SwarmHaptics: Haptic Display with Swarm Robots

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Figure 1: *SwarmHaptics* uses a swarm of robots to display various haptics patterns to different body parts that are on a surface or through external objects such as a mouse. It can be used to convey notifications, social touch, directional cues, etc.

ABSTRACT

This paper seeks to better understand the use of haptic feedback in abstract, ubiquitous robotic interfaces. We introduce and provide preliminary evaluations of SwarmHaptics, a new type of haptic display using a swarm of small, wheeled robots. These robots move on a flat surface and apply haptic patterns to the user's hand, arm, or any other accessible body parts. We explore the design space of SwarmHaptics including individual and collective robot parameters, and demonstrate example scenarios including remote social touch using the Zooids platform. To gain insights into human perception, we applied haptic patterns with varying number of robots, force type, frequency, and amplitude and obtained user's perception in terms of emotion, urgency, and Human-Robot Interaction metrics. In a separate elicitation study, users generated a set of haptic patterns for social touch. The results from the two studies help inform how users perceive and generate haptic patterns with SwarmHaptics.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; *Empirical studies in HCI*;

KEYWORDS

Swarm Haptics; Human-Robot Interaction; Ubiquitous Robotic Interfaces; Swarm User Interface; Haptics;

ACM Reference Format:
Lawrence H. Kim and Sean Follmer. 2019. SwarmHaptics: Haptic Display with Swarm Robots. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland Uk.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3290605.3300918

1 INTRODUCTION

Human-Robot Interaction (HRI) has become increasingly important as more robots begin to appear in our daily lives. We see an increase in both the number of robots we interact with (i.e. swarm UIs and 1374 drones display) and types of robots, ranging from anthropomorphic robot guides in malls to non-anthropomorphic vacuum robots. With increasing encounters with robots, HRI researcher have looked at various ways to convey information beyond speech [67]. However, many of these are limited to anthropomorphic form and cues such as pointing [2, 30] and gaze [2, 11, 70], thus may not apply as easily to abstract and multi-robot systems.

Here, we explore how to convey richer communication from a swarm of robots through touch. Similar to [48, 50, 51, 65, 66], we envision that these robots could ultimately be used as interactive tools for education, accessibility and force feedback. In this paper, we focus on haptic display and show example scenarios including haptic notifications, directional cues, and remote social touch, enabling people in distant places to connect through touch. As such, we introduce SwarmHaptics, a new type of visual and haptic display with a swarm of small mobile robots. These robots can approach users' different body parts close to the surface they are on and display haptic patterns that vary in spatial, temporal, and force coordination. The motions of the robots

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CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300918

can also serve as visual displays to provide more context and complement haptic feedback.

To better understand how people perceive SwarmHaptics and its personal space intrusion [62], we ran an in-lab within-subjects study to see the effects of different haptic stimuli using Zooids [39]. Specifically, we investigated how different haptic parameters such as the number of robots, force type, frequency of force applied, and force amplitude affect human perception of emotion, urgency, and HRI metrics. We displayed the haptic stimuli on the participants' dorsal side of the forearm as it is one of the more socially acceptable areas to touch [64] and provides ample room for multiple robots to make contact with. From the study results, we find that the number of robots, force frequency, and amplitude have significant effect on human perception, whereas force type only has interaction effects.

Lastly, to gain insights on how users would convey different types of social touch such as positive affection and ritualistic touch, we developed a platform to control multiple robots simultaneouslyand ran an elicitation study. We asked participants to generate different haptic pattern given referents relating to social interactions (e.g. greeting, hug), affective communications (e.g. happy, sad), and functional communications (e.g. notification). Although some referents elicited similar interactions, the results help demonstrate the expressiveness of SwarmHaptics for social touch.

In summary, our contributions are:

- Exploration of the design space for SwarmHaptics,
- Perception study results on swarm haptic stimuli,
- Interface to control multiple robots simultaneously,
- Elicitation study results for social touch.

2 RELATED WORK

Other Haptic Devices

There already exists many different types of haptic devices. Examples include vibrotactile [32, 69], wearables [6, 16, 17, 31], shape displays [25, 33], hand-held [13, 42, 52] and encountered-type haptic devices [1, 37, 73]. While SwarmHaptics may not be able to provide the richest sensation compared to the other haptic devices, it can support multiple users simultaneously and it does not have to be constantly worn by the user which can cause discomfort. Also, the robots are mobile, allowing haptic designers to control when and where the haptic sensation should be delivered. Finally, SwarmHaptics can be used for many other applications such as object manipulation and not just dedicated to haptic display.

