Capability

With the numerous moving parts of the ReelBot and HIB system, measuring the control the system provides aids in understanding the system's physical capabilities. In this sense, we measured the different carrying capacities of the balloon and assemblies of the HIB, the maximum height to which the HIB can levitate, and the speed at which the rover mechanism travels along the ground.

*5.1.1 HIB Carrying Capacity.* Because the helium within the HIB provides excess buoyant force, allowing it to levitate into the air, we can utilize this force to maintain upward levitation while also attaching add-ons for various scenarios. We define the amount of additional weight a HIB can carry as its carrying capacity. Using

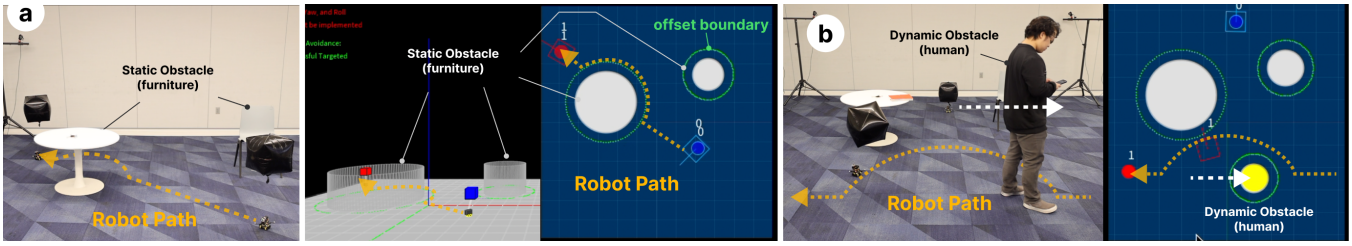



**Figure 10: Collision Avoidance: (a) avoiding static obstacles like a chair and a table, (b) avoiding dynamic obstacles like a person.**

a Newton Force Meter Spring Scale attached to the bottom of the HIB in place of the fishing line, we measured the amount of upward force that the HIB provided from a static position. We carried out the measurement for various types, amounts, and assemblies of HIBs. However, because the buoyant force was small relative to the scale of our Newton Force Meter Spring Scale, when measuring the force of the cubic and spherical mylar HIBs, our minimum amount of HIBs for measurement is 2 whereas the single A-shaped balloon provided enough force for a clear register on the probe. Additionally, because we chose to employ mainly cubic HIBs for our assembly, we only tested larger than 2 HIB assemblies with the cubic HIB.

Through our measurements, we found that the minimum HIB configurations produced the following buoyant forces: 11 grams for 2 cubic HIBs; 10 grams for 2 spherical HIBs; and 10 grams for a lone A-shaped HIB. Furthermore, 3, 5, 7, and 9 balloons had a capacity of 18, 39, 59, and 75 grams respectively. While the experimental measurements resulted in a non-linear relationship, with an $R^2$ of 0.991, it is relatively safe to assume a linear relationship across the carrying capacity and amount of HIBs.

These findings give us estimates of the weight of potential add-ons. We should note that in order for the HIB to maintain its ability to levitate upwards, the attached accessory should ideally weigh less than its carrying capacity.

*5.1.2 Maximum Height.* Because the HIB is attached to the ReelBot via fishing line, the higher the HIB travels, the more fishing line it will carry. This implies that there exists a maximum height to which a HIB can travel and/or represent information as shown in a future section. With the estimate of the single HIB carrying capacity, we were able to have a basis as to how long we expected the balloon to travel based on a calculated length-to-weight ratio, which we found to be roughly $\sim$ 13.2 meters per gram. From this expected carrying capacity, we continued to release fishing line, until the HIB stalled in the air.

We found that with the 24-inch cubic Mylar HIB, it was able to travel $\sim$ 114.62 meters. It is important to note that because this was done specifically with a fully-inflated 24-inch cubic Mylar HIB, other HIBs may be able to travel shorter or taller heights. Switching to a rubber material, lighter connecting string, or larger HIB will result in a higher maximum height, whereas adding accessories, heavier connecting string, or utilizing smaller HIBs will result in shorter maximum heights.

*5.1.3 Ground Plane Speed.* As the RoverC.pro utilizes Mecanum wheels, it is able to achieve 360° motion along the ground plane without the need for rotation. Thus, creating the potential for varying speeds with each form of locomotion being forward/backward and left/right.

We found that moving directly forward or backward, with all four wheels moving in the same direction, resulted in faster movement compared to when the rover was forced to move sideways, where the wheels opposed each other. Moving forward and backward resulted in similar movement of the speed of $\sim$ 0.415 meters per second and left and right about 0.269 meters per second. It is important to note that these measurements were made on an even and uniform hardwood floor. Different types of flooring with different levels of evenness may affect the speed and accuracy of the rover's motion. Across hardwood flooring, the speed of the rover is about one-third the speed of the average human walking speed of $\sim 1.2 - 1.4$ meters per second [30]. Thus, while the rover may not keep up with a human in real-time, it will still provide an adequate speed for interaction.

## 5.2 Selection of Reeling Motor and Trade-Offs

*5.2.1 HIB speeds along the Z-axis.* With the motor being the main component of controlling the HIB along the Z-axis, there are a few details crucial for different contexts. As shown in Figure 11, we found that an N20 gear motor with a gear ratio of 30:1 resulted in an average speed of 57.3 and 53 centimeters per second when moving up and down respectively, whereas the 210:1 DC motor had a much slower average speed of 8 centimeters per second when moving up and down. What is important when considering a gear ratio, is the HIB's speed of levitation, or its levitation speed. With the speeds of the upward and downward motion of the HIB being relatively similar, it will generally be the case that the levitation speed of the HIB will be relatively slow, as the motor works with the buoyant force in the upwards direction whereas they oppose each other when reeling down. This especially becomes the case in motors with smaller gear ratios. This finding leads to the case where the speed of the HIB is at minimum limited by the speed of the HIB, and thus smaller gear ratios while providing faster rotation will not result in higher levitation speeds.

