

Floating Companion: Exploring Design Space for Soft Floating Robots in Indoor Environments

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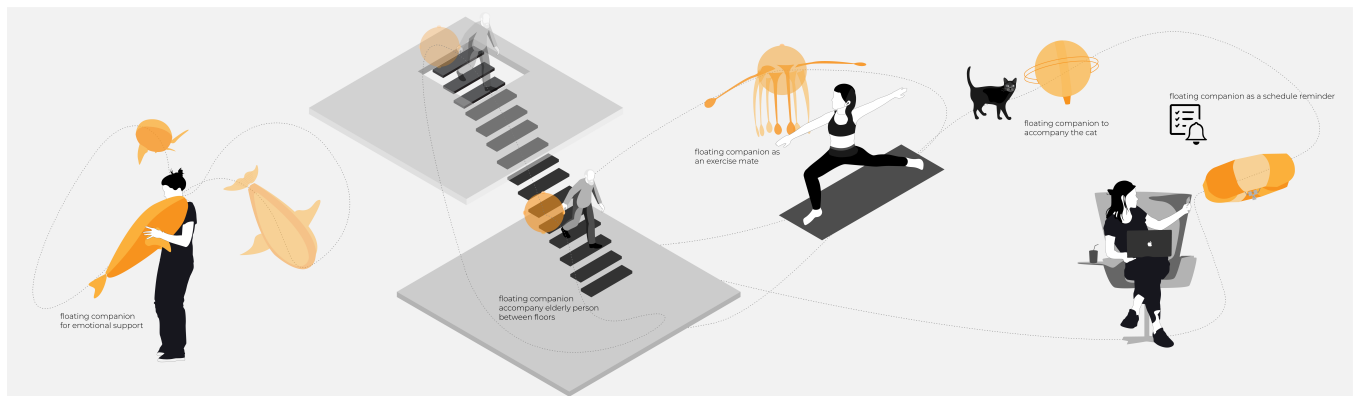


Figure 1: We explore how soft floating robots (SFRs) can integrate into indoor environments through varied relational, assistive, and atmospheric interactions. Illustrated here are different SFR forms supporting users in daily life (left to right): (1) a fish-like SFR exhibits lifelike swimming motions, circling around the user and offering gentle, calming touch that evokes the tranquility of an underwater world for emotional support; (2) a balloon-shaped SFR follows and orbits the user, providing on-demand assistance while freely navigating across floors and varied terrain; (3) a jellyfish-inspired SFR uses pulsating rhythms as visual cues for breathing, guiding meditation and fitness through embodied tempo; (4) an agile omnidirectional SFR enables remote interaction with pets at home, supporting playful engagement when the owner is away; (5) a cloud-like SFR gently approaches to deliver reminders, such as upcoming schedules or prompts to take a break after prolonged desk work.

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Abstract

Soft floating robots (SFRs) represent a shift from rigid machines, offering gravity-defying, compliant, and tactile embodiments for indoor cohabitation. However, their development remains fragmented across isolated prototypes, lacking a coherent design vocabulary. Without a systematic understanding of their interactional capabilities, designers struggle to leverage SFRs' unique affordances, and these systems often remain limited to novelty applications that are

difficult to integrate into everyday life. To address this, we propose a design space for interaction with SFRs. Informed by an exploratory study with 12 experts from HCI, Design, and Robotics, we identify ten design dimensions spanning physical, interactive, and behavioral properties, along with a range of application scenarios. We further present proof-of-concept design examples to demonstrate how this design space can support diverse interaction possibilities. This work contributes a structured framework for understanding and designing interactions with SFRs, supporting their integration into everyday indoor environments.

CCS Concepts

• **Human-centered computing** → **Ubiquitous and mobile devices**; **Interaction design theory, concepts and paradigms**.

Keywords

Soft Floating Robots, Design Space, Indoor, Human-Robot Interaction

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1 Introduction

From the mischievous glow of Tinker Bell¹, the gentle drift of Ghibli's Soot Sprites², and the loyal companionship of airborne pets like Pokémon's Drifloon³ and Mew⁴, popular culture has long imagined gentle, floating beings that share our living spaces. In fantasy role-playing games, such as *Dungeons & Dragons*⁵, these entities often act as extensions of the player, enriching perception and experience. Such visions reflect a persistent human desire for gentle, floating presences that are soft, ethereal, and untethered from the ground, cohabiting our full three-dimensional (3D) spatial environment rather than remaining bound to surfaces.

Recent developments in lighter-than-air soft floating robots (SFRs) bring us closer to this possibility. Defined as lighter-than-air robots with soft helium-filled envelopes, SFRs combine buoyancy-based 3D mobility, soft compliance, and relatively quiet operation [70, 113], making them promising for close-proximity indoor interaction under appropriate safety constraints [57, 105, 112].

Prior work on SFRs reveals several unique material and interactional qualities: (1) Safety through compliance: Their soft, lighter-than-air construction enables lower-risk gentle contact and operation above people [105, 112], unlike rotor-based drones; (2) Quiet and gentle 3D mobility: They utilize mid-air space for spatial interaction without downwash or noise of drones [70, 113]; (3) Customizable form: their inflatable bodies support diverse morphologies, from marine animals [13, 30, 31, 111, 112] to clouds [94, 117], humanoid silhouettes [24], and geometric shapes [42, 66, 113]. In

summary, SFRs hold significant potential to enrich our physical environments with embodied spatial experiences. We envision a future in which floating companions drift through indoor spaces, taking on companionship-oriented, assistive, and ambient roles that enhance daily life. In this paper, we use the term *Floating Companion* to describe one relational orientation in which soft floating robots support nearby co-presence and interaction in shared indoor environments. This is not intended as a label for all SFR applications; rather, the broader design space also includes assistive and atmosphere-based roles. In that sense, we use the term *companion* to describe entities that engage in ongoing, non-hierarchical co-presence with users, encompassing emotional, ambient, and assistive interactions beyond purely instrumental use. By embracing human imagination, SFRs can open new avenues for ubiquitous computing, aligning with a broader shift toward adaptable, seamlessly integrated robotic systems [17, 35, 92].

Yet, despite promising progress, we lack a coherent design vocabulary for this emerging morphology. Most studies investigate single prototypes or narrow scenarios, offering limited guidance for designing interactions more broadly. As a result, we lack a systematic understanding of how SFRs can move, behave, and interact with humans across diverse contexts. There is currently no unified design space that articulates the interactive possibilities afforded by SFRs, leaving designers without actionable guidance for developing interactions with soft floating robots.

To address this gap, we move beyond singular prototypes and present a design space that maps the interactive possibilities of this emerging class of robots. Our goal is to establish a foundational framework that can inform future research and design. We explore how SFRs might support a broader range of activities in everyday indoor environments and how their unique 3D mobility can extend their usefulness beyond functional tasks. As floors, tables, and other surfaces become increasingly saturated with smart devices, the volumetric mid-air space remains an underutilized interaction space—one that SFRs are uniquely positioned to occupy. Leveraging this spatial layer offers new opportunities for SFRs to provide meaningful support in people's daily lives.

While prior work has introduced diverse SFR prototypes, the field lacks a unified framework to guide their interaction design. This study addresses this gap by moving beyond isolated examples to establish a structured foundation for interaction with SFRs. Our study explores the following research questions:

RQ1: What is the design space for creating interactions with soft floating robots?

RQ2: What roles and functions might soft floating robots fulfill in everyday indoor environments?

To answer these questions, we conducted an exploratory study with 12 experts from HCI, HRI, Design, and Robotics. Through thematic analysis of the interview data and informed by existing literature, we derived a ten-dimensional design space describing how SFRs can move, behave, and engage with humans and environments (Sec. 4). The study also yielded a rich set of application use cases, expanding the known functionalities of these robots (Sec. 5). Then, we ground these possibilities in engineering reality through a Physics-Design Dependency Framework (Sec. 6.1), synthesizing actionable design principles (Sec. 6.2). Finally, to demonstrate the generative power

¹<https://fairies.disney.com/tinker-bell>

²<https://ghibli.fandom.com/wiki/Susuwatari>

³<https://www.pokemon.com/us/pokedex/drifloon>

⁴<https://www.pokemon.com/us/pokedex/mew>

⁵<https://www.dndbeyond.com/>

and technical feasibility of the design space, we implemented proof-of-concept demonstrations that instantiate design dimensions and principles (Sec. 7). Collectively, our approach highlights how SFRs can be leveraged to enhance and support contemporary lifestyles.

In summary, this work establishes a foundational framework for SFR interaction through four key contributions:

- (1) **A 10-dimensional design space** for creating interactions with SFRs, derived from an expert study—to our knowledge, the first systematic framework for SFR interaction design.
- (2) **A diverse set of application cases** that illustrate the range of SFR roles, spanning presence-based, function-based, and atmosphere-based scenarios.
- (3) **Three core design principles** distilled from the design dimensions. Grounded in the physics-design entanglement of lighter-than-air bodies, these principles provide actionable guidance for navigating trade-offs and leveraging SFRs' unique qualities.
- (4) **Proof-of-concept design examples** implemented on a representative flapping-wing platform, illustrating how the principles can be instantiated to enable novel SFR interactions.

2 Related Work

2.1 Soft Floating Robots: Embodiments and Actuation

Our work builds on the growing interest in materiality within HCI. Researchers have explored soft interfaces [14, 83, 95] to support physical and emotional interactions. In parallel, a substantial body of work has investigated flying robots designed to interact with people in human-drone interaction (HDI) [9, 46, 53, 61, 77, 93, 106], conceptualizing them as flying companions that could enter everyday life [38, 40, 58]. However, most of this research has focused on rigid, propeller-driven drones. In contrast, soft floating robots (SFRs) extend this line of inquiry into mid-air by combining softness and buoyancy, thereby liberating soft interfaces from ground-based constraints and opening new possibilities for aerial interaction.

Our research focuses on soft floating robots. For this study, we define a soft floating robot (SFR) as an untethered, autonomous, or semi-autonomous agent that can typically hover in the air without active power. An SFR satisfies three core conditions:

- (1) Its primary interactive surface is soft and compliant.
- (2) It possesses controlled actuation and sensing, enabling mobility and interaction.
- (3) It is lighter-than-air, generating lift primarily through static buoyancy (e.g., helium).

