UbiSwarm: Ubiquitous Robotic Interfaces and Investigation of Abstract Motion as a Display

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As robots increasingly enter our everyday life, we envision a future in which robots are ubiquitous and interact with both ourselves and our environments. This paper introduces the concept of *ubiquitous robotic interfaces* (URIs), multi-robot interfaces capable of mobility, manipulation, sensing, display and interaction. URIs interact directly with the user and indirectly through surrounding objects. A key aspect of URIs is their ability to display information to users either by collectively forming shapes or through their movements. In this paper, we focus on the use of URIs to display information in ubiquitous settings. We first investigate the use of abstract motion as a display for URIs by studying human perception of abstract multi-robot motion. With ten small robots, we produced 42 videos of bio-inspired abstract motion by varying three parameters (7 x 2 x 3): bio-inspired behavior, speed and smoothness. In a crowdsourced between-subjects study, 1067 subjects were recruited to watch the videos and describe their perception through Likert scales and free text. Study results suggest that different bio-inspired behaviors elicit significantly different responses in arousal, dominance, hedonic and pragmatic quality, animacy, urgency and willingness to attend. On the other hand, speed significantly affects valence, arousal, hedonic quality, urgency and animacy while smoothness affects hedonic quality, animacy, attractivity and likeability. We discuss how these results inform URI designers to formulate appropriate motion for different interaction scenarios and use these results to derive our own example applications using our URI platform, UbiSwarm .

CCS Concepts: • **Human-centered computing → Ubiquitous computing**; *Empirical studies in HCI*;

Additional Key Words and Phrases: Ubiquitous Robotics, Human Perception, Human-Swarm Interaction, Swarm Robotics

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1 INTRODUCTION

Robots have begun their immigration from factories to our homes. They have extended their core functionalities from manufacturing automobiles and assembling electronic devices to cleaning our floors and other domestic tasks. As the boundary between robots and humans becomes smaller and the cost of microchips and robots decreases, it seems inevitable that the number of robots that we interact with will increase and that robot size will decrease as well. With the advent of miniature-sized robots, robots will become ‘invisible’, ubiquitous, and embedded in our everyday environment.

The abundance of robots will affect the way we interact with them. Human-swarm interaction (HSI) researchers have looked into issues specific to these swarm systems such as cognitive complexity of solving tasks, human-swarm communication, state-estimation and visualization, and human control of swarms [34]. On the other hand, ubiquitous robotic researchers have investigated problems like cloud robotics, activity recognition, semantic reasoning, context-awareness and test-bed development [13, 27]. While studying functional and technological aspects of human-swarm interaction and ubiquitous robotics is critical, we believe there is a large opportunity to use these ubiquitous robots not only for domestic tasks but also as information displays and for ubiquitous

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Fig. 1. URIs' mobility, manipulation and display demonstrated in situ. From left to right: UbiSwarm displaying calendar information on a vertical surface, UbiSwarm manipulating a mobile phone, UbiSwarm displaying iconic weather information, and UbiSwarm using abstract motion for a phone call notification.

interaction. Thus swarms of many robots may use their form to both convey their goals, intent, or current state, as well as to display information such as weather through icons or urgency of notification through abstract motion. In addition, users may want to interact with robots not only to control them but also to control an interactive display.

We see many parallels between robotics and computers in their trend toward ubiquity, moving out of the lab and into the home, as well as great possibilities for synergies. The vision for ubiquitous computing [69] is already here, but currently devices are either fixed in our environment or move parasitically (in our pockets or on our bodies). Due to their lack of mobility, this type of computing interface is limited to certain locations. As an attempt to bridge that gap, researchers have looked at using steerable projectors to create on-demand computing interfaces anywhere in the room [32, 52, 66]. However, there are still limitations such as requiring a dark environment, lacking physical form, and needing line of sight to avoid occlusions. Robots on the other hand can move to different locations, sense and manipulate surroundings, form both static and dynamic tangible shapes for display, and interact with both the user and environment.

In this paper, we introduce ubiquitous robotic interfaces (URIs), multi-robot interfaces that are capable of mobility, manipulation, sensing, display, and interaction both with user and environment. With these capabilities, URIs enable ubiquitous interaction with users either directly or indirectly through other objects. For example, URIs might be used in daily life to bring appropriate seasonings to novice cooks, inform users of weather through icons, and indicate status of tea steeping through motion surrounding the mug.

A central question in the use of URIs is how to display meaningful information to users through robotic motion. Much literature on human robot interaction has explored the use of limbs and facial expressions to convey intent, affect, and information [10], but this limits the ability of robots to seamlessly blend into our environments and does not scale well when interacting with many small robots. While formations of many robots can form iconic patterns [1], we believe that abstract motion is an important direction to explore. Designers can use essential features like motion and form to convey meaningful information and seamlessly move between manipulation and display. In this paper, we study the motion of URIs and its effect on human perception of not only emotion, but also user experience, measures for Human-Robot Interaction (HRI), and urgency.

For our study, we vary three multi-robot motion parameters: bio-inspired behavior (rendezvous, dispersion, random, torus, and flock), speed (fast or slow), and smoothness (smooth, synchronously jittery, or asynchronously jittery) as shown in Figure 6. User perception and experience are self-evaluated through measurement tools such as Self-Assessment Manikin (SAM), AttrakDiff2, and HRI metrics [4, 7, 22]. From a crowdsourced between-subjects video user study, we find that these different bio-inspired abstract motion parameters significantly impact user's perception. Finally, we apply findings to derive example applications in everyday scenarios with UbiSwarm , a URI system built on the Zooids robot platform [35].

2 CONTRIBUTIONS

- Exploration of the design space of Ubiquitous Robotic Interfaces
- Crowdsourced between-subject study to investigate perception of abstract multi-robot motion.
- Design guidelines for multi-robot movement
- Preliminary exploration and demonstration of abstract motion in the context of URIs

3 RELATED WORK

Our work is related to several research fields: ubiquitous robotics, tangible user interfaces, swarm robotics, and robot motion perception.

3.1 Ubiquitous Robotics

Ubiquitous robotics is often seen as an extension of ubiquitous computing, a vision by Mark Weiser [69]. In addition to the networked touchscreens of various sizes, ubiquitous robotics includes a non-flat physical form, mobility, actuation, and/or external sensing. Integrating cloud computing into stand-alone robots enhances their cognitive capabilities further. Due to their extensive capabilities to harm as well as help, it is vital to equip them with "advanced cognitive capabilities to understand what exists and what happens in the environment" [13]. Overall, ubiquitous robotics should not only provide a physical mobile platform to the existing ubiquitous computing but also interact with both user and environment.