However, what must also be considered when selecting the motor are the demands involved in the lifting application, which is explored in further detail in later sections. With the ReelBot weighing up to 271 grams, the motor must have sufficient torque for this application to be successful. In measuring the additional carrying capacity of the motor when lifting, as opposed to the HIB, we find the 30:1 DC motor with a specification of 0.57 kg/cm can carry an additional 170 grams when actively maintaining its position while

incapable when passive. On the other hand, the 210:1 DC motor specified for 3 kg/cm can carry an additional 400 grams when active and 230 grams when passive. In joint with the velocity findings, we see that there is a trade-off of lifting speed vs. lifting weight, meaning that there is also a minimum gear ratio that one must consider when selecting the motor.

Buoyancé requires a motor that provides enough torque, through the gear ratio, to lift the body and any additional demands. However, the gear ratio must not be so high that it makes the motor excessively slow, nor so low that the motor's speed outpaces the HIB's levitation speed. For our purposes, we found that the 30:1 gear ratio satisfied most of our desires, providing a speed compatible with the HIB and strong enough to lift the ReelBot into the air for docking and storage.

| | *HIB Reeling Speed* | | *Lifting Capabilities* | | |
|---|---|---|---|---|---|
| | Reel Up Speed (cm/s) | Reel Down Speed (cm/s) | Lift Body Speed (cm/s) | Lifting Weight [motor active] (g) | Lifting Weight [motor off] (g) |
| **30:1 Motor** | 57.28 | 52.99 | 46.93 | 170 | N/A (can't hold its own weight) |
| **210:1 Motor** | 7.55 | 7.58 | 8.2 | 400 | 230 |

**Figure 11: Reel Mechanism Evaluation with two different geared motors.**

## 5.3 Assembly and Disassembly

Since HIBs can be assembled in various configurations mid-air, it is crucial to assess the ease of assembly and disassembly using different connection methods. As illustrated in Figure 3b, we developed three assembly techniques for HIBs: Scotch-Mount Removable Poster Tape joints (double-sided tape), magnetic joints, and VELCRO Brand Thin Clear Tape joints (velcro joints). Each HIB features a joint on four sides, excluding the top and bottom. Following the results from the technical evaluation of weight capacity, each magnetic joint incorporates 12 magnets, with dimensions of 3.8 cm by 2.5 cm and a total weight of 1.36 g. Similarly, each Velcro joint consists of two strips of Velcro tape, measuring 7.5 cm by 2 cm and weighing 1.16 g.

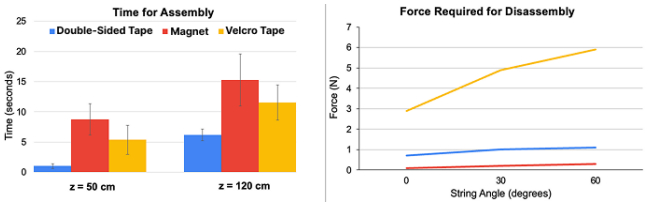



**Figure 12: Assembly and Disassembly Evaluations: (a) time for assembly, (b) force required for disassembly.**

*5.3.1 Assembly.* We evaluated the time required for one HIB to assemble with another using the three previously discussed assembly methods. Prior to analyzing the results, we defined the assembly time as the interval between the moment when two HIBs, positioned in close proximity via the GUI and with all XYZ movements halted, initiate the assembly process to when they are fully connected. The tests were conducted at two heights, 50 cm, and 120 cm. To ensure accurate timing, we utilized slow-motion video footage and a timer. Given that environmental factors like wind can significantly impact assembly time, we conducted five trials for each method at different heights and calculated the average assembly time for each scenario.

The results are shown in Figure 12a. We found the average assembly times for double-sided tape joints at 50 cm and 120 cm to be 1.034 and 6.186 seconds, respectively, with standard deviations of 0.83 and 2.05 seconds. For the magnet joints, the average assembly times were 8.748 seconds at 50 cm and 15.258 seconds at 120 cm, with standard deviations of 5.23 and 8.61 seconds. Velcro joints averaged 5.394 seconds at 50 cm and 11.544 seconds at 120 cm, with standard deviations of 4.91 and 5.92 seconds. Overall, the longer average assembly time for magnets and Velcro tape indicates a greater challenge in achieving precise alignment compared to double-sided tape. The increased times at 120 cm also suggest greater assembly challenges at higher heights. These results highlight that both height and connection methods significantly influence assembly time, with double-sided tape joints being the most consistent and fastest, particularly at lower heights.

*5.3.2 Disassembly.* To measure the force required for disassembly, we first assembled two HIBs using each of the three connection methods. One HIB was then fixed in place while the other was pulled at varying angles using a Newton Force Meter Spring Scale, with a measuring range of 0–10 N, attached to the connection point between the HIB and the string. The angles were set at 0, 30, and 60 degrees, relative to the horizontal plane of the string. We recorded the force at which the HIBs detached from each other. The results, shown in Figure 12b, demonstrate that the disassembly force increased as the angle increased. Among the three methods, magnet joints required the least force to separate, followed by double-sided tape joints, while Velcro joints required the most force.

We also tested the pulling force generated by ReelBots. When moving in the x-direction, ReelBots provided a pulling force of 0.8 N, and in the y-direction, 1.4 N. This shows that for controlled disassembly, the force required for each connection method should not exceed the force provided by ReelBots. At the same time, mid-air assembly requires relatively strong connections for tasks like rotation. Considering both factors, double-sided tape joints were found to be the most suitable option. Future work could explore alternative materials or connection methods to improve the assembly and disassembly process.