This definition explicitly distinguishes SFRs from heavier-than-air soft drones (e.g., [44, 107]). Unlike the drones that rely on high-speed propellers or flapping wings for lift—introducing noise and safety hazards—SFRs rely on buoyancy, enabling close-proximity indoor interaction. Within this definition, the emerging SFR domain exhibits diverse actuation methods (Figure 2). We classify propulsion into two high-level categories: Bio-Inspired Propulsion and Vectored Thrust Propulsion. Bio-inspired Propulsion includes flapping wings [30, 31, 69, 81, 112], oscillating tail fins [25, 64], and jellyfish-like peristaltic motion [32]. These robots mimic animal locomotion, producing organic, life-like movements that appear to “swim”

through the air with gentle, rhythmic trajectories and low noise. Vectored Thrust Propulsion relies on engineering-based thrust generation via propeller-driven or propeller-free methods. Propeller-driven type generally offers stronger maneuverability, speed, and payload capacity with mature control models, though their motion often appears more mechanical [60]. A notable Propeller-free SFR is the ultrasonic micro-blower system in [113], which uses vibrating piezoelectric elements to create jet flows. This enables quiet propulsion and safe, close-proximity interaction [91, 113].

Despite this hardware diversity, SFRs share fundamental material properties that separate them from other platforms. Table 1 summarizes representative trade-offs between SFRs and multirotor drones in indoor human interaction. While flapping-wing drones are also a relevant aerial morphology for comparison, prior HDI research has focused predominantly on multirotor platforms, with physical interaction studies on flapping-wing drones remaining limited. We therefore use multirotor drones as the primary comparison baseline here. SFRs uniquely bridge the gap between mobility and safety by combining 3D flight with “safety through compliance.” Yet, physical advantages alone do not guarantee meaningful interaction. To address these gaps, our study moves beyond single-prototype evaluation to synthesize a structured design space that supports the intentional design of interactions with SFRs.

2.2 Technical Capabilities for Human-Robot Interaction

SFRs have demonstrated a growing range of sensing and interaction capabilities. The GT-MAB (Georgia Tech Miniature Autonomous Blimp), equipped with a monocular camera, has achieved face detection and following [96, 114], hand-gesture recognition [88, 115], and interaction through pointing motions [48]. Approaches utilizing Ultra-Wideband (UWB) localization have further enabled user following and mid-air gesture recognition, even supporting dynamic theatrical performances [66]. These advances lay the groundwork for responsive and socially aware floating companions. Given the absence of GPS indoors, researchers have explored a variety of localization and navigation solutions. SFRs can navigate autonomously as single robots [23, 42, 75] or operate in coordinated groups. eMotionSpheres [33] demonstrated collision-free swarm flight using infrared tracking, while installations such as FLOCK OF [13] and Aerobes [54, 55] showed that SFR collectives can move safely around visitors and create immersive spatial experiences.

Semi-autonomous SFRs have also expanded possibilities for remote presence. The Floating Avatar transformed a blimp into a telepresence platform using projected visuals and audio [99], while flapping-wing robotic avatars enabled embodied remote control through a body-tracking system [111]. Other work has introduced autonomous docking for teleoperated airships, enabling continuous operation via automated landing and charging [79].

Together, these studies highlight diverse technical capabilities—from perception to mobility to telepresence—that begin to support the vision of intelligent floating companions. However, most techniques have been developed and tested in isolation. We still lack an understanding of how these capabilities can be integrated and orchestrated to create coherent user experiences across varied contexts. From an HCI perspective, realizing the everyday potential of SFRs

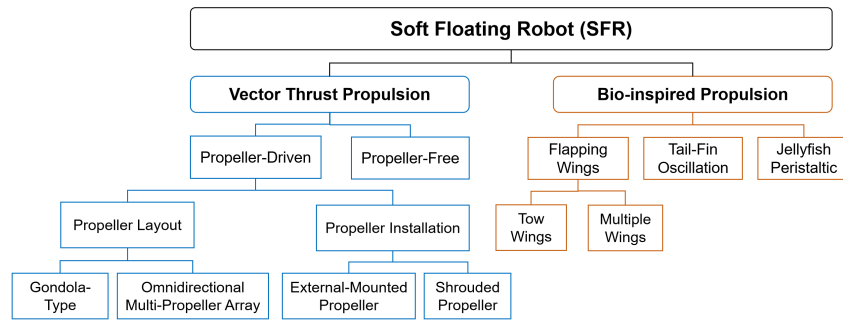


Figure 2: Actuation taxonomy of soft floating robots (SFRs). Based on propulsion mechanisms, SFRs can be broadly categorized into vectored-thrust propulsion and bio-inspired propulsion. Vectored-thrust systems rely on controlled force generation, typically using propellers or equivalent mechanisms: gondola-type propeller-driven SFR (e.g., [115]), omnidirectional multi-propeller array SFR (e.g., [34]), external-mounted propeller SFR (e.g., [18]), shrouded propeller SFR (e.g., [50]), and propeller-free SFR using alternative thrust mechanisms (e.g., [113]). Bio-inspired systems emulate biological motion patterns, such as flapping or oscillation: multi-wing flapping SFR (e.g., [81]), two-wing flapping SFR (e.g., [30]), tail-fin oscillation SFR (e.g., [25, 64]), and jellyfish-like peristaltic SFR (e.g., [32]).

Table 1: Representative trade-offs between soft floating robots (SFRs) and multirotor drones in indoor human interaction. The comparison emphasizes interaction-relevant tendencies rather than absolute properties.

	Soft Floating Robot	Multirotor Drone
Lift Mechanism	Static buoyancy-based lift	Continuous rotor thrust
Environmental Disturbance	Typically lower airflow disturbance	Strong downwash; disturb lightweight or fragile objects
Motion Speed	Slow, gentle motion	Fast, agile maneuvering
Motion Quality	Organic, floating, indeterminate drift	Precise, mechanical, vector-driven
Payload Budget	Lower; typically limited by helium volume	Often higher relative payload capacity
Contact Tolerance	Soft body and low mass absorb impact	High-speed rotors require strict no-touch zones
Proxemic Zones	Often favorable in low-disturbance indoor conditions	Often constrained by noise, downwash, and exposed rotors
Failure Mode	Floats or slowly descends	Falls or crashes abruptly
Positional Precision	Often lower; drift and compliance may be interactionally useful but reduce precision	High precision and maneuverability
Acoustic Profile	Lower noise	High-frequency noise
Sensitivity to Airflow	Often high sensitivity to airflow	Lower in holding position, though generates its own airflow
Hovering Endurance	Extended endurance (power-free floating)	Limited endurance (constant thrust required)
Morphological Customizability	Inflatable envelopes often support broad shape variation	Morphology is more constrained by rigid frames

requires not only technical progress but also a systematic investigation of their interaction design. Establishing a structured design space for SFRs is therefore a critical first step.

2.3 Experiential Dimensions: Safety, Proximity, and Emotion

Robots increasingly engage with humans in everyday contexts, taking on social roles [21, 26, 49] and offering emotional support [29, 56, 90]. Recent HCI and HRI research emphasizes the need for safe, physically accessible interactions [1, 22, 28, 82, 89]. Across several empirical studies—each centered on a specific SFR prototype—a shared picture has emerged: SFRs hold unique potential for shaping new experiential dimensions in physical and social interaction.

A foundational insight from prior work is the perception of safety and approachability. BalloonBot [105] demonstrated that users view balloon-shaped robots as safe and socially acceptable, forming a positive basis for interaction. Cuddle-Fish [112] extended

this by exploring close-proximity interaction; participants not only felt safe around a flapping-wing SFR but also initiated spontaneous touch and affective behaviors. These findings suggest that SFRs can support a progression from safe coexistence to emotionally meaningful engagement. Further work shows that SFR forms and motions—especially flapping wings—can serve as expressive social gestures such as hugging, shoulder patting, or high-fives [110, 111]. Additional studies exploring hand-gesture interaction with GT-MAB [88, 115] and user perceptions of autonomous floating interfaces like Diri [70] further enrich the interaction design landscape for SFRs. Beyond one-to-one interaction, SFRs have also enabled immersive spatial experiences. FLOCK OF [13] presents a school of fish-like robots that “swim” through the air, allowing visitors to walk among—evoking a robotic aquarium. The Aerobes [54, 55] demonstrate long-term autonomous operation in public spaces, with each agent expressing its own behavioral tendencies and responding to crowds via thermal sensing, illustrating the potential for context-aware group behavior.

3 Methodology

To explore the potential capabilities of soft floating robots (SFRs) and define a design space for interaction, we conducted an expert-informed study. Given the nascent stage of SFR technology, engaging end-users with current prototypes risks conflating technical hardware limitations with interactional failures. Accordingly, our objective was not to validate end-user needs or preferences, but to elicit a generative, expert-informed design space that can guide future user-centered investigations. Therefore, we conducted an interview study with a speculative provocation structure inspired by prior work exploring the untapped potential of domestic cleaning robots [92].

3.1 Participants

We recruited a diverse group of 12 experts (5 female, 7 male) specializing in HCI, HRI, Design, and Robotics. We engaged these individuals not merely as study participants, but as co-speculators. This ensured a holistic perspective covering both user experience (HCI and Design) and technical feasibility (Robotics). Their experience ranged from 2 to 40 years ($M = 10.42$, $SD = 11.28$), and their backgrounds spanned from academic faculty to industry professionals. In addition to professional diversity, experts were based across seven residence locations (Table 2).

3.2 Procedure

We conducted individual semi-structured online sessions. The process was divided into three phases: **(a) Briefing**: experts were introduced to the study goals and provided consent; **(b) Provocation**: to ground the speculation, experts viewed video probes of existing SFRs to stimulate creative thinking, employing methods from [92]; **(c) Co-Speculation**: experts discussed their daily routines and co-created scenarios describing how SFRs could inhabit and support their everyday life. We probed for specific details regarding the robot's behavior, spatial positioning, and communication modalities. Sessions lasted approximately one hour and were recorded for analysis. The protocol was approved by the university's ethical review committee.