Kim et al. laid out the architecture of ubiquitous robot system with three main components: Software robot, Embedded robot and Mobile robot [30]. While the essential layers of ubiquitous robots have been proposed and interaction with software robots have been studied, they have not tested any interaction with physical robots, an essential part of ubiquitous robotic interfaces. Others have developed multi-robot platforms for different applications such as experiment multi-robot testbeds [15, 43, 59], smart cities [11] and surveillance [16, 28]. Additionally, some have explored functionality of these platforms for the applications of multi-agent coordination [23, 41], and networking and localization [14, 39, 67]. While the technical contributions of this previous work have helped build the foundation of the field, again none have explored actual interactions with physical ubiquitous robots. We build on these prior works by introducing a ubiquitous robotic interface, an interface capable of physical interaction with users and surroundings, and in this paper we focus on its use as a information display through abstract motion.

3.2 Tangible User Interfaces

Tangible user interfaces (TUIs) on the other hand emphasize user interaction. TUIs aim to augment interaction by coupling digital information with passive physical form [25] and more recently with kinetic tangibles [24, 57]. Different actuators such as arrays of electromagnets [47, 48], arrays of ultrasonic transducers [40], vibration [58] and robots [61] have been used in tabletop tangibles with sizes ranging from coin-size [47] to 10 cm [50]. With actuated tangible user interfaces such as shape displays [20, 26, 56] and tabletop tangibles [46, 50], wide ranges of applications are possible such as information communication, mechanical work, and digital/physical world consistency [57]. For example, inFORM allows dynamic synchronization between the physical and digital worlds (e.g. bar graphs and CAD model), manipulates objects (e.g. cellphone and ball), and presents information physically for better learning (e.g. math equation plots) [20].

However, current TUIs including shape displays and tabletop tangibles do not explore what could be possible with ubiquitous robots. Current shape displays consist of many actuators but are not perceived as multiple entities as they are grounded together. Thus, interaction with shape displays differs significantly from interaction with ubiquitous robots. Existing tabletop tangibles improve on this aspect with increased numbers of tangibles but still lack interaction with many (e.g. 10 or more). Recently, a new type of interface emerged: the swarm user interface (Zooids) [35]. With Zooids, users can both interact with a swarm of small actuated tangibles and use them as a display. Using Zooids as the base, it is possible to explore URIs which are contextual and embedded in user's environments. In this paper, we also study human perception of abstract multi-robot motion for use in URI display.

3.3 Swarm Robotics

Swarm robotics draws inspiration from biological swarms ranging from ants and bees to birds and fish [8]. Swarms robots are robust in failure and can produce complex collective behaviors with simple individual rules. The largest robot swarm of one thousand was developed by Rubenstein et al. [62]. They can collectively form different shapes and manipulate objects through simple rules albeit at a slow rate (1cm/s) [5, 62]. We build on this past research on swarm robotics and apply it to ubiquitous settings with interaction [18, 19].

Until recently, most swarm robotic systems did not involve direct interaction with the user but rather interaction methods were tested on computer simulations through mouse based interfaces [31, 33]. Alonso-Mora developed a multi-robot platform for physical display and extended it to include interaction through mid-air gestures and a hand-held tablet [1, 2, 21]. With Zooids, direct touch interaction with a group of robots was possible [35]. However, it still lacks interaction with and manipulation of the surroundings. In addition, UbiSwarm has a larger interaction space which includes not only ordinary flat surfaces but also ferromagnetic vertical surfaces.

3.4 Robot Motion Perception

Researchers have previously looked into emotional perception of single robot motion. Even with different test robot platforms, results have indicated significant influence of speed/acceleration on the arousal axis in the circumplex model of affect [38, 55, 63]. On the other axis for valence, smoothness, roundness and perceived stability of movement have been found to be the relevant motion features [38, 49, 63]. Other literature found specific relations between motion and emotion such as small and slow movement eliciting sadness/fear while large, fast and jerky movement eliciting anger [54, 60, 64].

While many researchers have investigated perception of single robot motion, very few have studied human perception of multi-robot motion. Podevijn et al. found that increasing the number of robots provokes stronger responses in the psychophysiological state of humans [53]. On the other hand, Dietz et al. noticed synchronization led to higher positive affect albeit without statistical significance [17]. In this paper, we study humans' general innate perception of multi-robot motion in various categories beyond emotion such as user experience, human-robot interaction, and urgency.

4 UBIQUITOUS ROBOTIC INTERFACES

Ubiquitous robotic interfaces (URIs) are composed of many robots and have the following key elements as shown in Figure 2: Mobility, Manipulation, Sensing, Display and Interaction. For each element, we describe its role in ubiquitous robotic interaction.

4.1 Mobility

URIs need to be highly mobile. Their mobility separates URIs from traditional pixel-based interfaces. It enables URIs to initiate interaction with users and drastically increase the interaction space compared to static interfaces.

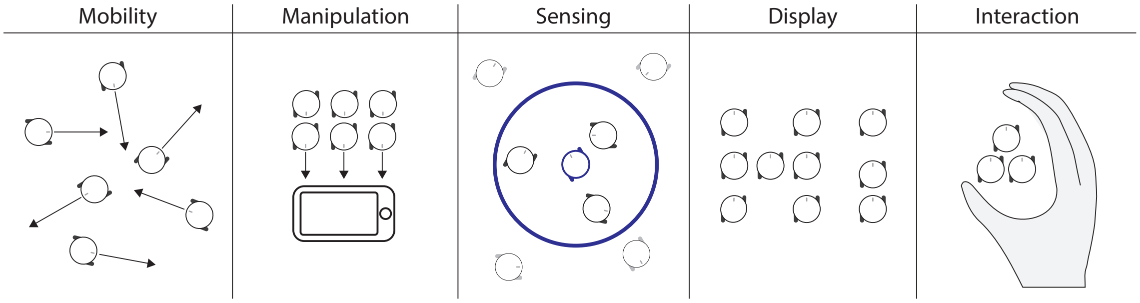


Fig. 2. Key elements of Ubiquitous Robotic Interfaces

Mobility also allows URIs to be embedded in a user's environment, moving from one area to another. We envision URIs moving from the wall to a table, to another room seamlessly. Their mobility is key not only for interaction and display, but also for carrying out other robotic tasks. The degree of mobility in terms of speed and interaction space is also important. Ideal URIs should be both fast (ideally approaching the visually perceptible refresh rate of the eye) and have infinite interaction space.

4.2 Manipulation

Manipulation is another element that is unique to URIs compared to traditional interfaces. It enables physical interaction with both the user and environment. It can either provide direct haptic feedback to the user or manipulate objects for the user's convenience or to display contextual information (by moving or actuating a passive object). Ideally, URIs should be able to freely manipulate all objects regardless of weight and geometry.