## 5.4 Multi-Robot Control Capability

Finally, we evaluated the multi-robot control capabilities in terms of pitch, yaw, and roll angles. Two scenarios were designed for this evaluation: the first involved controlling only pitch and yaw, such as in setups with two ReelBots and one or two HIBs; the second allowed for control of pitch, yaw, and roll, as seen in configurations with four ReelBots and four HIBs arranged in a 2x2 matrix. Since yaw control relies only on the XY movement of the ReelBots and can achieve a full 360-degree rotation, the evaluation primarily focused on measuring the maximum rotation angles for pitch and roll in both scenarios. Our result shows that in the first scenario, the maximum pitch angle achieved with two ReelBots and one HIB is 49 degrees, while with two ReelBots and two HIBs, the maximum

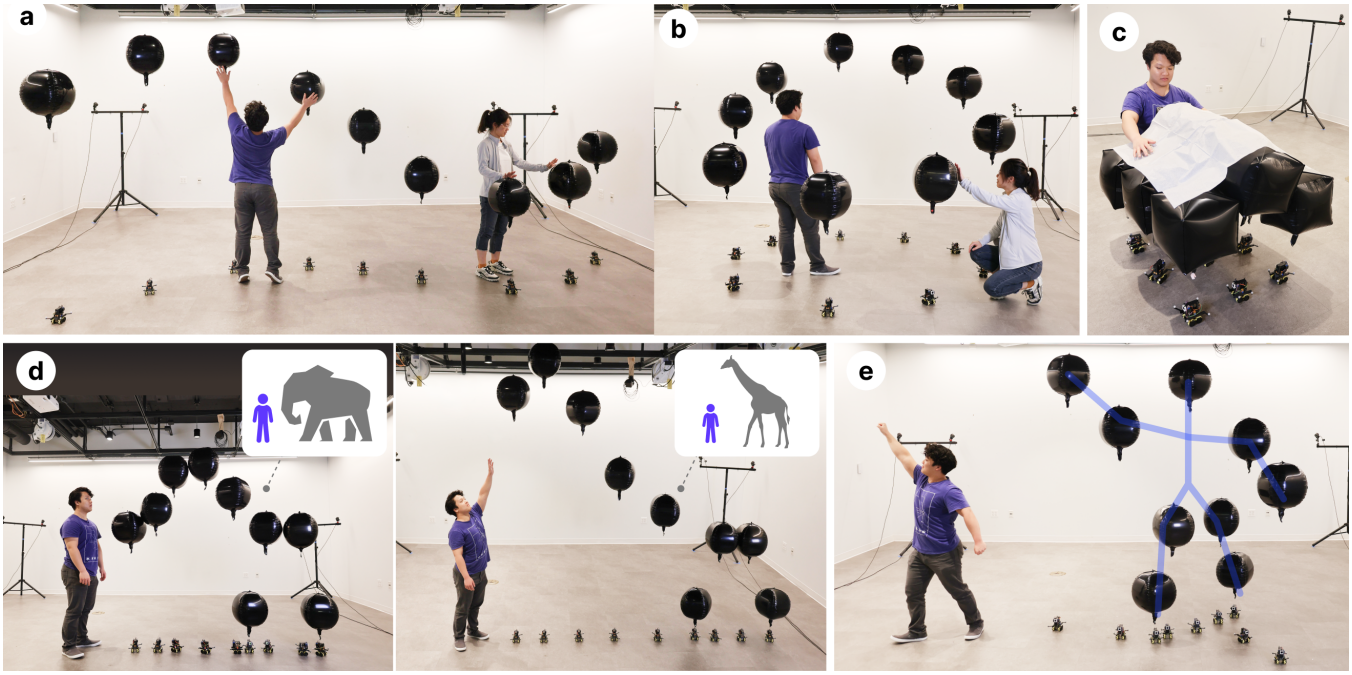



**Figure 13: Display of Interactive Information in real-time: (a) Sine Wave, (b) 3-dimensional interactive circle, (c) terrain, (d) direct height representation of various animals (elephant and giraffe), (e) Body Tracking of a user's poses.**

pitch angle is 43.5 degrees. In the second scenario, the maximum angles for both pitch and yaw were recorded at 44 degrees.

## 6 Applications

To showcase the capabilities of Buoyancé, we highlight its applications in three key areas: (1) information display, (2) assistive room configuration, and (3) dynamic shape formation for texts and characters.

### 6.1 Information Display

In the information display application, we demonstrate the feature of Buoyancé in visualizing various types of information.

**3D Data Display:** Data physicalization [25] has been an active area of research in HCI, and Buoyancé offers ways to fill entire rooms with 3D-positioned HIBs to display information. For example, wave data could be displayed filling the entire room (Figure 13a), allowing people to walk through the dynamic data to see, touch, and interact with them. Such a large-scale data representation may be suitable for museum exhibitions, science communication/education, multi-user interaction scenarios, as well as interactive dynamic kinetic sculptures.

**Terrain Representation:** In addition, our system also supports continuous terrain representation by putting light wrapping tissue paper on them. As shown in Figure 13b, we combined two sheets of wrapping tissue paper, each measuring 60.96 cm by 91.44 cm and weighing 8.63 g, using double-sided tape to create a single sheet measuring 117 cm by 91.44 cm. This sheet was then placed on a 3x3 grid of HIBs. By adjusting the string length of the HIBs beneath the paper, the prototype displayed continuous contours, which have the potential to represent geographical terrain.