3.3 Data Analysis

All interviews were transcribed and checked against the recordings for accuracy. We conducted a thematic analysis [15] to develop the design space and application categories. To establish an initial coding structure, the first and second authors independently open-coded the same subset of transcripts (2 of 12 interviews) at the level of meaning units relevant to the research questions. They then compared their codes, discussed overlaps and discrepancies with reference to the original excerpts, and consolidated them into a preliminary codebook. This preliminary codebook was organized into two broad analytic clusters: codes related to design-space dimensions and codes related to application use cases. Using this preliminary codebook, the same two researchers independently re-coded the shared subset, yielding an inter-rater reliability of Cohen's kappa = 0.72 and percentage agreement = 85.2% [62]. Disagreements were resolved by revisiting the original transcript segments and refining code definitions. The refined codebook was then used to code the remaining transcripts and was iteratively

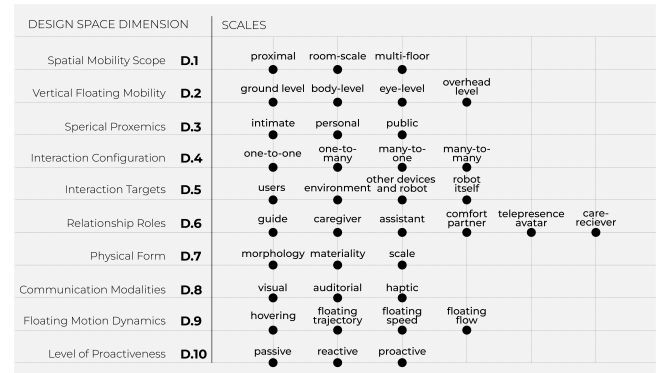


Figure 3: Overview of the ten-dimensional Design Space for Interaction with soft floating robots (SFRs). The diagram synthesizes key attributes across mobility, behavior, and form, illustrating the spectrum of interactive qualities inherent to lighter-than-air embodiments in indoor environments.

revised through discussions among the research team. Lower-level codes were regrouped into candidate higher-level themes, which were merged, split, renamed, and clarified until a stable thematic structure was reached. This process resulted in a final codebook of 49 codes⁶, which supported the development of the ten design dimensions and three primary categories of application use cases. We do not claim exhaustive saturation of all possible SFR interactions or use cases; rather, we reached sufficient thematic coverage at the level of the final framework, with no substantially new top-level design dimensions emerging in the final three interviews. All procedures adhered to data protection and privacy requirements and the ethical research policy of the local institutional ethics review board.

4 Design Space

Based on expert sessions and informed by existing literature, we identify ten dimensions for designing interactions with soft floating robots (SFRs) (Figure 3). We use bio-inspired SFRs as our main examples, as this form was most frequently discussed by experts. These dimensions are grounded in the physical properties of helium-based flight (See Sec. 6.1), including buoyancy, softness, and low inertia, which fundamentally shape how SFRs move, interact, and are perceived.

While some dimensions relate to established HRI and interaction design concepts, such as social perception (e.g., form and expressiveness) [8], interaction dynamics (e.g., responsiveness and autonomy) [47], their realization is shaped by SFRs' physical properties, enabling forms of interaction not present in conventional robots. These properties enable close-range interaction, gentle contact with people and surroundings, and access to mid-air space without noise or downwash. The following dimensions characterize these interaction possibilities from complementary design perspectives, each capturing a different aspect of interaction design.

⁶The final codebook for this study is available at <https://osf.io/4m82r/>.

Table 2: Professional and demographic details of the expert participants.

ID	Gender	Residence	Occupation	Experience (in years)	Area of Expertise
1	M	USA	Professor	40	HCI (Tangible User Interfaces)
2	M	China	PhD Candidate	4	Robotics and HRI (Soft Robot)
3	F	Netherlands	PhD, Researcher	13	HCI (VR, Human-AI Collaboration)
4	M	Japan	Professor	25	HCI (Ubiquitous Computing)
5	M	China	PhD Candidate	5	Robotics and Aerospace
6	M	Japan	PhD Candidate	6	Robotics and Computer Vision
7	F	Japan	Industry (Research Engineer)	3	Interactive Design
8	M	Canada	Industry (Research Engineer)	8	Interactive Design
9	F	Hong Kong	HCI Researcher	2	HCI (Embodied Interaction)
10	F	Japan	PhD, Industry (Research Engineer)	4	HCI (Affective Computing)
11	F	Germany	Professor	11	HRI and HCI (Inclusive Technology)
12	M	Japan	PhD Candidate	4	HRI (Human Augmentation)

4.1 D1: Spatial Mobility Scope

SFRs can operate across multiple spatial scales, from proximal interactions to room-scale and even multi-floor environments, enabled by their buoyant movement (Figure 4). Their low inertia with soft envelopes allows safe interaction through gentle contact with people and surroundings, reducing spatial constraints and expanding the robot's usable movement space. They can hover quietly near users without generating downwash or noise, and occupy mid-air space to move over obstacles and navigate more freely. As P3 noted, this vertical mobility enables SFRs to inhabit unused "dead space" in domestic environments: *"It can float over living-room clutter or drift up the stairs, occupying air that ground robots can't reach."* This capability allows SFRs to transition across floors via staircases or open atriums, extending their range of operation beyond a single room [27, 84]. This dimension guides designers in selecting appropriate spatial ranges for interaction, helping them align the robot's mobility with intended use scenarios.

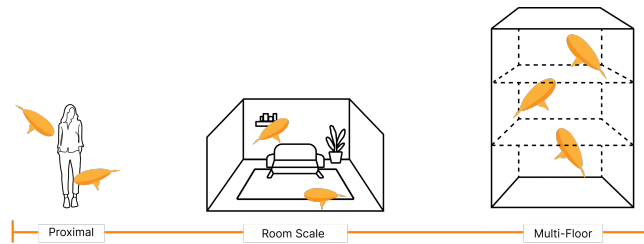


Figure 4: Spatial Mobility Scope: (1) Proximal: The SFR floats within the user's arm reach for close interaction. (2) Room-Scale: The SFR moves freely through mid-air space, bypassing ground obstacles. (3) Multi-Floor: The SFR transitions vertically between floors via staircases or atriums.

4.2 D2: Vertical Floating Mobility

This dimension captures an SFR's ability to modulate its altitude to position itself relative to the user's body (Figure 5). SFRs can align with users' postures across vertical zones, enabling flexible spatial interaction. At the ground level, their soft bodies enable safe,

animal-like behaviors such as gently nudging a user's legs [97], supporting natural interaction with children and pets. At body and eye levels, SFRs position themselves for face-to-face interaction. As P9 noted, *"It feels respectful [...] if I sit down, it lowers itself to meet my gaze."* The overhead zone, typically inaccessible to ground robots and unsuitable for rigid drones, becomes a usable interaction space, where SFRs can hover without occupying floor area. This dimension focuses on where interactions occur relative to the user's body. It helps designers use height as a design parameter to position interactions across vertical zones, supporting different forms of engagement.

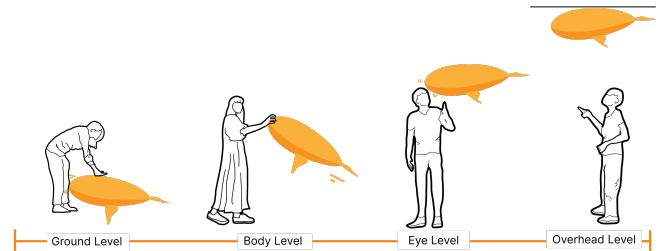


Figure 5: Vertical Floating Mobility: (1) Ground Level: The SFR operates near the floor for low-position interaction. (2) Body Level: The SFR aligns with the user's torso for mid-level interaction. (3) Eye Level: The SFR positions at eye height for face-to-face interaction. (4) Overhead Level: The SFR operates above the user, using upper spatial zones.

4.3 D3: Spherical Proxemics

This dimension extends Hall's proxemics [43] from a 2D planar model to a 3D volumetric one (Figure 6). While D2 focuses on physical positioning in vertical space, D3 addresses how distance is perceived and interpreted in terms of social and emotional proximity. SFRs move across both vertical and horizontal axes, forming a spherical proxemic field that allows them to enter, inhabit, or exit personal space from multiple directions, including overhead. They can hover quietly within peri-personal space and also move into more distant zones to provide ambient awareness while remaining

non-intrusive. As P4 described: “It’s like a pet bird landing on your head or shoulder, soft and not noisy, but a drone would feel dangerous.” Rather than treating proxemic zones as fixed categories, we conceptualize them as a continuous 3D spectrum [103]. This dimension helps designers use distance in three dimensions to regulate interaction intensity, shifting from intimate, close-range engagement to more peripheral interaction.

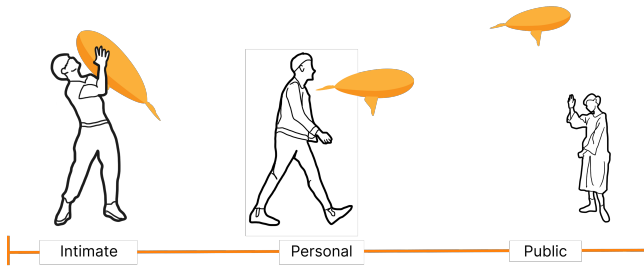


Figure 6: Spherical Proxemics: Distance is interpreted as a continuum of social and emotional proximity. (1) Intimate: The SFR operates very close to the user, supporting highly personal interaction. (2) Personal: The SFR maintains a comfortable distance for interaction. (3) Public: The SFR remains more distant, supporting shared or ambient interaction.

4.4 D4: Interaction Configuration

This dimension describes the ratio of robots to users, ranging from one-to-one interaction to multi-user and multi-robot configurations (Figure 7). SFRs can flexibly shift between configurations due to their soft structure and low inertia, enabling safe operation in close proximity and higher-density clustering in mid-air. This allows collisions to be experienced as safe interactions rather than failures, supporting new forms of collective engagement. As P7 envisioned: “We can create an air aquarium [...] the robots bump and drift like a swarm of jellyfish, and we can walk through the swarm, feeling the touch.” In multi-user settings, this enables shared physical interaction, where users can pass, guide, or play with SFRs. This dimension helps designers choose appropriate interaction configurations by balancing the number of robots and users, enabling both individual interaction and collective experiences.