4.3 Sensing

Mobility, manipulation and interaction require URIs to have sensing. URIs need to first sense their locations and surroundings before they can move, manipulate, or interact with any object. While ideal URIs should have these sensing abilities onboard, sensing can also come from other ubiquitous sensors such as cameras although we do not explore this extensively in this paper.

4.4 Display

URIs can display information through spatial distribution and motion. These displays can be ambient, taking advantage of people's preattentive processing of motion [44, 45], or function as an interactive display with the user's full attention. As discussed by Le Goc et al., multi-robot interfaces can represent both "Things" and "Stuff" with movable elements instead of fixed pixels in screens [35]. The number of elements and identity of each element can also be varied. We envision URIs displaying information through both iconic form and abstract motion.

4.4.1 Iconic.

Similar to screens, URIs can combine robots to form icons. Icons are an efficient way for communicating information universally without instruction when designed appropriately [6]. With a quick glance, users can understand an icon. Ideally, URIs should instantaneously form shapes of infinite resolutions to enable information display similar to current pixel-based interfaces.

4.4.2 Abstract Motion.

Some information can be effectively communicated through motion. For instance, humans communicate their personal feelings such as emotion, intent, and affection both consciously and unconsciously through their body [10]. Researchers have shown that motion of simple shapes alone can elicit basic affective attributions [49, 60]. Abstract motion has a variety of benefits. It can be layered over pragmatic motions (e.g. moving to manipulate an object) to provide more information, it can tap into our preattentive processing making it easy and fast to perceive, and finally it does not require a specific form factor or end effectors.

4.5 Interaction

URIs can create user interfaces on demand, leveraging their mobility, when and where they are needed. URIs can also interact with users both directly and indirectly through surroundings/objects using their mobility and manipulation. Ideal URIs have machine learning and activity tracking to allow smart and appropriate interaction. In this paper, we focus on using abstract motion as a display and do not explore interaction greatly.

5 UBISWARM

We introduce UbiSwarm, a URI built on the Zooids platform [35]. Consisting of many inch diameter robots, UbiSwarm is capable of the five key URI elements. In this section, we first describe its use cases and capabilities in everyday settings followed by its implementation.

5.1 Example Scenario

To better understand how URIs can fit into users' everyday experiences, we provide an example scenario in which an imaginary person, Jen, interacts with UbiSwarm on a normal day. Here, we assume URIs are truly ubiquitous.

In the morning, Jen prepares to get dressed. On the wall, UbiSwarm forms an umbrella icon and today's temperature. Jen dresses accordingly and heads to the kitchen. UbiSwarm collectively push a plate of her favorite donuts to the center of the kitchen table. At work, she prepares a cup of tea. As soon as the tea bag touches hot water, the robots slowly circle around the cup and disperse after a minute. Every 30 minutes, UbiSwarm flocks toward and taps Jen to remind her to stretch and take a break. Back home, she prepares steak for dinner. In the kitchen, the robots locate and move salt, pepper, and olive oil for her to use. Before going to sleep, she decides to read a book while lying down. Robots slowly move toward the bed and shine light. She makes final adjustment by moving them by hand. After Jen falls asleep, the robots turn off the light and disperse back to their charging stations.

5.2 Implementation

UbiSwarm is a URI built on top of the Zooids platform [35]. It is a set of robots that communicates with a centralized computer. As shown in Figure 3, the existing motors (26:1 gear ratio) in Zooids were replaced with a higher gear ratio motor (136:1) in order to render more uniform and stable swarm movements, albeit at a slightly slower speed (16cm/s vs 44cm/s). Magnets were added on the bottom of the robots as shown in Figure 4 to increase mobility, extending the interaction space from just flat surfaces to horizontal and ferromagnetic vertical surfaces.

The applications and movements were programmed in C++ in Visual Studio. Our current implementation utilizes projection based tracking [36, 37], so the applications only work in a small area with a mounted projector. We envision other localization techniques such as HTC Vive's lighthouse tracking system expanding this. For more details about implementation refer to [35].

6 INVESTIGATING ABSTRACT MOTION AS A DISPLAY

For proper design of URIs, it is necessary to study how people interact and perceive them. In this paper, we first investigated how people perceive abstract multi-robot motion as a display. Through this study, we demonstrate that UbiSwarm, even with fixed form and no body or face, can elicit different perceptions including but not limited to affect and urgency through abstract multi-robot motion. This is done by varying a number of motion parameters:

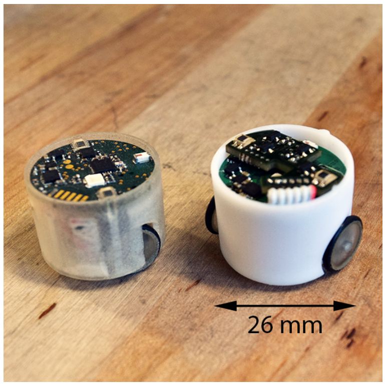


Fig. 3. Robot used in Zooids (left) and UbiSwarm (right). For UbiSwarm , higher gear ratio motor (136:1) is used for smoother motion.

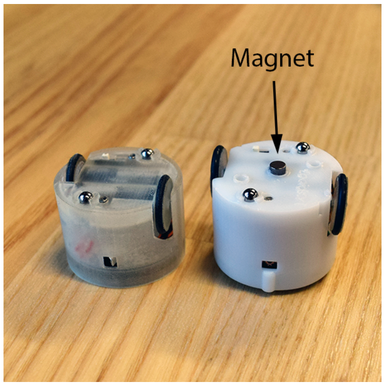


Fig. 4. Bottom of the robot for Zooids (left) and UbiSwarm (right). Magnet is added in UbiSwarm for mobility on ferromagnetic vertical surfaces.

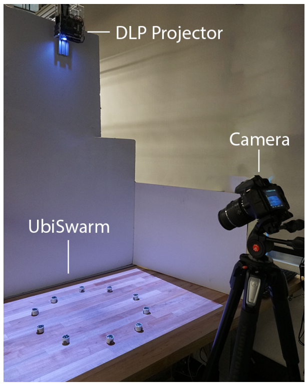


Fig. 5. Filming apparatus for the study: DLP projector producing a gray code pattern for localization, UbiSwarm as URI testbed, and camera for capturing video.

bio-inspired behavior, speed and smoothness. With the study results, we provide both design guidelines for abstract motion and example applications.