**Abstract Expressions:** Leveraging the wide vertical range offered by HIBs, Buoyancé can effectively depict abstract expressions. In this application, we introduce two types of displays: one for animal representation and another for body representation. The animal representation includes images of an elephant and a giraffe (Figure 13c), helping users experience the true scale of each figure to be seen and touched in front of them. This capability can be applied in various areas, including education, entertainment, and human-robot interaction, providing a tangible and immersive way to experience real-world objects. The body representation, on the other hand, physically replicates a human body figure in real-time (Figure 13d), which could be a unique system for telepresence applications.

As a room-scale tangible information display system, Buoyancé allows for tangible interaction with the displayed information for engagement and interactivity. Utilizing the real-time body-tracking methods mentioned in section 4.3.4, users are able to tangibly manipulate the HIBs to create in-time dynamic changes. This capability enables a tangible observation of how changes in variables affect the outcome in a tangible and 3D-manner, allowing for a different perspective and added understanding of various real-life scenarios. Additionally, due to the energy efficiency with constant levitation, thanks to Helium, the system could be employed for a day-long public display system, museum exhibitions, or advertisements (like add balloons), by equipping ReelBots with sufficient batteries.

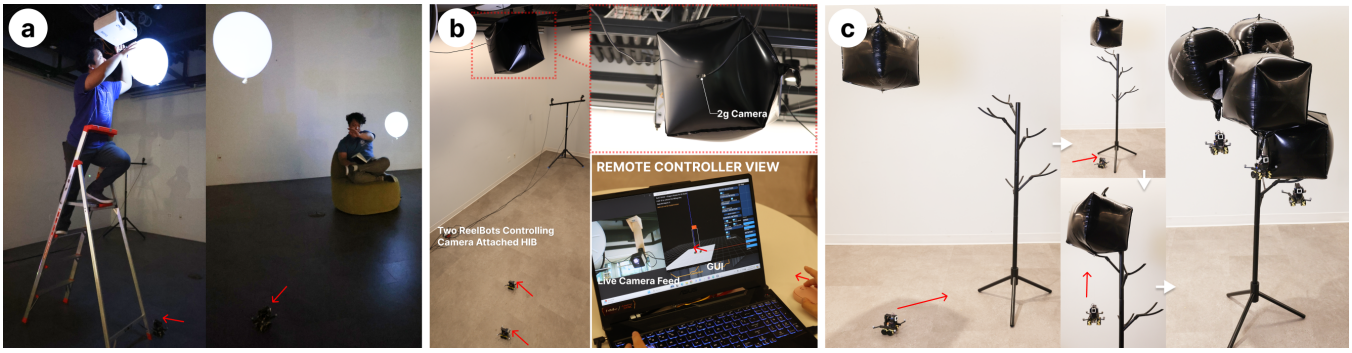



**Figure 14: Examples of Assistive Room Configuration: (a) controlling a light source via hand control, (b) virtual presence via remote control, (c) compact storage.**




**Figure 15: Assembly of HIBs to create various shapes and objects: (a) Step-by-step assembly of the letter C, and other letters, (b) assembling into a friendly caterpillar character, affording for cuddling interaction.**

## 6.2 Assistive Room Configuration

There are numerous possibilities in Buoyancé for configuring everyday household items within our living space.

**Control of Lighting:** With the addition of the LED into a rubber HIB, the HIB is capable of shining light onto hard-to-access surfaces such as ceiling fixtures (Figure 14a). When utilized in conjunction with the OptiTrack or gesture tracking system, the ReelBot is able to control the position of the light to fit the needs of its user without lighting up areas where light is not necessarily needed.

**Virtual Presence:** Similar to how the LED is attached to the rubber HIB as an accessory, a small camera can be attached to the HIB (Figure 14b). The camera, which is attached to an unaccounted-for USB cable, is able to provide footage to the user via remote imaging. The user is able to control its desired image and placement in space through the GUI's remote control capabilities. This could be useful when wanting to survey hard-to-access areas such as excessively tall or narrow locations.

**Storage Capabilities:** Finally, with ReelBots compact form factor with lifting capability, it can be stored out of the way of everyday life. As shown in Figure 14c, after the ReelBots are done with completing their tasks, they can drive to the storage station where the prong-like hooks are positioned at a certain height of the room, so that ReelBots can lift their body onto the hook, keeping the floor completely clear. Compared to storing items away on the ground, the prongs can be set up near the ceiling, allowing the ReelBots to remain fully out of sight and mind for the users, Thus, opening up more usable and walkable space along the ground.

The application of assistive room configuration should specifically benefit from the collision avoidance feature (section 4.3.6) to ensure the ReelBots do not hit and collide with environmental objects and humans while maneuvering in the everyday environment.

## 6.3 Dynamic Shape Formation for Texts and Characters

Lastly, we demonstrated using HIBs towards dynamic shape formation for texts and characters. As shown in Figure 15a, where users can manipulate each HIB, connected via ReelBots through our GUI, to form images such as "H," "C," and "I." Users can further adjust the orientation of the letters across multiple axes, including pitch, yaw, and roll, giving them full control over the display's three-dimensional positioning. Another example is the assembly of a patchwork caterpillar, where each body segment—head, feet, and tail—is individually controlled and assembled into a cohesive structure (Figure 15b), demonstrating the use for animatronics, storytelling, and entertainment, allowing for soft, and comfortable tangible interaction by users.

## 7 User Study

To evaluate the general user experience with the proof-of-concept system of Buoyancé and to compare the three hand-based HIB control methods (Figure 7b), we conducted a user study. The main goals for our study were to understand:

(1) How well the proof-of-concept system works as an interactive system and users' general reaction to it.
(2) How the three hand-based HIB control methods (as in section 3.2) compare for user perception [ratings of COMFORTABLE, INTUITIVE/EASY, and ENJOYABLE/FUN] and user preference to be employed at different HIB heights.
(3) The research opportunities and implications for future system implementations and interaction design of Buoyancé based on the user experience and feedback.