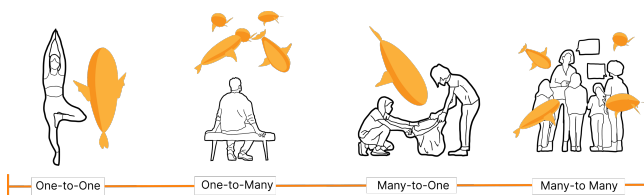


Figure 7: Interaction Configuration: (1) One-to-One: A single user interacts with one SFR. (2) One-to-Many: A single user interacts with multiple SFRs. (3) Many-to-One: Multiple users interact with a single SFR. (4) Many-to-Many: Multiple users interact with multiple SFRs in a shared space.

4.5 D5: Interaction Targets

This dimension categorizes the entities with which an SFR can interact (Figure 8), including users, the environment, other robots or devices, and the robot itself. Due to their softness and low down-wash, SFRs have the potential to engage with a wider range of interaction targets. For example, they may move through plant canopies or hover near pets while generating less airflow disturbance than rotor-based drones. Their soft bodies may also tolerate gentle contact with walls or furniture, enabling designers to consider contact-based interaction rather than treating all collisions as failures.

SFRs can further collaborate with ground robots through spatial complementarity: while ground units operate at the floor level, SFRs provide overhead access, enabling coordinated multi-layer coverage of indoor environments. Experts also identified a unique target category—the self. SFRs can remain in a free-floating idle state, where subtle drifting motion introduces variability in behavior. As P2 noted: “When a vacuum robot docks, it becomes dead weight. But the floating robot drifts and rotates on its own, as if engaging in self-play, it keeps a pulse of life even when it’s doing nothing.” This dimension helps designers determine what the SFR interacts with, supporting the design of interactions with people, environments, other systems, and the robot’s own behavior.

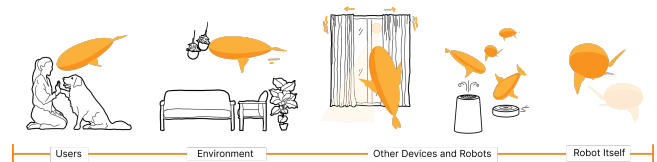


Figure 8: Interaction Targets: (1) Users: The SFR interacts directly with a person. (2) Environment: The SFR engages with surrounding objects and surfaces. (3) Other Devices and Robots: The SFR coordinates with other systems across spatial levels. (4) Self: The SFR exhibits self-directed motion during idle states.

4.6 D6: Relationship Roles

This dimension describes the social roles an SFR can take in relation to the user (Figure 9). The softness, buoyancy, and gentle motion of SFRs enable a range of relational roles that are difficult to achieve with rigid drones. SFRs can act as guides, leading users from overhead or side-by-side positions while maintaining a consistent position relative to the user, even when moving across levels such as staircases. Their soft, floating presence evokes cultural archetypes such as guardian angels or sprites, making them well-suited for caregiving roles. Their ability to adjust height supports inclusive interaction with users of varied physical conditions, from crawling infants to wheelchair or bedridden users. As assistants, SFRs can operate from an overhead vantage point, providing support without occupying floor or table space. SFRs can also take on more affective roles. For example, their soft bodies allow safe physical contact, enabling forms of touch-based interaction. In telepresence scenarios, SFRs can act as embodied proxies, allowing remote users to interact physically through movement and positioning.

Finally, central to the care-receiver role, the SFR's inherent clumsiness and balloon-like fragility align with the "weak robot" concept [72] and design approaches that frame vulnerability as a mechanism to elicit care [6]. As P10 noted, *"When it gets stuck in a draft, it looks like a clumsy puppy asking for help."* This vulnerability is not a functional failure but a relational resource, fostering empathy and attachment through acts of care. This dimension helps designers map the robot's physical properties (e.g., height adaptability, softness, limited control) to social roles, supporting interaction design across guidance, assistance, and care-oriented scenarios.

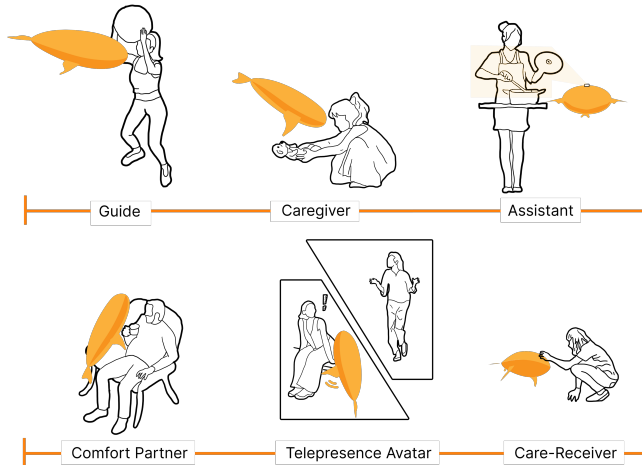


Figure 9: Relationship Roles: (1) **Guide:** The SFR supports navigation or task flow. (2) **Caregiver:** The SFR interacts at a low height to engage with users such as young children. (3) **Assistant:** The SFR provides support from a peripheral or overhead position (e.g., displaying cooking recipes). (4) **Comfort Partner:** The SFR enables gentle touch-based interaction (e.g., hug). (5) **Telepresence Avatar:** The SFR serves as a remote embodiment, enabling physical interaction that conveys touch cues from a distant partner. (6) **Care-Receiver:** When the robot becomes stuck due to airflow, it emits a soft sound cue that invites the user to help.

4.7 D7: Physical Form

This dimension focuses on the SFR's physical form, including morphology, materiality, and scale (Figure 10). Unlike rigid robots with fixed shells, SFRs use inflatable envelopes that offer extensive morphological plasticity. Designers can shape them into zoomorphic, geometric, or abstract forms, each conveying different emotional tones. As P7 noted: *"You can shape it into a cloud, it can give people a calm, relaxed feeling just by floating there."* Such visual language shapes first impressions and influences perceived animacy and approachability. Materiality is also crucial. Because SFRs enter intimate spatial zones (D3) and invite physical touch, the tactile quality of their surfaces matters. Options range from technical balloon films (e.g., nylon-aluminum film, TPU) to soft, fabric-like coverings (e.g., cotton) that enhance warmth and reduce perceived threat. Scale further expands design possibilities. Inflatable bodies can range from

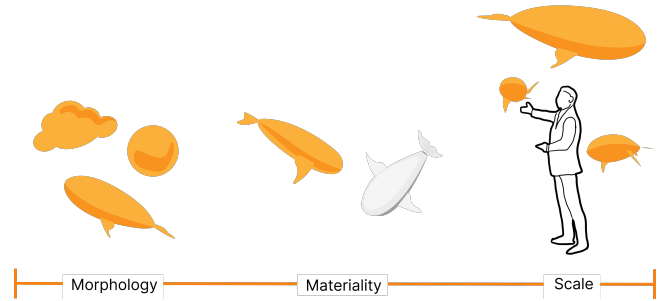


Figure 10: Physical Form: (1) **Morphology:** The SFR adopts diverse shapes, such as clouds, geometric spheres, or marine-inspired forms. (2) **Materiality:** Different materials provide distinct textures and visual qualities. (3) **Scale:** SFRs range from small, body-proximal robots to large-scale installations in public space.

small personal robots (e.g., GT-MAB [115]) to large, architectural-scale installations (e.g., Festo Air_ray [31]). However, designers must balance scale with payload-volume constraints (Sec. 6.1) to ensure flight feasibility. This dimension encourages designers to leverage the SFR's customizability, using soft forms, tactile materials, and appropriate scale, to align physical embodiment with desired social character and interaction style.

4.8 D8: Communication Modalities

This dimension describes the channels through which an SFR communicates (Figure 11). The softness and floating motion of SFRs enable a unique set of multimodal strategies. Visual communication extends beyond screens or LEDs to include kinetic cues. Bio-inspired SFRs can use rhythmic appendage motions, such as flapping wings or undulating fins, and expressive 3D trajectories to signal intention or emotion. Auditory communication benefits from the SFR's quiet operation. Unlike drones with disruptive rotor noise, SFRs produce only gentle motor hums that can serve as soft localization cues without being disruptive. They also generate subtle environmental sounds, such as lightly brushing against a wall, to request attention. Haptic communication is enabled by the robot's deformable, helium-filled body. Users can squeeze or tap the robot as a form of input, while the robot can initiate gentle physical contact. As P3 imagined: *"It could remind me not with an annoying beep, but by lightly bumping me, like a pet nudging you."* This dimension helps designers to choreograph multimodal communication by combining visual, auditory, and haptic cues, leveraging soft contact, quiet motion, and subtle environmental interaction.

4.9 D9: Floating Motion Dynamics

This dimension describes the kinematic qualities of an SFR's movement (Figure 12). SFR motion is shaped by passive buoyancy, resulting in dynamics that are smooth, inherently slow, and partially indeterminate. Rather than maintaining rigid stillness, SFRs naturally float and often exhibit small drifts influenced by air currents. As P5 observed: *"It doesn't just hang there like a drone, the way it drifts around feels like a living thing breathing."* SFRs tend to follow

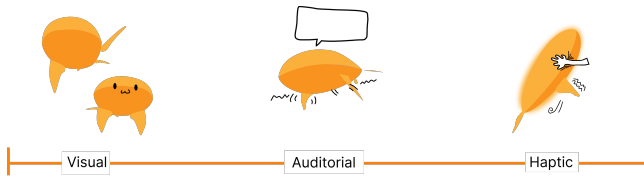


Figure 11: Communication Modalities: (1) Visual: The SFR uses shape, motion, and trajectory to convey information (e.g., displays facial expressions) (2) Auditorial: The SFR produces subtle motor sounds and environmental interactions that support localization and signaling. (3) Haptic: The SFR enables gentle physical contact through its soft body.

curvilinear, continuous paths rather than sharp, linear drone-like trajectories. Because SFRs are light and move through air slowly, they accelerate gradually and avoid abrupt movements. This results in smooth, gentle motion. Air currents can also cause small, natural variations, such as slight swaying or drifting.