6.1 Method

To study effects of different abstract multi-robot motions, we performed a crowdsourced between-subjects experiment using UbiSwarm. The between-subjects design enabled participants to watch and rate only one single video instead of many videos that a within-subjects study would require. This reduces both user fatigue and the carry-over, context, and sensitization effects that can improve the overall quality of the responses [12].

Researchers have looked at whether video-based HRI studies yield similar results to live in-lab HRI studies. Woods et al. showed that there was a high agreement between the two studies when investigating how a robot should approach users [70]. On the other hand, Xu et al. demonstrated that physically present robots yielded greater emotional and social user feedback than robots through video or text [71] while Bainbridge et al. showed that people trusted and provided more personal space to physically present robots than video-displayed robots [3]. However, they also showed that both physical and video-displayed robots were effective in conveying contextual information and in eliciting feedback on general attitudes [71], and were greeted and cooperated with equally [3]. From these studies, it seems that the different results occur when there is significant interaction between the users and robots. Thus, since our study is focused solely on perception of abstract motion and does not involve significant interaction with participants, we concluded that video-based trials will yield reasonable results compared to live study.

6.1.1 Video Preparation. The overall filming apparatus for the study is shown in Figure 5. The videos were filmed with ten robots on top of a table with a white background. The camera angle was oriented such that it matched the viewpoint of a person sitting down. Due to the projector tracking system, the videos were filmed in a dimly lit room with a high-speed DLP projector shooting down from above. The video durations varied from 3 to 24 seconds depending on the type of abstract motion. Robot motion was filmed until the robots completed their motion for the applicable behaviors (rendezvous, dispersion, and flock), and for 10 seconds for torus and random behaviors.

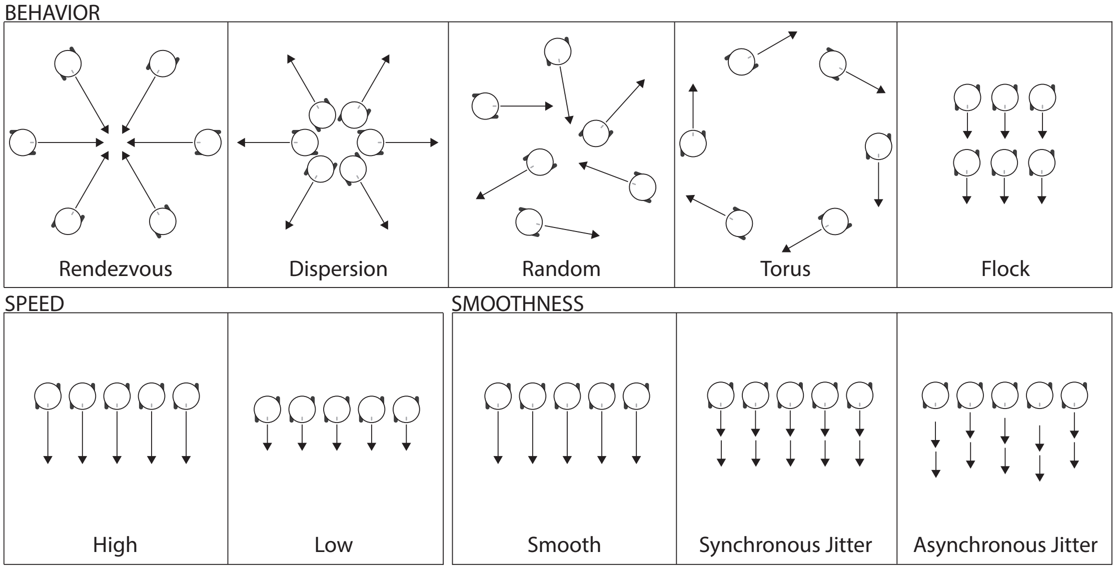


Fig. 6. Swarm Motion Parameters

6.1.2 Abstract Multi-robot Motion Parameters. With more than a single robot, it is possible to create a wider range of abstract motion than just changing speed and smoothness. From the literature on swarm motion, we identified bio-inspired behavior to be the additional motion behavior unique to multi-robot systems. Thus, the following motion parameters were varied for each video: bio-inspired behavior, speed and smoothness.

Bio-inspired behavior:

To leverage the additional degree of freedom (DOF) that groups of robots afford in contrast to a single robot, we looked at natural swarms for inspiration. Natural swarms have exhibited many complex collective behaviors following a simple rule. We have identified five different swarm behaviors discussed in existing literature as depicted in Figure 6: rendezvous [68], dispersion [68], torus [9, 29, 65], random (swarm) [9, 65], and flock [9, 29, 68].

Rendezvous behavior is when all the robots move toward the center of the swarm, while dispersion is the opposite of rendezvous where all the robots move away from the center. For torus, random, and flock behavior, the robots move in a circle, random direction, and same direction, respectively.

Speed:

Speed has consistently been found to be the most significant variable for single robot motion perception. In our study, two values of speed are chosen such that they are most differentiable with in our robots: high and low speeds corresponding to average values of 16 cm/s and 9 cm/s respectively.

Smoothness:

Besides speed, researchers have shown smoothness to be the second most significant parameter [38]. Previous studies involving a single robot could only change the intensity of smoothness [38]. However, in our setup with a swarm of robots, it is also possible to change the timing of the smoothness. Thus in our study, we used three versions of smoothness: smooth, synchronous jitter, and asynchronous jitter. For smooth movement, a constant speed is commanded from point A to point B. For synchronous and asynchronous jitter movements, zero speed is commanded for 150 ms every 400 ms either synchronously for each robot or asynchronously (where each robot is seeded with a random starting time in the 400ms cycle).

6.1.3 Dependent Variables. To understand humans' general perception of the abstract multi-robot motion, we collected Likert scale ratings on four relevant categories: emotion, user experience, human robot interaction and urgency. In addition, we collected users' perceived speed and smoothness rating scales to confirm their match with the commanded values. At the end, users could optionally leave additional comments about the study.

Emotion:

Emotion is integral in all experiences. Emotions influence physiological, cognitive and behavioral states of users. To mediate and control emotion elicited by UbiSwarm , it is crucial to study the effect of abstract motion on users' affect. In order to measure perceived emotion, we used a seven-point scale of self-assessment mannequin, SAM [7]. SAM is a visual scale of parameters in the PAD emotional state model [42]: valence, arousal, and dominance. Due to its reliance on pictures instead of words, it is widely used in both user experience and HRI research across different countries.