### 7.1 User Study Procedure

The core user study task was based on a series of spatial targeting tasks to bring the HIB to a designated 3D target in space.

After signing a consent form, and wearing the hand-tracking marker on their dominant hand (Figure 7a), participants were provided with the instruction of the overall task to control an HIB to specified 3D positions for each control method.

For each control method, four targeting tasks were asked to be completed sequentially in the space depicted in Figure 16. The desired 3D locations were specified in a sequence based on a combination of floor markers (points A or B, 250 cm apart), and corresponding height references labeled on a stand placed near each point (HIGH [200cm] and LOW [100cm] in Figure 16). During each control method's four sequential targeting tasks, participants were instructed to move the HIB to alternating targets between A-LOW and B-HIGH or A-HIGH and B-LOW. By performing four targeting tasks for each of control method (the order was counter-balanced across the 12 participants), participants performed a total of 12 targeting tasks. The tasks were video recorded to measure the targeting time of each task. Before starting the targeting tasks for each control method, participants familiarize themselves with each control for up to two minutes, and was asked to perform two practice targeting tasks.

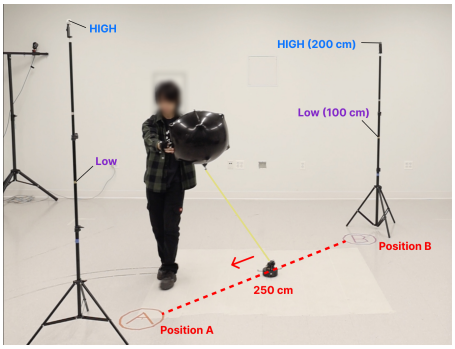



**Figure 16: User Study Setup.**

Upon completing all tasks, participants were asked to complete a questionnaire with a mix of quantitative and qualitative questions. Specifically, the survey collected subjective ratings on a scale from 1 (not at all) to 7 (very much) for three perceptual ratings (COMFORTABLE, INTUITIVE/EASY, and ENJOYABLE/FUN) for each control method based on their experience from completing the targeting tasks. As a follow-up, participants were then also asked to provide ratings based on the GENERAL IDEA of the control method, disregarding the system's performance (e.g., slow speed of robots), and to indicate their preferred control method with respect to different height ranges of the HIB.

Overall, the study consisted of general introductions/instructions(~ 15 minutes), targeting tasks (~ 25 minutes), and a post-survey questionnaire (≥ 15 minutes), totaling between 50 and 60 minutes. The targeting tasks further consisted of ~ 6 minutes of practice, more specific instructions for each control mode, in-between breaks, and the targeting tasks themselves. The experimental protocol was reviewed and approved by our university's ethics committee under IRB protocol ID IRB25-0407.

**Participants :** We recruited 12 participants from our university (ages 20–52 [average of 25.75], 7 females and 5 males). Only one participant was left-handed, and the rest were right-hand dominant.

### 7.2 Results

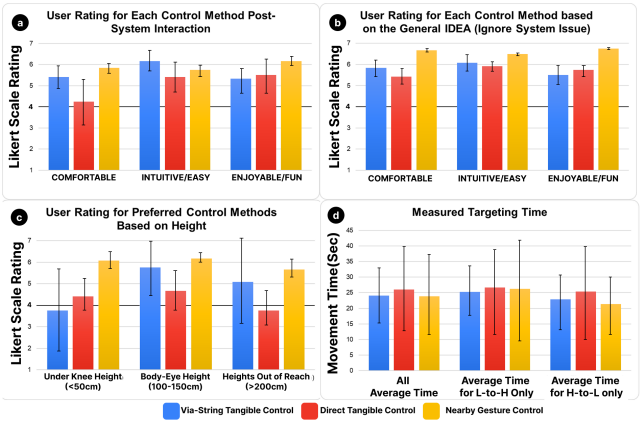



**Figure 17: a - c: Participant's rating for the 7-point Likert scale questions (4 to be neutral), d: the average measured targeting time for each control, based on raising [Low-to-High(L-to-H)], or lowering [High-to-Low(H-to-L)].**

*7.2.1 Control Methods - Ratings, Preferences and Performances.* **General Rating of Control Methods:** The user ratings for the three control methods are shown in the graphs in Figure 17 a-c. Overall, for the user rating with our system for each control (shown in a), the Nearby Gesture Control was rated the highest for COMFORTABLE (average: $5.8\overline{3}$), and ENJOYABLE/FUN ($6.1\overline{6}$), while Via-String Tangible Control was rated the highest for INTUITIVE/EASY ($6.1\overline{6}$). Direct Tangible Control was the lowest for COMFORTABLE (4.25), and INTUITIVE/EASY (5.42), and Via-String Control was the lowest for ENJOYABLE/FUN (5.5). As a follow-up, we asked participants to rate each control without the system issue [e.g., slowness of the robot movement] (shown in Figure 17b), the order of the rating didn't change significantly, except for the INTUITIVE/EASY

rating, where Nearby Gesture Control became more highly rated than Via-String Tangible Control.

As can be seen from the larger deviation with the error bars, general thoughts about the Via-String and Direct Tangible controls were quite mixed. As per the freeform answers associated with explaining their ratings, most reflected that *Via-String Tangible control* was intuitive, as it was *"how balloons are usually moved"* or *"like flying a kite."* However, the appreciation of the tangibility was mixed — some participants appreciated the natural way of tangibly interacting with the balloons, while those who positively rated Nearby Gesture over both tangible controls stated that *"having to hold the string was restrictive"* and were just *"regular ways you'd interact with a balloon."* While another participant who rated the Direct Tangible Controls higher stated, *"Touching a balloon... reminds me the memory of childhood when I play with a helium balloon,"* echoing the inherent unique affordance and materiality of the HIBs in the system. Conversely, people who enjoyed *Nearby Gesture Control* often had statements along the lines of *"felt like I'm using telekinesis"* or *"felt like I was Magneto"*, appreciating and enjoying the super-power-like gesture control. Through taking advantage of the natural affordances of a HIB and its seemingly magical levitating properties, both have benefits for creating an immersive interactive system.