This dimension encourages designers to embrace, rather than correct, the inherent imprecision, slowness, and environmental drift of SFR motion. Leveraging smooth trajectories and slow velocity profiles can shape a relaxed interaction tempo while maintaining a non-threatening presence.

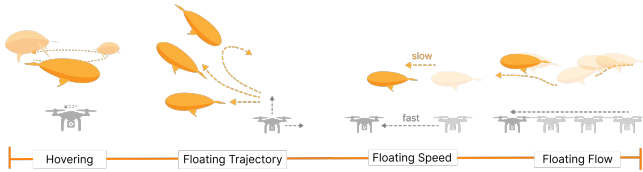


Figure 12: Floating Motion Dynamics: (1) Hovering: The SFR maintains position with slight drift (e.g., like a cloud). (2) Floating Trajectory: The SFR approaches the user following smooth, curved paths. (3) Floating Speed: The SFR moves at a slow, gentle pace, with smooth acceleration and deceleration. (4) Floating Flow: The SFR exhibits continuous, non-uniform motion influenced by environmental forces (e.g., air currents).

4.10 D10: Level of Proactiveness

This dimension describes how the SFR behaves, ranging from passively responding to external forces to actively initiating interaction. (Figure 13). In a passive mode, the SFR is driven by external forces. Users can push, hug, or toss it safely. In a reactive mode, it adjusts its height (D2) or proximity (D3) in response to user actions or environmental changes, for example, lowering itself when a user sits to stay at eye level. In a proactive mode, the SFR initiates interactions based on internal triggers. Unlike rigid robots that depend on audio-visual alerts, SFRs can express proactivity through gentle physical cues. As P4 described: “It doesn’t just beep from a distance, it floats over and gently bumps my shoulder to say ‘hey’.” This is enabled by its soft, low-inertia structure. This dimension helps designers calibrate the SFR’s level of agency across passive, reactive,

and proactive behaviors, using physical actions to initiate interaction, shaping how the robot engages with users and is perceived by them.

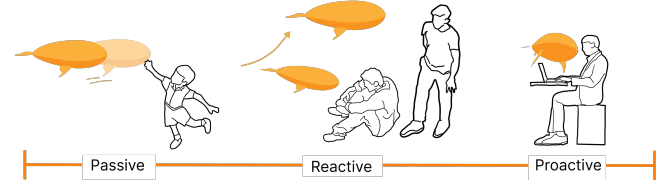


Figure 13: Levels of Proactiveness: (1) Passive: The SFR responds to external forces and user manipulation (e.g., like a balloon). (2) Reactive: The SFR adjusts its position in response to user actions or environmental cues. (3) Proactive: The SFR initiates interaction through movement and gentle physical touches.

4.11 Linkages in the Design Space

The design dimensions presented here serve as foundational elements for developing SFR interactions. Together, they provide a starting point for translating the distinctive qualities of SFRs, such as buoyancy, softness, lightness, and aerial mobility, into design considerations. In this section, we clarify how these dimensions relate to one another while preserving their distinct roles.

4.11.1 Interdependencies Between dimensions. Some dimensions influence one another due to the complexity of robot interactions [92] and are often coordinated when shaping the robot’s presence around users. For example, proximal mobility in D1: *Spatial Mobility Scope* can support intimate or personal engagement in D3: *Spherical Proxemics*, while the same vertical layer in D2: *Vertical Floating Mobility* may correspond to different proxemic qualities depending on distance. For instance, an overhead SFR may hover close above the user to create a sense of closeness, or remain farther away as a more ambient and less intrusive presence. D8: *Communication Modalities*—particularly haptic interaction—is tightly linked to D3: *Spherical Proxemics*. Haptic communication presupposes that the SFR operates within the intimate proxemics. This intimate configuration, in turn, places critical demands on D7: *Physical Form*, specifically scale. If an SFR is too large, its volumetric presence may itself generate a sense of encroachment that psychologically pushes users away. Designers should therefore carefully calibrate scale to remain approachable rather than overwhelming. D7: *Physical Form* shapes how D8: *Communication Modalities* can be realized. Morphology, materiality, and scale affect how the robot is perceived, how touchable it feels, and how communicative cues are experienced. Finally, D10: *Level of Proactiveness* can support particular relationship roles in D6. Lower-proactiveness modes, especially passive behavior, can support the care-receiver role by making the robot’s vulnerability and reliance on user assistance more visible, whereas more proactive behavior may align more readily with roles such as guide, assistant, or caregiver.

4.11.2 Distinct Yet Complementary Dimensions. All ten dimensions address distinct aspects of interaction, although many are complementary in practice. For example, *D1: Spatial Mobility Scope* concerns the extent of space within which the robot can operate, whereas *D3: Spherical Proxemics* concerns how the robot's presence is socially experienced in relation to the user. In this sense, the two dimensions may be coordinated in practice, but they address different layers of interaction: one concerns operational reach, while the other concerns interpersonal distance and interaction intensity. *D5: Interaction Targets* identifies who or what the robot engages, whereas *D6: Relationship Roles* describes the social role the robot takes in that interaction. A robot may engage the same target while taking on different roles. Likewise, *D7: Physical Form* and *D8: Communication Modalities* address different but connected layers of design: the former concerns the robot's embodied appearance and material presence, while the latter concerns how it expresses intentions or states.

While the dimensions are interdependent, in practice, we suggest prioritizing a relational-spatial-embodied core. *D5: Interaction Targets* and *D6: Relationship Roles* define whom the SFR engages and what relation it is meant to establish; *D1: Spatial Mobility Scope*, *D2: Vertical Floating Mobility*, and *D3: Spherical Proxemics* determine how that relation is situated and experienced in space; and *D7: Physical Form* should be considered early because morphology, materiality, and scale strongly shape how the SFR is perceived, approached, and touched. *D9: Floating Motion Dynamics* and *D10: Level of Proactiveness* then shape how the relation unfolds over time, while *D8: Communication Modalities* and *D4: Interaction Configuration* often act as later refinements that express or scale an already defined interaction concept. This ordering is not universal, but it offers a practical way to prioritize design decisions when technical and design resources are limited.

5 Application Use Cases

The thematic analysis of the expert interviews also provided insights into addressing our **RQ2**: "What roles and functions might soft floating robots fulfill in everyday indoor environments?" Through an iterative process, we categorized the identified application use cases into three main categories (as shown in Figure 14)—presence-based, function-based, and atmosphere-based—comprising five sub-themes: presence-based (emotional support and companionship; social facilitation and communication), atmosphere-based (ambient experience and atmosphere), and function-based (daily living assistance; public space services).

5.1 Emotional Support and Companionship

Expert participants frequently highlighted the potential of soft floating robots (SFRs) to provide emotional support and companionship, especially for alleviating loneliness. They described SFRs as envisioned to offer a gentle sense of presence—"a sense of a living being in the room" (P4)—for people working alone or family members at home. Participants envisioned SFRs floating nearby during daily routines, such as integrating with smart speakers to tell children bedtime stories. They also proposed semi-public applications: for example, in waiting areas where, as P8 noted, "the time would feel

less boring because I could play with the robot" or in children's spaces where SFRs could accompany users and reduce caregivers' burden.

Participants frequently compared SFRs to pets, highlighting their perceived liveliness and capacity for pet-like responses. An SFR might greet its owners at the door or gently nuzzle their leg. As P7 remarked, "it could be like a cat, keeping the distance but still making you happy just by being there. Or like a dog, coming to you for touch and play." P3 noted the practical advantages: "A robot pet wouldn't shed hair, and you wouldn't need to spend time walking and feeding it. It would be nice for people who want a pet but don't have the time to take care of it, or who are allergic."

5.2 Social Facilitation and Communication

Participants also envisioned SFRs as mediators of social connection. As telepresence robots, they could integrate with video calls to provide remote companionship with a tangible, tactile presence, or act as physical emojis that perform gestures synchronized with messages. As P3 suggested, "I could send my friends an emoji through the robot near them, like having it roll twice in the air." Participants also noted that expressive flight patterns could convey emotion [20] and enrich remote or co-located communication.

In workplace settings, SFRs were compared to office dogs that lighten the atmosphere and strengthen collegial bonds. As P7 explained, "When a cute SFR enters the office as an office dog, it can trigger people to care for it. That makes colleagues see each other as kind, caring people." At social gatherings, SFRs could function as icebreakers, helping spark conversation and reducing social anxiety.

5.3 Ambient Experience and Atmosphere

Compared to rigid robots such as drones, participants emphasized that SFRs are better-suited for shaping dynamic atmospheres. Bio-inspired SFRs that "swim" through the air can evoke the calm of an underwater world, helping people relax and reduce anxiety. Participants also imagined SFRs serving as dynamic ambient artifacts: floating through the home in sync with lighting to improve the aesthetic appeal, or moving among guests to enliven a party. As P8 suggested, "In an office lounge, a cloud robot could change its color in response to the environment to enhance the atmosphere."

Participants also envisioned applications in public spaces. In museums, shopping malls, or immersive theaters, SFRs could appear as ghosts, sprites, or alien-like NPCs that interact softly with visitors. On stage, they could serve as expressive flying props, moving between performers and audiences to enhance connection. In amusement parks or zoos, animal-shaped SFRs could invite tactile play for children. These applications were seen as especially compatible with large indoor environments; as P10 noted, "Theaters and shopping malls often have bigger spaces that could support larger robot sizes."