User Experience:

Before releasing interactive products, it is important to study their perceived qualities or their user experience. Hassenzahl identified three major qualities that contribute to the user experience: perceived pragmatic quality, hedonic quality and attractiveness of interactive products [22]. To measure these qualities, Hassenzahl created the AttrakDiff2 questionnaire. In this study, we used a nine-point scale, ten-item abridged version of it to measure user experience on abstract multi-robot motion. AttrakDiff2 has been widely used in user experience research to assess the overall experience. It uses semantic differentials on a set of words such as tacky/stylish and unpredictable/predictable. For a complete list, refer to [22].

Measures for Human Robot Interaction:

HRI researchers use questionnaires specific to measuring perception of robots. Bartnet et al. designed a set of standardized measurement tools for human robot interaction (HRI) on five key concepts: Anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety. [4]. We excluded anthropomorphism since the shape of robots do not change and perceived intelligence due to lack of significant interaction between the robots and subjects. Thus, we used a nine-point semantic differential scales for rest of the three concepts that were most relevant to our perception study: animacy, likeability, and perceived safety.

Urgency:

As we envision robots to be ubiquitous in the future, we expect them to be often used for notifications such as event reminder or phone calls. We adopted method used in [51] to measure urgency. Through a nine-point semantic differential, we measured the perceived urgency of the abstract motion and asked whether they will dismiss or attend to them.

6.1.4 Participants. We recruited 1067 participants through Amazon Mechanical Turk for a between-subjects study. For each condition, approximately 25 participants viewed and rated the corresponding video. For quality control, only participants that satisfy the following requirements were included in the analysis:

(1) Location is US
(2) HIT approval rate is greater than 90
(3) Number of HITs approved greater than 50
(4) He/she has not previously participated in any of our pilot studies
(5) He/she Is not experiencing any symptoms that may affect performance in the experiment
(6) He/she has participated only once.

Requirements 1-4 were enforced through Amazon Mechanical Turk. For requirement 5, we asked whether the participants are experiencing any of the following symptoms at the end of the survey : neurological disorders, impaired vision, headache, fatigue, and any other conditions that may affect their performance. The 67 participants that checked "yes" were removed. For requirement 6, 38 participants with duplicate IP addresses were also removed leaving a total of 962 participants for the analysis.

Due to this filtering process, numbers of participants across different conditions for the analysis became uneven although equal numbers were recruited. Authors did not recruit more participants to balance the number because the numbers of participants were still relatively even (< 8% difference).

Participants reported ages ranging from 18 to 81 with mean = 37.8 and SD = 12.4. A total of 51% identified as men and 49% as women, and 21%, 63% and 16% of participants reported education levels of middle/high school, college and advanced degrees respectively. After completing the experiment with average completion time of 3.5 minutes, each participant received $0.60 US dollars corresponding to a hourly salary of $10.30 US dollars.

6.1.5 Procedure. Before showing the abstract multi-robot motion video, we informed the participants that they would be seeing a group of robots moving in a particular manner and would be asked to rate their perception of their movements. Then with no training session, participants viewed their assigned video. The next button was shown only after the video finished but the participants were allowed to rewatch if desired before moving on to the questionnaire. After the video, participants answered a set of questionnaires including SAM, AttrakDiff2, urgency, and HRI questionnaires. At the end, they filled out demographic information and received compensation.

6.1.6 Analysis. To examine effects of the three independent variables including interaction effects, an n-way ANOVA was performed for each of the dependent variables. If any single independent variable or combination had statistically significant effects ($p < 0.05$), Bonferroni-corrected post-hoc tests were performed to determine which pairs of means are significantly different. All of the analysis was performed through MATLAB.

Table 1. Summary of the study results for emotion and user experience. Mean values are displayed with the 95% confidence interval in parentheses.

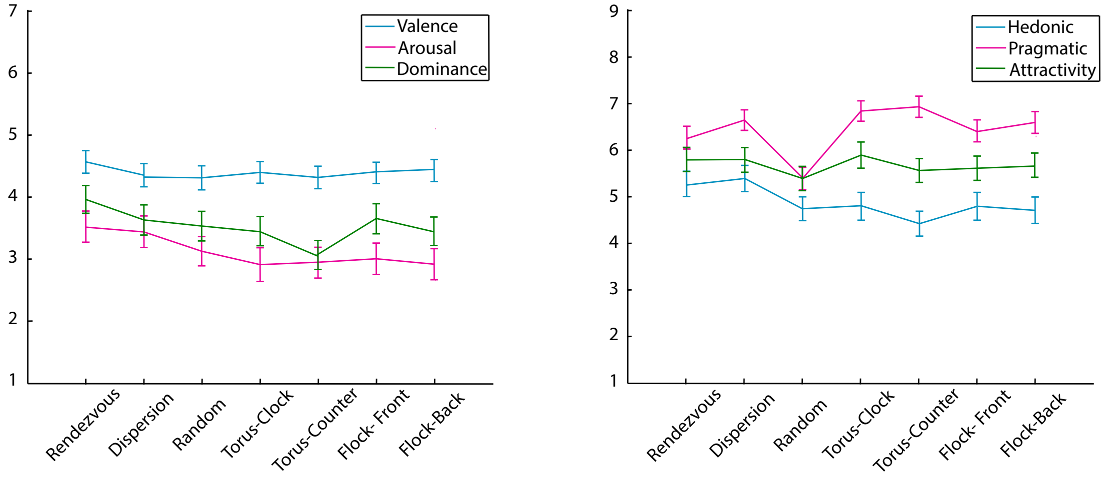
			Emotion			*User Experience*		
		N	Valence	Arousal	Dominance	Hedonic	Pragmatic	Attractive
Behavior	Rendezvous	141	4.55(.17)	3.50(.24)	3.95(.23)	5.26(.27)	6.25(.22)	5.78(.25)
	Dispersion	139	4.34(.17)	3.43(.24)	3.62(.23)	5.39(.27)	6.63(.22)	5.79(.25)
	Random	132	4.29(.17)	3.12(.24)	3.52(.23)	4.73(.27)	5.37(.22)	5.38(.24)
	Torus-Clockwise	131	4.38(.18)	2.90(.25)	3.43(.24)	4.79(.28)	6.83(.23)	5.88(.26)
	Torus-Counter	137	4.30(.18)	2.93(.25)	3.05(.23)	4.42(.27)	6.91(.23)	5.56(.25)
	Flock-Forward	138	4.37(.17)	2.99(.24)	3.63(.23)	4.79(.27)	6.40(.22)	5.60(.25)
	Flock-Backward	133	4.41(.18)	2.91(.25)	3.44(.23)	4.69(.28)	6.58(.23)	5.66(.25)
Speed	Slow	484	4.31(.09)	2.93(.13)	3.44(.12)	4.74(.14)	6.43(.12)	5.61(.13)
	Fast	478	4.44(.09)	3.30(.13)	3.60(.12)	4.99(.15)	6.42(.12)	5.72(.13)
Smoothness	Smooth	318	4.46(.12)	3.05(.16)	3.62(.15)	5.11(.18)	6.44(.15)	5.86(.16)
	Async Jitter	324	4.34(.11)	3.24(.16)	3.47(.15)	4.76(.18)	6.34(.15)	5.57(.16)
	Sync Jitter	320	4.33(.11)	3.04(.16)	3.47(.15)	4.73(.18)	6.49(.15)	5.56(.16)

6.2 Results

The overall results of the study are shown in Table 1 and Table 2. They report the means of all dependent variables for each shape parameter along with their 95% confidence intervals and sample size. The interaction factors are not reported because N-way ANOVA found almost no interaction effects except for arousal and willingness to attend.