**Preferred Control based on Heights:** As shown in Figure 17c, the preferred control method based on different heights had distinct rating differences. For Under-the-Knee Height (<50cm), people least preferred using Via-String Tangible Control due to the HIB being too low, inhibiting their ability to grab hold of the string. Direct Tangible Control was less preferred for all heights, while it scored the lowest for Heights Out of Reach, with the obvious reason that Direct Tangible Control is not feasible when the HIBs are not in reach.

**Measured Targeting Time:** Figure 17d represents the measured average time for the targeting time with respect to each control method. While the resultant average time ranged from 20 to 25 seconds, the measured time had a general correlation with their preferred ratings - the less time it took to move, the more they preferred the control method. For the cause that Direct Tangible Control took the longest among the three, we noticed several participants had an issue that, after reaching the floor targets (A or B), the robot occasionally fluctuated to move in and out of the floor targets while adjusting the Z height, taking extra time. We assume this was caused by the unstable hand position when using two hands to manipulate the balloon, that tracking system was too sensitive to reflect unstable hand movements to the robot's movement.

*7.2.2 Overall System Issues.* The results and our observations highlighted certain limitations of the implementation. One major system issue was the hand-gesture recognition for grasping detection (section 4.3.4), based on the marker occlusion. While the system was designed to detect 'grasping' while the marker on the finger was occluded, when the hand was too close to the HIB, the system incorrectly detected 'grasping'. We believe this is one of the reasons that the two tangible control methods performed worse than the Nearby Gesture control, as users were able to keep some distance from the balloon, minimizing unintentional occlusion of the marker. Another technical issue that arose was the slow speed of the ReelBot, for both XY locomotive behavior and vertical reeling control. Participants often had to wait for the robot to follow and catch up with their intended position, while the tasks required them to reach to target ASAP. While our system's speed was limited partly due to safety prioritization, the speed of the robot could be optimized to balance the trade-off of ease of control and safety.

Additionally, some participants noted that movement upwards felt *"not smooth at times"* while *"downward balloon movement... feels comfortable"*, which can be due to the limitation of the slower upward speed of the HIB itself.

*7.2.3 Other Observation and Feedback.*

**Paying More Attention to Robots than HIBs:** Likely due to the relatively slow ReelBot motion, many participants paid more attention to the ReelBot when interacting with the system, as opposed to the HIBs. We observed that P1 said *"We have to go"* towards the robot (Figure 18a), and many others often focused their gaze on the ReelBots while interacting with HIBs (Figure 18b). While we rather intended the interaction target to be the HIBs (considering ReelBots to be 'stagehands'), the actual users had to pay more attention to ReelBots. Future interaction design could take this user behavior into account, making a smooth interaction and expectation design between the user and the ReelBots/HIBs.

**Unintended Usage of Control Methods:** While we designed the control methods with intended usage and gesture in mind, participants exhibited unintended ways of using the control methods. For example, Nearby Gesture Control was meant as a targeting method, where the controlling hand would be the intended target, as in Figure 18c. Some participants instead found it more sensible to focus on directionality rather than solely the target, like in Figure 18d. Similarly, it was intended for the participants performing Direct Tangible Control to hold the sides of the HIB (as in Figure 18e), while P6 instead found it more intuitive to grab the top of the HIB with their left hand as guide on the side, as seen in Figure 18f. These unexpected ways of interaction could be incorporated into the future design space for Buoyancé.

**Alternative Control Methods and Applications:** Our questionnaire inquired if participants had any ideas they preferred for controlling the HIBs that weren't previously covered. Suggested control methods include pointing gestures, (game) controllers, mouse, pushing HIBs, or body-repelling movements (making robots move away from the user's body). We also asked about potential applications of our system, and users answers contained varied responses, such as, helping people with disabilities, helping find lost kids, smart furniture/lighting, concerts, advertisements, art installation, decoration, and more. These responses highlight how the system inspired them to come up with diverse interactivity and application ideas, enriching physical 3D space in a dynamic, practical, and aesthetic manner.

## 8 Discussions, Limitations and Future work

With Buoyancé, we introduced an approach to enrich our physical space with multi-robot systems and HIBs. In this section, we discuss the limitations of the current implementation and the general approach, as well as potential future work to share the extended research opportunities.




**Figure 18: Examples of behaviors observed during the user studies. (a) P1 talking to the ReelBot as a companion. (b) P7 focusing their gaze on the movement of the ReelBot rather than the HIB. (c) P2 performing Nearby Gesture Control, placing their hand over their desired position versus (d) P3 using their hand as a directional control. (e) P11 performing Direct Tangible Control with both hands on the sides of the HIB versus (f) P6 placing one hand on top and the other hand on the side of the HIB.**

## 8.1 General Limitation of Proposed Approach

While employment of HIBs offers unique capabilities for spatial interaction, there are overall inherent limitations for the approach, which are shared with other helium-employing robots [5, 19, 35, 36, 55, 56, 60].

**Inertia-Affected Position Control of HIB:** While the ReelBots on the ground are controlled fairly accurately, as HIBs are levitated with buoyancy force, they tend to be affected by inertia force, for the HIBs to be dragged and pulled through ReelBot's lateral motion, and bounce (or oscillate) by reel-mechanism movements, resulting in unwanted movements, depending on the needed accuracy. For the next step, advanced control for anti-swing and minimal bouncing could be implemented by closed-loop balloon tracking of HIBs in the future [46, 61]. Additionally, as HIBs are weak towards wind or even slight atmosphere changes (e.g., just people walking by affects HIB position), making outdoor usage particularly limited. While the HIBs can reach very high (>20m), this limitation of stability could be tackled by anchoring a HIB with at least three strings/robots to increase stability.