5.4 Daily Living Assistance

Participants envisioned SFRs as everyday assistants that support routine tasks through subtle, non-intrusive interactions. Their softness enables gentle wake-up experiences, as P4 described: "The robot could float over and make gentle physical contact to wake me up, like a soft floating alarm clock." They might also remind desk workers to take breaks, as P9 noted, "Objects flying in the air are more



Figure 14: The application use cases fall into three categories: presence-based, function-based, and atmosphere-based. Presence-based examples (from left to right): (A) the SFR welcomes a user upon arriving home, (B) the SFR accompanies a user during exercise, (C) the SFR narrates a book to a child, and (D) the SFR stays with a child while a caregiver is busy. Function-based examples (from left to right): (E) IoT communication with surrounding devices, (F) the SFR reminds a user to take breaks and stand up, (G) the SFR brings sugar to a user, and (H) the SFR guides a library user to the bookshelf. Atmosphere-based examples: (I) a group of SFRs creates a synchronous art installation, (J) a group of people dance together, (K) an SFR provides soothing sleep light while resting on a bed, and (L) the SFR creates an ambiance for a meditative environment.

likely to catch people’s attention,” or intervene in gaming overuse by drifting in front of the screen. For meeting reminders, participants suggested soft nudges or wing taps, as P3 noted: “It could remind me by lightly bumping me, or tapping me with its wings.”

Leveraging their 3D mobility, SFRs could help locate misplaced items by hovering above them as visual markers. As P10 suggested, “At home, the SFR could team up with ground robots, the floating one searching from above, the ground one checking under the sofa.” Their reach also makes them useful for ceiling inspections, detecting leaks or cracks, or checking dusty shelves, with potential for light cleaning. Participants further envisioned SFRs as follow-me cameras that “can film users from different angles, distances, and heights” (P3). With near-neutral buoyancy, SFRs exert almost no weight when perched on the user’s body; P8 remarked, “I would place the floating robot on my lap and then put books, tablets, and snacks on it, it would make things more convenient.”

5.5 Public Space Services

Participants envisioned SFRs as mobile guides and information providers in public spaces. Their ability to float alongside users makes them well-suited as museum tour guides or airport assistants. As P2 described, “It could be like Paimon from Genshin Impact, a floating guide always by your side, ready to answer questions and explain things.” They could also serve as shopping assistants in malls or library helpers, aiding users in locating products or books

on shelves at different heights. Participants further highlighted the potential of SFRs as flying advertisements, extending existing uses of indoor blimps. With customizable appearances and expressive movement, SFRs can attract attention in malls or restaurants and create interactive experiences beyond static displays. As P8 noted, “This kind of interactive advertisement can fly around the audience and let them touch, making it more engaging than common flat advertisements.”

6 Design Guidelines

To bridge the gap between our design space and practical implementation, we present a set of design guidelines. We begin by outlining the fundamental physical constraints that define what is feasible for soft floating robots (SFRs), and then propose three core design principles to guide the development of meaningful interactions.

6.1 Design Within Physical Feasibility Boundaries

While the design dimensions articulate the possibilities, their realization is governed by the specific materiality of SFRs’ helium-filled structures. As illustrated in our Physics-Design Dependency Framework (Figure 15), interaction design is not separate from engineering constraints but is entangled in a rigid Buoyancy-Mass

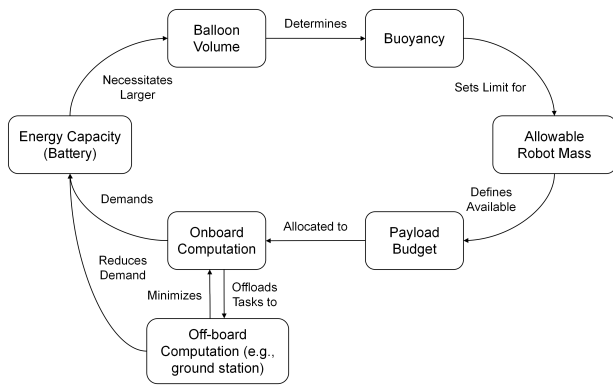


Figure 15: The physics–design dependency framework. This diagram illustrates the coupled interdependencies created by the buoyancy-mass cycle, in which balloon volume determines the payload available for computation and energy. The framework shows how hardware choices can trigger cascading volume adjustments. To manage these constraints and enable miniaturization, we identify mitigation strategies such as offloading computation to the environment and adopting lightweight components (e.g., micro-drone parts) with favorable performance-to-weight ratios.

Cycle. For lighter-than-air robots, payload capacity is directly determined by the volume of the helium-filled envelope. Consequently, design decisions such as form, scale, and the weight of on-board hardware are tightly coupled: changing one parameter cascades into constraints across the system. This framework aims to help designers navigate this material entanglement, moving beyond simple trade-offs to holistic design decisions.

6.1.1 The Buoyancy-Mass Cycle as Material Entanglement. The fundamental characteristic of this materiality is that total lift must equal or exceed total mass. Under standard atmospheric conditions, one liter of helium provides approximately one gram of net lift. This creates a rigid Buoyancy-Mass Cycle: increasing payload (e.g., for autonomy) requires a larger balloon volume, which in turn increases drag and material weight, potentially demanding even more lift. Consequently, volume establishes a strict budget for all non-structural components, such as sensors, battery, and computing unit. This entanglement forces designers to negotiate explicit design tensions. For example, demanding higher proactiveness (D10) necessitates more sensors and battery capacity, which increases mass and requires a larger envelope. This, in turn, impacts the robot’s Physical Form (D7) and restricts its Spatial Mobility (D1). Although prior work suggests that large inflatable robots can support intimate physical interaction [12], their size may overwhelm small rooms. Designers must therefore balance the desire for autonomy against the spatial requirements of the intended environment (D3). Material choices also influence this entanglement: adding tactile, comfort-oriented coverings (e.g., fur or fabric) supports comfort-partner roles (D6) but consumes the lift budget, potentially forcing a reduction in battery life or sensor capabilities.

6.1.2 Enabling Strategies. To address these constraints and realize capable SFRs, we suggest three key mitigation strategies:

Strategy A: Adopt drone-grade lightweight components. Designers should leverage the supply chain of the micro-UAV industry. Modern flight controllers, motors, and batteries designed for racing drones offer superior performance-to-weight ratios compared to components repurposed from ground robots, which typically do not prioritize weight reduction.

Strategy B: Offload computation and perception. To relieve onboard weight pressure, designers can shift the computational burden from the robot to the environment. This includes streaming data to off-board workstations for heavy processing and utilizing external sensing systems (e.g., motion capture, external camera arrays, ultra-wide band networks) for localization, thereby eliminating dependency on heavy onboard LiDAR or SLAM cameras. This approach not only avoids the weight of bulky sensors but also reduces onboard processing power required to handle the data.

Strategy C: Leverage “safety through compliance” to reduce computation. Unlike drones that require complex algorithms to ensure strict obstacle avoidance, SFRs can leverage their softness [101]. Because their compliant bodies allow safe physical contact with the environment (D5) and even with other robots (D4) [87], navigation does not depend on rapid collision-avoidance processing. This aligns with the “weak robot” concept [72], where reliance on physical compliance rather than computational control becomes a design feature. This reduced need for intensive real-time computation lowers power consumption and enables the use of lighter onboard processors, further supporting miniaturization.

6.2 Design Principles

Building on the ten-dimensional design space and the feasibility strategies outlined above, we distill three core design principles. These principles guide designers and researchers in moving beyond traditional rigid-robot paradigms and fully leveraging the unique affordances of SFRs.

6.2.1 Design Principle 1: Embrace Soft Physical Contact Interaction. Unlike drones that rely on “safety through avoidance,” maintaining distance to prevent injury, SFRs enable “safety through compliance” through their low inertia, inflatable bodies, and buoyant dynamics. This shift allows designers to treat physical contact not as a failure mode but as a legitimate interaction modality. Rather than avoiding touch, designers should actively invite it, leveraging the SFR’s ability to remain quietly and safely within the user’s proximal space (D1) and intimate zone (D3)—areas where drones cannot operate quietly and safely for extended periods.

To apply this principle, designers can use the robot’s lightness to initiate soft contact. Beyond audio-visual cues, SFRs can proactively approach (D10) and gently nudge, tap, or brush against the user to capture attention or provide guidance. Examples include a soft tap on the shoulder for notifications, a gentle push on the back for directional guidance (D6), or pet-like behaviors such as nuzzling a user’s legs. Conversely, the robot’s physical form and materiality (D7) can be intentionally crafted to invite touch, enabling users to pat, hug, or press the robot’s body as intuitive haptic input (D8). Prior work has shown that soft, tactile forms encourage deeper

physical and emotional engagement through full-body interactions such as hugging, dancing, and play [12].

This principle also reframes navigation. Instead of relying heavily on collision-avoidance algorithms, SFRs can safely make light contact with the environment (D5)—such as walls or furniture—to maneuver through tight spaces or produce soft, non-threatening sounds (D8) that signal presence. Tolerance for gentle collisions also facilitates dense multi-robot configurations (D4), where SFRs can cluster, drift, and bounce without risk of damage. This relaxed constraint environment expands the robot's effective mobility across different spatial scales (D1).

6.2.2 Design Principle 2: Design with Proxemics - Make Use of Mid-air Space and Social Distance. Because SFRs operate freely in three dimensions, designers should shift from traditional planar proxemics to volumetric proxemics (D3) and Vertical Floating Mobility (D2). Height (z-axis) and spherical interpersonal distance become continuous variables that can be modulated to regulate interaction intensity, social presence, and attentional demand. Unlike rigid drones—unsuitable for close proximity due to noise, down-wash, and safety risks—SFRs can quietly navigate the full spatial spectrum, entering, inhabiting, and exiting the user's personal space from unique angles, including overhead (D2).

To implement this, designers should use vertical flexibility to support inclusive, human-centered engagement. By adjusting altitude to match the user's posture (D2), SFRs actively adapt to the person (D10) rather than forcing users to accommodate the robot—whether the user is a crawling child, a wheelchair user, a bedridden patient, or a standing adult. This ensures accessible, face-to-face alignment across diverse physical conditions.

Vertical layers can also be used to manage attention and functional roles. The overhead level (D2) and public zone (D3) serve as low-attention, ambient presence layers or idle positions that avoid occupying floor or table space. For higher engagement or emotional support, the SFR can descend into the intimate zone (D3) or eye level (D2). Finally, by leveraging multi-floor mobility (D1), SFRs can accompany users through staircases or atriums, maintaining continuous interaction difficult for ground-based robots to achieve.