Table 2. Summary of the study results for HRI metrics and urgency. Mean values are displayed with the 95% confidence interval in parentheses

			HRI Metrics			*Urgency*	
		N	Animacy	Likeability	Perceived Safety	Urgency	Attend?
Behavior	Rendezvous	141	5.24(.24)	6.01(.23)	6.07(.22)	4.46(.36)	62%(8%)
	Dispersion	139	5.13(.25)	5.96(.23)	6.28(.22)	4.91(.37)	70%(8%)
	Random	132	4.82(.24)	5.87(.23)	6.18(.22)	3.60(.36)	38%(8%)
	Torus-Clockwise	131	4.69(.25)	6.02(.24)	6.18(.23)	3.17(.38)	44%(9%)
	Torus-Counter	137	4.36(.25)	5.83(.23)	6.07(.22)	2.95(.37)	38%(8%)
	Flock-Forward	138	4.78(.25)	5.85(.23)	6.18(.22)	3.87(.37)	63%(8%)
	Flock-Backward	133	4.73(.25)	5.78(.24)	6.20(.22)	3.73(.37)	58%(8%)
Speed	Slow	484	4.67(.13)	5.84(.12)	6.20(.12)	3.56(.20)	51%(4%)
	Fast	478	4.97(.13)	5.96(.13)	6.13(.12)	4.07(.20)	57%(4%)
Smoothness	Smooth	318	4.93(.16)	6.09(.15)	6.33(.14)	3.88(.24)	51%(6%)
	Async Jitter	324	4.91(.16)	5.90(.15)	6.09(.14)	3.94(.24)	57%(5%)
	Sync Jitter	320	4.62(.16)	5.73(.15)	6.08(.14)	3.63(.24)	54%(5%)



(a) Emotion through SAM questionnaire

(b) User experience through AttrakDiff2 questionnaire

Fig. 7. Mean ratings and 95% confidence interval for different bio-inspired behaviors

6.2.1 Emotion. SAM includes three variables for emotion: valence, arousal and dominance. For valence, only speed was found have statistical significance ($p < 0.05$). The Bonferroni post hoc test showed that fast motion has statistically higher valence rating than slow movement.

For arousal, both behavior and speed were statistically significant with $p < 0.001$. Similar to previous research on single robot perception, faster movement had a higher arousal rating. As for behavior, rendezvous had the highest mean rating of 3.50 (.24) while clockwise torus had the lowest mean rating of 2.90(.25) in a seven-point scale. Behavior was the only statistically significant parameter for dominance ($p < 0.001$). Again, rendezvous had highest mean rating of 3.95 (.23) while counterclockwise torus had the lowest mean of 3.05 (.23). The overall effect of bio-inspired behaviors on emotion variables is plotted in Figure 7a.

6.2.2 User Experience.

User experience was evaluated with the abridged version of the AttrakDiff2 questionnaire with three key qualities: hedonic quality, pragmatic quality, and attractivity.

All three shape parameters had statistical significance on hedonic quality ($p < 0.05$ for speed, $p < 0.01$ for behavior and smoothness). Fast and smooth movements had higher hedonic rating than slow and jittery movements respectively. For behavior, dispersion had the highest average rating of 5.39 (.27) while counterclockwise torus had the lowest average of 4.42 (.27) as in Figure 7b.

For pragmatic quality, only behavior had statistical significance ($p < .001$). As expected, random behavior had the lowest average rating of 5.37 (.22) while both clockwise and counterclockwise torus behaviors had the two highest average ratings of 6.83 (.23) and 6.91 (.23) respectively.

For attractivity, smoothness was the only statistically significant factor ($p < .05$). The results show that smooth movements are rated more attractive than both synchronously and asynchronously jittery motions.

6.2.3 HRI metrics.

Out of the five key categories that Bartnet et al. developed as measurement tools for HRI, we chose to look specifically at three most relevant: animacy, likeability, and perceived safety.

All three shape parameters are found to be statistically significant for animacy in the following order: behavior, speed and smoothness ($p < .001$, $p < .01$, and $p < .05$ respectively). Rendezvous is perceived to be the most animate behavior (mean = 5.24 (.24)) while counterclockwise torus is rated the lowest animate (mean = 4.36 (.25)) as shown in Figure 8a. Fast movements had higher average animacy rating than slow ones. For smoothness, interestingly both smooth and asynchronously jittery movements had higher average ratings than synchronously jittery movement.

Only smoothness had a statistically significant impact on likeability. Smooth motion had a higher average likeability rating than synchronously jittery motion.

No statistically significant factor was found for perceived safety although speed was very close ($p = 0.057$).

6.2.4 Urgency.

Two questions were asked for urgency: semantic differential scale of not urgent-very urgent and a dichotomous question on whether to dismiss or attend to the robots. Results from both correlated very well as shown in Figure 8b. For both questions, behavior was the most statistically significant factor ($p < 0.001$). For both, dispersion had the highest average of 4.91 (.37) and 70% (8%) respectively while counterclockwise torus had the lowest average of 2.95 (.37) and 38% (8%) respectively. Speed had statistical significance only for the urgency scale ($p < 0.001$). As expected, fast motion was perceived as more urgent than slow movements.