**Limited Payload:** As we proposed to attach light objects to HIBs (LEDs and camera in Figure 14), each HIB can only carry approximately 5g, limiting the range objects that can be controlled by our system relative to others[61]. Future research could investigate combining multiple HIBs or larger HIBs to increase the payload (while balancing the trade-off with the HIB sizes), or light MEMS technology may be integrated to add very light functional components.

**Vertically Positioning Multiple-HIBs:** Also, there are other limitations caused by the use of reeling mechanisms. In terms of displaying 3D information spatially (as in Figure 13), the system can't place multiple objects in the same Z axis (or stacking HIBs), only using a 1 HIB and 1 ReelBot setup. This requires each HIB to be rigged with two or more robots to position multiple HIBs in the same Z-axis, but this will increase the number of robots to control an HIB, as a trade-off. Additionally, there is a risk for the reeling strings of each robot to get entangled, which can be problematic, especially with the instability being easily affected by atmospheric changes. While the current system only tracks the ReelBots' positions, future systems could add closed-loop control by tracking HIBs and strings as well to avoid undesired entanglement.

**Obstacle Collision, Entanglement, and Floor Clutters:** While we partially tackled the concern of robots' collisions with environmental obstacles using our optional collision avoidance via 2D paths (section 4.3.6), the future system could improve it in the 3D space with regards to HIB and strings' 3D placement to minimize unwanted collision or entanglement. Similarly, another limitation of our approach is their limited mobility on floors with heavy clutters, a common problem for other room-scaled mobile robots [21, 50]. This could be tackled by employing a robot base with advanced locomotion capability, such as quadruped robots.

**Helium Scarcity:** As a non-renewable resource, helium is reported to become less accessible overall, posing supply-chain issues in other industries [48]. Future work could seek to employ alternative, accessible, and sustainable light gas materials to support the approach of Buoyancé, by referring to research in aeronautics and other domains [24, 44], though safety and accessibility are needed for further improvement.

Alternatively, future work could explore recycling or reusing the helium that is leaked out of the HIB into the atmosphere. Research has been conducted towards recapturing leaked helium[1], though in an industrial context posing challenges for smaller-scale setups.

**Contrasting Buoyancé with Prior Research:** Together with the above listed challenges of our approach, in Figure 19, we provide a table that contrasts and compares our approach with relevant works in HCI, specifically enabling 3D, tangible, room-scale actuated UIs with levitating objects including ones mentioned in sections 2.1 and 2.2 (hence, excluding non-levitating TUIs [21, 50]). For example, Buoyancé features *(1) accessible deployment without special space instrumentation* by place mobile robots on the floor, unlike ceiling rig systems [2, 9, 61] requiring ceiling instrumentation. Secondly, Buoyancé enables *(2) safe, tangible interactions with levitating objects* thanks to the soft, light, and quiet HIBs, unlike works using drones [4, 20]. *(3) Scalable actuation area* is another advantage of our system, reaching high altitudes (>20m) while anchored to the

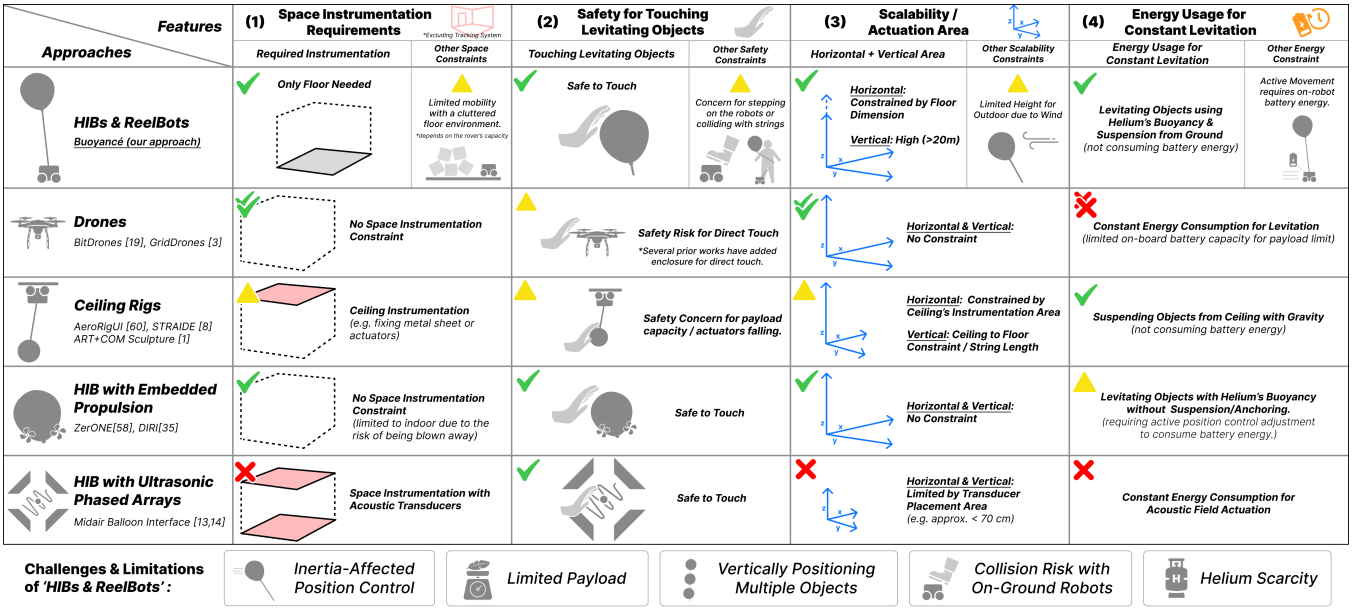



**Figure 19: Comparison of Buoyancé with relevant works in HCI, specifically enabling 3D, tangible, room-scale actuated UIs with levitating objects and Challenges of the proposed approach. — Icons for each cell represent subjective assessment [Double Checks: Excellent, Check: Good, Triangle: Fair, Cross: Poor, and Double Crosses: Very Poor. ]**