6.2.3 Design Principle 3: Leverage the Floating Property to Evoke Lightness, Slowness, and Lifelike Presence. The anti-gravity lightness of SFRs fosters a distinctive mental model of harmlessness and dreamlike presence—qualities rarely achievable with ground robots or rigid aerial systems. Designers are encouraged to harness this not only for mobility but also to cultivate an aesthetic of enchantment and perceived animacy.

Freed from ground friction and mechanical noise, SFR motion is shaped by passive buoyancy and aerodynamic drag, imposing a mandatory slowness and damped velocity profiles (D9). Unlike the sharp, forceful maneuvers of drones, SFRs exhibit gradual acceleration and gentle, air-current-driven drifts. Designers should embrace these indeterminate and organic motion dynamics, which resemble the tranquil suspension of jellyfish, clouds, or drifting dandelion seeds. This effect is especially pronounced in the free-floating idle state (D5), where the robot engages in unpredictable behavior—drifting aimlessly, rotating slightly, or softly rebounding off surfaces.

To evoke a stronger lifelike presence, morphology (D7) and kinetic signaling (D8) should align with metaphors such as marine creatures, spirits, or clouds. In multi-robot scenarios, this enables fluid, jellyfish-like swarm dynamics (D4), with robots gently bumping, separating, and regrouping in ways that resemble collective life. Prior work has shown that soft, organic forms incorporating slow, deliberate movement foster trust, comfort, and emotional response in close-contact interactions [12]. Finally, designers can leverage the robot's visible vulnerability and susceptibility to airflow as a relational resource to support care-receiver roles (D6).

7 Design Examples

To demonstrate how the proposed design principles (Sec. 6.2) and design space dimensions (Sec. 4) can be translated into concrete interactions, we developed a series of examples (see Figure 16 and the supplementary video). Building on the application scenarios identified in Sec. 5, these examples serve as instantiations of our framework. They are presented not as exhaustive empirical validations, but as existence proofs demonstrating the technical feasibility and how SFRs can support diverse roles in everyday indoor contexts.

All demonstrations were implemented on a custom-built flapping-wing SFR platform to maintain consistency across examples. We use this platform as a representative case that makes key SFR qualities—such as softness, buoyant flight, and close-proximity interaction—concrete and demonstrable. At the same time, we do not claim that all dimensions manifest identically across propulsion mechanisms. Other SFR configurations, such as propeller-driven, may differ in acoustic profile and motion character, which may change how particular dimensions are realized or prioritized in practice. We thus position the current prototype as a probe to explore the broader design space, acknowledging that future work can extend these principles to diverse hardware configurations.

The flapping-wing SFR platform was adapted from our prior SFR prototypes [112]. The prototype consists of a helium-filled envelope, a flapping-wing propulsion mechanism, and a central control unit. Each wing is actuated by a 3 g micro-servo with nylon-film surfaces reinforced by carbon-fiber rods. An XIAO ESP32S3 microcontroller handles control and is powered by a 3.7V lithium battery. Symmetric wing flapping generates forward motion, while differential flapping enables yaw control, providing controlled and stable flight suitable for indoor environments. We adopted a Wizard-of-Oz approach, using remote operation to operationalize interaction concepts rather than implementing full autonomy. This method, common in early-stage HRI research [80, 85], enabled rapid iteration of interaction patterns.

While SFRs can take many forms, we chose the flapping-wing design for the interaction design examples. This decision was guided by the following considerations: marine-inspired morphologies are common in SFR research; flapping motion is quiet, safe to touch, and life-like, making it particularly suitable for close-proximity scenarios. At the same time, hardware constraints limited us to constructing a single platform. We therefore use this flapping-wing prototype as a representative instantiation to demonstrate the feasibility of our framework, while acknowledging that future work should extend these demonstrations across other configurations.



Figure 16: Proof-of-concept demonstrations illustrating how the proposed design principles guide interaction design: (a) Gentle wake-up: The SFR hovers above a user and contacts at a set time, offering a calm alternative to traditional alarms. (b) Dynamic reading support: While the user reads on a sofa, the SFR rests on the lap as an inflatable book stand, adjusting naturally to posture. (c) Tactile comfort: The robot approaches a waiting user, who holds and interacts with it, alleviating boredom and loneliness. (d) Well-being intervention: To counter sedentary behavior, the robot approaches a desk-bound user, delivering a gentle shoulder nudge and hovering to invite movement. (e) Companionship in mundane tasks: as a user folds laundry, the robot floats nearby, transforming a routine chore into an engaging experience. (f) Expressive dance partner: During music and dance, the robot synchronizes wing flaps with the rhythm, encouraging social play and easing awkwardness. (g) Music companion: While the user plays an instrument, the remote operator adjusts the robot's flight path and wing motion to match the musical tempo.

7.1 Applying Design Principle 1: Embracing Soft Physical Contact

Guided by Design Principle 1, these examples illustrate a shift from collision avoidance to purposeful physical contact. They demonstrate how the inherent softness of SFRs enables haptic interactions that would be unsafe or impractical with rigid drones.

7.1.1 Gentle Wake-Up. To provide a calmer alternative to traditional alarms, the SFR acts as an assistant (D6) delivering a haptic wake-up routine. Using its Vertical Floating Mobility (D2), the robot begins at the overhead level and, at the designated time, slowly descends into the user's intimate zone (D3) until its soft body makes contact. Instead of producing jarring sound cues, the robot relies on tactile communication (D8), illustrating the potential of soft physical contact as an interaction modality.

7.1.2 Dynamic Reading Support. In this example, the SFR becomes a reading aid, illustrating passive Proactiveness (D10). While the user sits on a sofa, the robot gently settles onto their lap. With near-neutral buoyancy, it exerts almost no weight, allowing the user to rest a book on its soft body. This demonstrates how an SFR's physical form (D7) can provide contextual assistance through gentle, adaptive contact.

7.1.3 Tactile Comfort. To address emotional needs, the SFR proactively (D10) approaches a waiting user to invite touch. The user responds by holding and squeezing the robot (D8). Acting as a comfort partner (D6) within the proximal range (D1), the SFR aims to transform a moment of idle waiting into a soothing, tactile interaction.

7.2 Applying Design Principle 2: Utilizing Volumetric Proxemics

Following Design Principle 2, these examples illustrate how SFRs free interaction from the 2D ground plane, utilizing the z-axis to regulate attention and social presence.

7.2.1 Well-being Intervention. To address sedentary behavior, the robot acts as a caregiver (D6) by leveraging Vertical Mobility (D2) to manage attentional demand. It begins at the overhead level, occupying a low-attention, ambient layer that does not disrupt the user's work. When intervention is needed, the robot gradually descends to body level (D2) and employs gentle physical proactivity (D10) by delivering a soft shoulder nudge.

7.2.2 Companionship in Mundane Tasks. In a laundry folding scenario, the robot maintains a One-to-One (D4) relationship but remains in the public zone (D3). It drifts in slow, gentle circles around the room, utilizing its idle state (D5) to provide non-intrusive companionship without imposing cognitive load. This capability, difficult for noisy drones or ground robots to achieve, highlights SFRs' advantage as unobtrusive, atmospheric companions.

7.3 Applying Design Principle 3: Evoking Animacy and Enchantment

Aligned with Design Principle 3, these examples illustrate how an SFR's buoyant physics and organic motion can be leveraged to enrich the atmosphere of a space.

7.3.1 Expressive Dance and Music Companion. In social settings, the SFR acts as a kinetic mediator to ease interpersonal engagement (D4). During a dance scenario, the robot synchronizes its wing-flapping frequency (D8) with the rhythm of the music. Unlike rigid machines, its motion displays organic fluidity (D9) and gentle lateral drifts designed to evoke the metaphor of a living creature dancing in mid-air. Similarly, when a user plays an instrument, the robot was remotely operated to adapt its flight path, speed, and wing dynamics in real time to reflect the music's tempo and emotional tone.

8 Discussion

This study presents a systematic exploration of interaction with soft floating robots (SFRs), addressing our research questions regarding their interaction design space (RQ1) and potential social roles (RQ2). While Sec. 4 and Sec. 5 detailed the specific dimensions and use cases, this section reflects on the deeper implications of these findings. We discuss how the physics of floating shapes the unique experiential qualities of the design space (expanding on RQ1) and how vulnerability reframes the relational dynamics of SFR roles (deepening RQ2).

8.1 The Essence of Floating: From Physics to Experiential Qualities

Experts consistently emphasized that SFRs' value lies in ambience creation and social companionship rather than utilitarian efficiency, echoing calls to challenge the assumption that robots must be designed primarily as flawless, productive agents [6]. We position SFRs not as replacements for precision-based rigid robots, but as a complementary morphology specifically suited for low-speed, high-intimacy, and ambient contexts where mechanical silence is paramount. This invites a deeper question: What makes "floating" afford these qualities in ways other platforms do not? We argue that the distinctiveness of SFRs arises from the entanglement of their governing physical laws—buoyancy, inertia, and aerodynamics. These forces produce soft, slow, and naturally drifting behaviors that reshape how users perceive the robot.

8.1.1 Anti-gravity and the Form of Lightness. An SFR's quiet suspension in mid-air introduces a sense of "anti-gravity magic" [19] into everyday environments, echoing cultural imagery of spirits, fairies, and other floating entities. This transformation of ordinary spaces into sites of wonder and interaction aligns with insights from mid-air interface design [116]. Because SFRs exhibit physical characteristics similar to these floating cultural metaphors, designers can draw morphological connections—such as soft, cloud-like, or creature-inspired forms—to enhance familiarity and expressiveness [12]. Buoyancy-driven mobility also eliminates the high-speed rotors and downwash typical of drones, enabling a level of quietness essential for long-term companionship [58]. This quality resonates with the principles of calm technology [109], allowing SFRs to unobtrusively coexist with users. Experts noted that the robots' tactile qualities and gentle movements support stress relief and mindfulness, offering a soothing counterpoint to the sensory load of modern life. Prior work similarly suggests that interacting with such robots can provide a temporary escape from daily pressures [12, 59]. In contrast to drones—whose persistent noise demands attention and

drains cognitive resources [86]—SFRs show promise as serene, ambient entities capable of transitioning from “occasional tools” to “continuous companions.”