6.2.5 Perceived Speed & Smoothness.

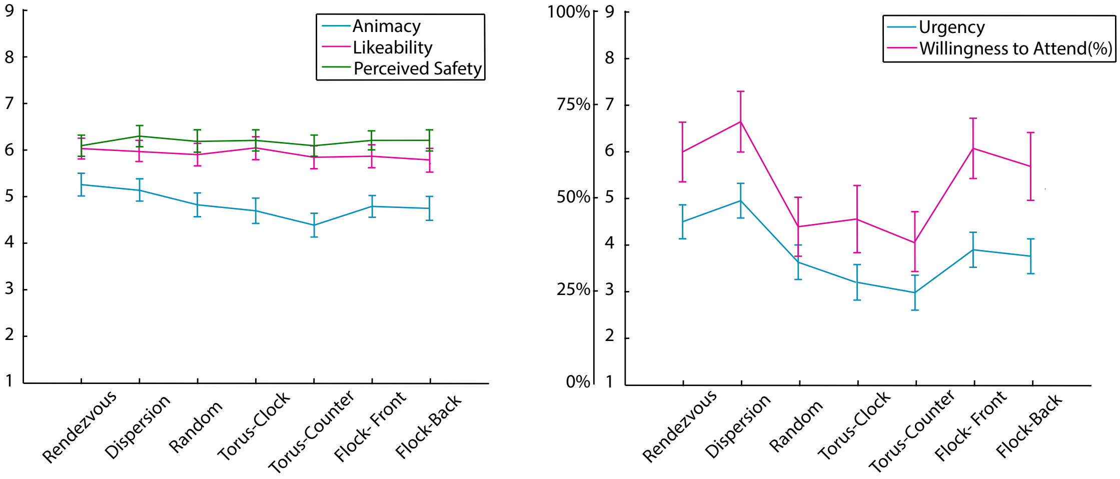
For both perceived speed and smoothness, results were as expected: speed and smoothness had the highest statistical significance respectively (both $p < 0.001$).

6.2.6 Qualitative Feedback.

We also gave participants freedom to leave any additional comments. Of the 371 participants left comments. 339 of them were not related to robots and their motion or were too general. The remaining 32 wrote their impressions of the robots and their motion. Eight of them were descriptive of their motion (e.g. “Some of the robots moved jerkily while a few moved smoothly"). Ten participants wrote robots were either ”cool” or ”cute” (e.g. “Robots - they are the future” and “I thought they were cute, though kind of useless”). Two thought the robots were creepy: “robots are a little creepy but they might be able to help people with disabilities”. One did not view them as robots: “they didn’t look like robots, at least to me”. Finally, three made metaphors (e.g. “They looked like hockey players skating!” and “The robots looked like mini trashcans :)”).

6.2.7 Effect of Number of Views.

As participants were allowed to rewatch the video as many times as desired, we also looked at whether the number of times participants watched the video affects their perception. Since we could not record the number of views, we used the time spent on the video page and divided it by the length of



(a) Measures for Human Robot Interaction

(b) Urgency and williness to attend

Fig. 8. Mean ratings and 95% confidence interval for different bio-inspired behaviors

the videos. With this calculated data, an ordinal logistic regression was performed and the coefficients of the covariates along with its p value were calculated. Out of the 10 dependent variables, only two had significant p-values ($p < 0.05$): Animacy and Urgency. Thus, it seems that the number of times participants watched the video did not broadly affect their perception.

6.3 Discussion & Design Implications

We envision that UbiSwarm can perform various tasks such as manipulation, display and interaction. The study results presented in this paper provide guidance on how to design swarm movements for both standalone and embedded displays.

6.3.1 Behavior. Behavior had statistically significant results in the following domains: arousal, dominance, hedonic and pragmatic qualities, animacy, urgency and willingness to attend. For these domains, some of the behaviors were perceived similarly to another. Specifically, rendezvous and dispersion behavior were rated closely, whereas for both torus and flock behaviors, direction of the motion did not influence the ratings significantly. The following discussions will be based on relative ratings among the different behaviors.

Rendezvous and dispersion behaviors were both perceived to be highly arousing, dominant, hedonic, animate, and urgent. They have the highest ratings for all categories except pragmatic quality. This suggests that these behaviors are appropriate for arousing, urgent, and hedonic notifications. The difference between the two behaviors is the direction of the motion, and thus the center of attention. For rendezvous, the focus is on the center whereas there is no focal point for dispersion behavior. Thus, rendezvous should be used in urgent and hedonic situations in which there is either a particular point or object of interest. For example, when receiving an important call, the robots rendezvous toward the phone. On the other hand, dispersion should be used in urgent and hedonic situations in which there is no particular point or object of interest. For example, when it is time to leave for an important meeting, robots disperse to alert the user.

Relative to other behaviors, users rated both directions of torus behavior to be non-arousing, non-dominant, low hedonic, inanimate, and non-urgent, but the most pragmatic behavior. This suggests torus behavior should be used in pragmatic but non-urgent scenarios such as a timer or progress bar to inform user of a status in low intensity applications. Although further research is needed, one interesting trend is that the two directions were perceived to be slightly different in some categories though not with statistical significance. Counterclockwise direction was perceived to be less dominant, less hedonic, less animate, and less urgent than clockwise torus. One potential cause may be the predominant exposure to clockwise motion in clocks in Western culture but this will need further investigation. In contrast, both forward and backward flock behaviors were perceived almost the same.

Relative to other behaviors, flock was rated average for dominance, hedonic and pragmatic quality, animacy, and urgency but high in willingness to attend and low in arousal. This suggests flock behavior to be used for average, everyday circumstances that are not urgent but nevertheless need attention. Examples include birthday reminders consisting of moving toward a picture frame of the person, and helping people cook by pointing toward appropriate seasonings/ingredients. Since both flock directions are perceived the same, the direction will depend entirely on the direction between the robots and the point or object of interest.

Random behavior was also perceived to be average but in different categories. Compared to others, random was rated average for arousal, dominance, animacy, and urgency but low in hedonic, pragmatic, and willingness to attend. Thus, random behavior is appropriate for un-pragmatic, arousing scenarios that do not need any attention, such as a music physicalizer or exercise motivator. People will not need to attend to them but will be moderately aroused.

6.3.2 Speed. Results for speed matched well with results from prior literature. Faster speed was perceived to be more pleasant, exciting, hedonic, animate, and urgent. Thus, motion speed should be fast for urgent, arousing and pleasant events such as important calls or reminders whereas it should be slow for low intensity, non-urgent applications like ambient displays, timers, and white motion.

6.3.3 Smoothness. Results for smoothness also aligned reasonably well with existing work where smoothness has been shown to affect pleasantness. Although smoothness was not a statistically significant factor for valence, it was for other relevant domains such as hedonic quality, attractivity, and likeability. Smooth motion was perceived to be more hedonic, attractive, animate, and likeable than synchronously jittery motion. Thus, robots should move smoothly for positive scenarios such as birthday reminders and music physicalizers while they should move in a jittery manner for negative scenarios like low battery or an approaching deadline. Interestingly, asynchronous jitter was perceived differently than synchronous jitter in some domains: it was rated as animate as smooth motion and as average for likeability between smooth and synchronous jitter. One possible cause may be that synchrony in jitter makes the robots look more machinelike and that negatively affects the likeability of the robots. Thus, to represent negative and less animate scenarios like low battery (20%), robots should employ synchronous jittery motion while moving in an asynchronously jittery manner for negative scenarios that require you to be more animate, such as a paper deadline approaching in an hour.