base robots on the ground, unlike works with limited spatial actuation area [14, 15]. Finally, Buoyancé features *(4) energy-efficiency for constant levitation* thanks to Helium, not requiring active energy consumption (e.g., batteries) to sustain the HIBs in the air, for example, having great potential for day-long usages.

As each method has pros and cons, we hope this comparison guides future researchers in selecting the technical approach, suiting their applications and needs across HIB-related and other technologies.

## 8.2 Functional Enhancements for Advancing Interactivity

**Enriching Sensing of ReelBots:** While our system employs external computer vision sensors to capture interactivity, sensing functionality could be fused into the ReelBots themselves. For example, ReelBots could be equipped with cameras to track human interaction (established topic in tracking humans with decentralized robots [22]). Such a collective tracking system could also be used to localize the robots [8], not requiring an external tracking system. Additionally, to enrich the sensing, HIBs could be turned into capacitive touch sensors, as the mylar materials are conductive [11]. Conductive strings could be employed for the reeling mechanism to track the delicate touch or proximity input/gesture by users. In such ways, prior research in extending the interactivity of balloons could be integrated [34, 43].

**Scaling the Number of ReelBots:** Increasing the number of robots is an evident future work we wish to investigate. Unlike Bluetooth-controlled devices (e.g., toio robots), our WiFi-controlled approach is suitable for scaling up the system. One of the bottlenecks to scaling up the number is the tracking method. Our current system (OptiTrack, 8 x Flex 13) is suitable to track up to 14 robots [4]. Self-localizing distributed systems in swarm robot research [7] could be integrated for future work.

**Extending and Improving Assembly:** The assembly procedure explored in this paper is preliminary and can be extended further in the future. For example, in our assembly, with the 1 HIB + 1 ReelBot setup, the HIB's yaw orientation was uncontrollable, and we had to wait until one of the HIB faces connected to the target face. In the future, advanced manipulation and string-handling for HIBs (e.g. using 1 HIB + 2-3 ReelBots setup) could be explored to achieve flexible, controllable, 3D assembly. Additionally, the HIBs are guaranteed to connect but only under the condition that there is no time limit and the faces that connect do not matter. In our implementation, the ReelBots simply moved towards one another to a distance smaller than the width of the HIBs. Thus, future research could explore more efficient automated controls for assembly such as overshooting or braking or accurately controlling the HIBs' orientation (e.g. two ReelBots to one HIB, two reels on one ReelBot, etc.). Alternatively, future research could explore fully-automated assembly (similar to [63]), which would require tracking of the HIBs and accurate 6DoF control. Future hardware design could also explore methods to unanchor HIBs from strings, allowing the assembled geometry to be employed independently (as seen in [51]).

## 8.3 Future Application Spaces and Studies

Finally, we hope to explore further application spaces that harness the unique capabilities of Buoyancé. For example, as the system can reach very high altitudes (>20m) for the size of the robots, the

[4] https://tinyurl.com/OptiTrackFlex13

height could be used for representational purposes (e.g. representing heights of buildings and architecture), locomotive purposes (e.g. extend the lifting functionality to locomote across floors in a building), and other functional purposes (e.g. delivering light objects to high floor windows or monitor emergent sights [55]). Other application spaces include harnessing the energy-efficient levitation capabilities for day-long public displays or advertisements by extending the info display applications.

Furthermore, future work could be geared towards enhancing the usability and overall user experience of Buoyancé. Many of the animations and motions of the ReelBots were designed purely through code, which is not accessible to a broad range of users. Thus, future work could explore incorporating elements such as a timeline for interactive swarm animations, potentially making it easier to transition between two different animations. Moreover, as the system currently allows for control by both hands of a single user (See Figure 9b), future work could explore implementing multi-user interaction given the nature of room-scale interaction.

Also, future studies could evaluate the user's acceptability or sense of safety in comparison to other research. As we have monitored in a public science exhibit that many children were comfortable interacting tangibly with the HIBs, we assume people may be more comfortable touching our system in contrast to other systems (shown in Figure 19) due to the balloons' inherent affordance and materiality.

Additionally, given the general acceptance of tangibly interacting with the HIBs, future work could explore Buoyancé as a haptic prop for VR. Past work has explored utilizing inflatable robots for soft haptics in VR [21], and Buoyancé presents potential to provide VR users with unique haptics, using HIBs and their extensive height capabilities.

## 9 Conclusion

This paper introduced Buoyancé, a novel approach for spatial actuated tangible interfaces, built with helium-inflated balloons (HIBs) controlled by on-floor omnidirectional wheeled robots with reeling mechanisms-concept implementation, based on a modified off-the-shelf omnidirectional rover, motion tracking system, with a custom control tools for users to easily manipulate the robots and HIB. Technical evaluation conveyed the capability, spec, and limitation of the system, and we demonstrated diverse applications across information display, room reconfiguration, and constructive assembly. Our user study studied and compared different control methods, and participants were able to quickly learn to move the HIBs in a seamless manner, providing insights into the perception of the system and control.

Through Buoyancé, we opened up a new pathway to build, design, and envision the future of everyday environments enriched and uplifted with spatially-distributed robots controlling gravity-defying HIBs.

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