8.1.2 Organic Motion and Perceived Animacy. SFR motion is characterized by a continuous negotiation with the air, dominated by aerodynamic drag and passive compliance [42]. Unlike the precise, mechanical movements of rigid drones, SFRs resemble the tranquil suspension of sea creatures, drifting clouds, or dandelion seeds. This organic fluidity can trigger an instinctive perception of animacy, conveying a sense of aliveness through movement fidelity rather than mechanical complexity. Prior work on robotic jellyfish [41] shows that such lifelike dynamics can evoke fascination and wonder, promoting playful and sustained engagement. The combination of quiet flight, soft inflatable bodies, and gentle, expressive motion has led to increasing deployment of SFRs in public spaces—from atriums and halls [3, 63] to museums [2] and live events [11]. In these environments, they float gracefully above crowds, curating an immersive, dreamlike spectacle that sparks curiosity and invites interaction. Their slow, non-threatening presence allows them to function as atmospheric agents, transforming overhead spaces into theatrical stages without inducing fear or discomfort.

8.1.3 Cultural Associations and Approachability. Beyond physical attributes, SFRs draw on cultural associations. Helium balloons are widely recognized symbols of celebration, play, and childhood [5, 52], imbuing SFRs with a friendly emotional tone and fostering openness to their behaviors [67]. The familiarity with balloon-like qualities lowers cognitive load and reduces uncertainty during interaction [78]. Prior research further shows that playful, rounded robots are often perceived as more extroverted and approachable than rigid, utilitarian designs [51].

8.2 Vulnerability and Benevolent Chaos in Relational Dynamics

While SFRs introduce unique opportunities for interaction, they also embody inherent physical limitations: they are lightweight, susceptible to airflow, and require protection from sharp objects. Rather than treating these limitations as flaws to be hidden, experts suggested reframing them as relational resources that support emotional connection.

8.2.1 Vulnerability and Mutual Care. Unlike industrial robots engineered for strength and precision, balloon-formed SFRs are perceptibly fragile. This vulnerability aligns with Okada et al.’s Weak Robot theory [72], which argues that imperfection can invite empathy [74] and caregiving behaviors [71, 76]. An SFR’s susceptibility to environmental influences can activate the care-receiver role (D6), prompting users to “care for” the robot, such as freeing it when it becomes stuck in a corner—thereby evoking empathetic responses [100]. Prior work shows that people often respond empathetically to robotic expressivity [45, 74]; in this context, moments of “help and rescue” may become opportunities to deepen emotional bonds. Such dynamics shift the relationship from robots simply serving humans to a model of mutual care, potentially fostering deeper companionship akin to bonds formed with pets.

8.2.2 Cultivating Benevolent Chaos. Experts highlighted the appeal of designing SFRs as robot pets, noting shared qualities: they inhabit human spaces, prompt people to interpret ambiguous behaviors, and sometimes require assistance from their owners [70]. The deeper insight, however, lies in recognizing that the charm of pet-like robots stems not from perfect obedience but from embracing a form of *benevolent chaos*. As experts noted, pets often disrupt routines, such as a cat stubbornly lying across a keyboard, yet such small inconveniences shape personality and invite deeper emotional engagement [7, 102]. SFRs are uniquely positioned to cultivate such benevolent chaos [65]. Their soft, lightweight form makes unpredictability essentially non-threatening. Whereas a malfunctioning rigid robot may pose risks, an SFR, such as the autonomous blimp Ollie [68], which flaps its wings in response to sound, may behave unexpectedly yet still be perceived as friendly and engaging. Designers can harness this by allowing controlled unpredictability; for example, rather than fully counteracting indoor airflow, subtle environmental influences could be allowed to shape the robot’s movement. However, distinct from these gentle drifts, strong environmental forces (e.g., strong ventilation currents) that overpower the robot should be framed as a visible physical struggle, triggering the robot to signal struggle or distress to solicit human assistance.

8.2.3 Balancing Unpredictability with Legibility. However, to ensure that this unpredictability—whether from internal whims or external drafts—is interpreted as personality rather than incompetence, SFR behaviors should retain a degree of emotional legibility [104]. Pure randomness risks causing confusion or frustration [4]. We suggest that designers draw on principles of animation to treat SFRs as kinetic storytellers to communicate meaning [49, 54]. For example, when fighting a draft, the robot could apply techniques such as “anticipation” (e.g., a slight dip before ascending) or “follow-through” (e.g., a gentle sway after stopping). These design choices frame the robot’s chaotic movements within a coherent narrative, encouraging users to perceive SFRs not as defective devices but as animated companions with characters.

8.3 Situating the SFR Design Space within HDI

Situated within broader HDI research, our design space includes both concerns shared with other flying robots and interaction qualities that are especially salient for SFR. Dimensions such as interaction configuration (D4), interaction targets (D5), and levels of proactiveness (D10) are not unique to SFRs; rather, they are also present in prior HDI work on drone roles [37, 108], application contexts [46], and how people interpret flying robots in inhabited environments [9]. What distinguishes SFRs, however, is not the introduction of an entirely separate set of dimensions, but how softness, buoyancy, low inertia, and quietness reconfigure these concerns in close-proximity interaction. In conventional multirotor HDI, noise, exposed rotors, and safety constraints often limit proximity and physical contact [16, 106, 118]. By contrast, SFRs make gentle touch, overhead presence, compliant contact with the environment, and slow drifting motion more available as interaction resources rather than hazards. This is especially visible in D2, D3, D8, and D9, where altitude, proxemics, communication, and movement are shaped not only by flight capability, but also by the material conditions [10, 106]. Our findings also complement recent

designerly HDI work that approaches flying robots as experiential, relational, and situated artifacts [19, 38–40]. Rather than proposing a single interaction concept or scenario, our contribution is to systematize how SFR embodiments reshape interaction design across roles, proxemics, communication, and motion.

8.4 Limitation and Future Work

This work is expert-informed rather than end-user validated. We adopted this approach because soft floating robots (SFRs), as an emerging form, remain technically immature, and early user studies risk conflating hardware instability with judgments of interaction quality. While this strategy enabled us to envision interactions beyond current technical constraints, it captures imagined possibilities rather than lived experience. Accordingly, the proposed design space and use cases should be interpreted as generative starting points rather than evidence of end-user desirability or long-term acceptance. Moreover, the subtle and emergent dynamics of long-term cohabitation—such as how users negotiate space with a floating agent over weeks or months—cannot be adequately captured in short-term sessions. Future research should therefore move beyond speculative exploration toward in-the-wild deployments, examining how SFRs are integrated, appropriated, and sustained in everyday indoor environments over extended periods. Such studies should also investigate diverse cultural contexts to determine whether the design space requires regional adaptations given varying attitudes toward robots, physical touch, and personal space.

Our demonstrations were instantiated on a single flapping-wing platform, which we position as a representative case study rather than a proxy for all SFRs. While this configuration prioritizes quietness and safety, other propulsion types (e.g., propellers or microblowers) would introduce different acoustic and kinematic profiles. We acknowledge that the current implementation represents one trajectory within the broader design space. Future work should develop and compare diverse hardware configurations to understand how different physical embodiments (e.g., sound, airflow, texture) influence the perception of animacy and comfort.

Finally, we acknowledge the inherent material challenges of helium-based flight. Issues such as helium leakage, resource scarcity, and the strict buoyancy-mass constraint remain practical barriers for ubiquitous adoption. We acknowledge the ethical tension of using helium, a finite resource. This design space invites us to think of SFRs not as disposable consumer gadgets, but as ephemeral artifacts. Their gradual deflation could be incorporated as part of an interactional lifecycle in appropriate contexts, while practical deployments should prioritize helium retention and reuse. Future engineering efforts should prioritize high-retention envelope materials, ultra-lightweight components, and sustainable solutions—such as gas recapturing [98] and recycling systems or safe and regulation-compliant alternative lift gases. We hope our design space provides the interactional motivation to drive these necessary hardware innovations.

9 Conclusion

This paper presented a systematic exploration of lighter-than-air soft floating robots (SFRs) for indoor human interaction. Through

interviews with twelve experts in HCI, Design, and Robotics, we developed a ten-dimensional design space that provides foundational guidance for shaping meaningful interactions. Crucially, to ground these possibilities in engineering reality, we introduced a physics-design dependency framework that models the trade-offs among volume, payload, hardware, energy, and computation. Synthesizing these insights, we derived design guidelines that help designers navigate these constraints while leveraging SFRs' unique qualities to create diverse interactions. Finally, to illustrate the generative potential of this framework, we implemented proof-of-concept design examples that instantiate these principles and demonstrate their value in enabling novel interactions that many conventional aerial and ground robotic platforms do not readily support. Our contributions lie in the following aspects: First, we introduce a structured design space that moves SFR research beyond isolated prototypes toward coherent design practices. Second, we identify SFRs' distinctive qualities, including softness, lightness, floating, and cultural associations, that uniquely position them as approachable, low-threat, and socially resonant interactive systems. Third, we show how engineering constraints such as airflow vulnerability can be reframed as design opportunities. Future research should validate and extend the design space through end-user participation, integrate emerging sensing and interaction technologies, and broaden the range of applications to realize the full potential of SFRs in daily life. Overall, we hope this work inspires further research on enriching indoor spaces with SFRs and advancing them toward meaningful applications that enhance modern life.

Disclosure about Use of LLM

We acknowledge that the authors' positionality shapes the perspectives and interpretations presented in this paper [36, 73]. Our multidisciplinary team, with backgrounds spanning HRI, HCI, robotics, user experience, and cognitive science, informed the framing of this work and the interpretation of the expert interview data. Data collection, coding, thematic analysis, and all substantive interpretive decisions were conducted by the research team. We used LLM-based writing assistants (GPT-5, Gemini 3 Pro, and Claude Sonnet 4) only to improve clarity and readability; all codes, analytic judgments, and claims remain the responsibility of the human authors.

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