6.4 Example Applications

Using the study results, we designed abstract multi-robot motion for several example applications using UbiSwarm.

6.4.1 Phone Call. For an important phone call that needs immediate attention, we designed a fast and smooth rendezvous behavior as shown in Figure 9. Out of the five behaviors, rendezvous has higher ratings for arousal, urgency, and willingness to attend. Although dispersion is also rated similarly, rendezvous is more suitable as it focuses attention to a point or in this case, to the phone. In addition, dispersion requires robots to be around the phone to begin with while robots can be anywhere for rendezvous. Fast and smooth motion is used as faster

Fig. 9. Phone call notification: UbiSwarm rapidly and smoothly moves (rendezvous) toward a phone for notification of an urgent call.

Fig. 10. Tea timer: UbiSwarm slowly and smoothly rotates around the tea acting as a timer and disperses when the tea is ready.

speed is perceived to be more pleasant, arousing, and urgent while smoother movement is more likeable and attractive.

6.4.2 Tea Timer. For the tea timer application, robots move in two distinct manners: initially, a slow smooth clockwise torus behavior while tea bag is immersed as in Figure 10 followed by a fast smooth dispersion to let the user know that the tea is ready. During the waiting phase, a clockwise torus is used due to its low perceived urgency, willingness to attend, and arousal while being perceived as highly pragmatic. We chose the clockwise direction due to its resemblance to normal clock hands movement. Slow and smooth movement was designed to elicit calm, likeable, and attractive perception. When the tea is ready, robots disperse rapidly and smoothly to provide arousing and urgent yet attractive and likeable sensation similar to the previous phone call application but with in the opposite direction.

6.4.3 Reminder. To remind the user of a paper deadline that is approaching, UbiSwarm rapidly flocks toward a physical calendar with asynchronous jitter as in Figure 11. Flock behavior is used since it is perceived average in terms of hedonic, pragmatic and urgency while rated high in willingness to attend. Fast movement with asynchronous jitter is designed to create an arousing, less hedonic, yet likeable movement.

6.4.4 Low Battery Status. To indicate low battery status for a phone, robots slowly rendezvous toward it with synchronous jitter as in Figure 12. Rendezvous motion draws attention toward the phone, while fast speed with synchronous jitter provides arousing, urgent, unpleasant, and life-less sensation to inform that the phone needs to be charged.

7 LIMITATIONS & FUTURE WORK

In this paper, we proposed ubiquitous robotic interfaces and their key elements along with example scenarios. We ran a study on human perception of URIs' motion as a display and provided design guidelines and example applications based on the study results. However, there is still more to study for interaction with URIs. For example, it would be interesting to explore how people perceive URIs displaying icons of both static and dynamic state, and how people perceive URIs manipulating different objects in everyday scenarios. There is also more to

Fig. 11. Event Reminder: UbiSwarm rapidly flocks toward a calendar with asynchronous jitter to notify of an urgent deadline.

Fig. 12. Low battery notification: UbiSwarm slowly moves (rendezvous) toward a phone with synchronous jitter to signal low battery.

investigate for interaction design with URIs and the abstract motion perception study presented here was just the first step to do so.

Although this perception study provides general design guidelines for abstract motion of URIs, it does not provide complete insight into abstract motion of all URIs. First, the study results are not generalizable for all sizes of robots, since only a specific size of robots was used here. Although we speculate that similarly scaled robots will be perceived similarly, we believe that human or automotive-scale robots will most likely yield different perception results. In future work, it would be interesting to see how different sizes of URIs, ranging from hand to human to automotive scale, elicit different human perceptions.

The number of robots used during the study is also limited to ten. This was due to the size of the workspace and it is possible that different numbers of robots will yield different responses. Similar to the size of robots, we speculate similar numbers of robots will yield similar results but hundreds or thousands of robots are likely to result in different perceptions. Either by decreasing the robot size or by increasing the workspace, we could study the effect of different numbers of robots.

While the study results suggest statistical significance of motion parameters for many dependent variables, the effects were relative. When looking at the absolute values in the Likert scale, one can see that the range of different perceptions is not well spread out except for urgency. In the future, we will look into different ways of widening the range of various perceptions such as comparing different sizes of robots and wider range of speed.

In terms of implementation, the mobility and sensing ability of the robots can be further improved. While they can move on both horizontal and ferromagnetic vertical surfaces, the transition from one to another is not possible yet. We hope to address this by adding a ramp between the surfaces. In terms of sensing, UbiSwarm can currently localize itself and sense user's touch but cannot detect other objects for obstacle avoidance or object manipulation. In the future, we will address this by adding either a tracking marker to the objects or by using an external camera to detect them.

Finally, there are fundamental limitations of URIs compared to ubiquitous display either through projection, screens or wearable displays. Although there are great benefits from having physical form such as ability to move around and manipulate objects, URIs are limited by their physicality. They cannot disappear instantaneously and appear elsewhere like projection or screens pixels. They are constrained by the laws of physics. We cannot simply 'copy and paste' these URIs to send them to remote locations. However, we believe that these URIs can be useful in circumstances where mobility and manipulation are required, and that URIs can complement pixel-based interfaces for other applicable scenarios. Also, just as screens have gotten more affordable over time, we believe URIs will become more affordable and truly ubiquitous in the future as costs of transistors and robots continue to fall.

8 CONCLUSION

In this paper, we introduce ubiquitous robotic interfaces (URIs) along with their key elements: mobility, manipulation, sensing, display through icons and abstract motion, and interaction. We provide an example scenario showing how we envision UbiSwarm being used in our personal everyday lives. To study interaction with URIs, we first ran a crowdsourced between-subjects human perception study to investigate abstract multi-robot motion as a URI display. The abstract motion consisted of three motion parameters: bio-inspired behaviors, speed, and smoothness. Study results suggest that different bio-inspired behaviors elicit significantly different responses in arousal, dominance, hedonic and pragmatic quality, animacy, urgency and willingness to attend. On the other hand, speed significantly affects valence, arousal, hedonic quality, urgency and animacy while smoothness affects hedonic quality, animacy, attractivity and likeability. These results serve as design guidelines for URI-based displays and we demonstrate these through our own example applications. In the future, more studies on interaction with URIs should and will be conducted to explore richer types of interaction.

A SUPPLEMENTARY MATERIALS

You can find the supplementary video here: https://youtu.be/oT7theBRBzI

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