Haptic Interaction with a Robot

HRI researchers have looked at the role of haptics in communication and coordination with robots. The most commonly investigated interaction method involves a human touching a single robot. PARO and other huggable robots have been found to improve mood, stimulate social interaction, reduce anxiety and stress levels [63, 72, 74].To recognize different touch inputs from human, researchers have used different approaches including conductive fur touch sensors [24], proprioceptive sensors [57], and inertial sensors [15].

Fewer works have explored touch from a robot to a human or mutual touch between robots and humans, and mostly with anthropomorphic robots. Touch from anthropomorphic robots have had mixed results. While some found it to have positive impact on human effort [60] and unfairness [26], others found people prefer touching the robots than being touched [29]. Verbal cues and perceived intent also were shown to effect human's response to a robot's touch [12].

While prior work has explored haptic interaction between a single anthropomorphic robot and human, none to our knowledge have looked into the haptic interaction between multiple, small non-anthropomorphic robots and user. As more robots enter our lives, it is important to not only study human-robot interaction in the context of dyads but also with multiple robots. Thus, we introduce a design space for haptic display with a swarm of robots and study human perception of various haptic patterns from the robots.

Swarm Robotics & Swarm User Interfaces

Biological swarms have inspired roboticists to imitate and develop swarm robots where a large quantity of robots is coordinated to achieve a common goal. There are many advantages for swarm robots as they can offer swarm intelligence, flexibility, and robustness to failure. There are swarm robotic platforms with as many as 1,000 robots [56] emulating swarm behaviors using distributed intelligence and fully autonomous agents [20, 21]. While many have looked at functional aspects of swarm robots such as control [3, 9, 59], less have focused on the physical interaction with them.

With robots becoming more abundant and reducing in size, it is important to investigate how to interact with a swarm of robots. Few HCI researchers have developed swarm user interfaces for applications like data visualization [39] and education [28, 51]. While many have looked at the use of their motions for interaction [18, 35, 54] and how it affects user perception, very few have looked at haptic interaction with a swarm of robots. Ozgur et al. investigated haptic interaction with a hand-held mobile robot that could potentially be expanded to swarm of robots [50]. In this paper, we study how a swarm of robots can be used as a haptic display, how humans perceive different haptic stimuli, and how users would use SwarmHaptics for remote social touch.

3 DESIGN SPACE OF SWARMHAPTICS

Here, we explore the design space for a haptic display with swarm robots. Specifically a group of simple, mobile robots with no end-effector is chosen because it is one of the most rudimentary type of robots. Thus, the resulting design space

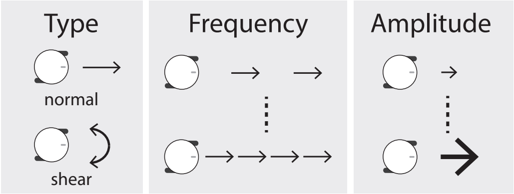


Figure 2: Force parameters for a single mobile robot. A robot can generate forces of different types (normal/shear), frequencies, and amplitudes to different locations.

can be more generalizable to other mobile robots. We first investigate the design space for a haptic display with a single robot, then broaden the scope to include a swarm of robots.

Haptic Parameters for a Single Robot

Force Parameters. A simple mobile robot can only move in 2-D space, and is limited to 2-D translation and 1-D rotation. Thus, the types of haptic stimuli that it can provide are also limited by its motion capabilities. When using pure translation, a simple mobile robot can apply normal force to the user. Whereas it can generate shear force through pure rotation or by moving along the skin. We can also control the magnitude and frequency of the haptic stimuli by adjusting the magnitude and frequency of the commanded speed/torque to the motors. By frequency, we refer to the rate at which the robot move forward and backward or rotate clockwise and counterclockwise to impart force on users. All forces generated by the robot are grounded to the surface that it is driving on. Overall, we can control the motion of a simple mobile robot to generate haptic stimuli with different force type, magnitude, and frequency as shown in Figure 2.

Contact Location. Because of its mobility, the robot can move to different accessible body parts and provide haptic stimuli. For instance, a robot on a desk can touch the user's finger, hand, wrist, elbow, and both sides of the forearm. On the other hand, a robot could provide haptic feedback to the user's feet on the ground to push away from certain areas or to the body while lying down to wake him/her up. Due to the varying mechanoreceptors and haptic sensitivities of different parts of the body, the same touch stimulus can feel different depending on the location, even just throughout the arm [61]. For example, pushing with 1N of force on a fingertip will feel much greater than pushing on the shoulder with the same force. In addition, the social appropriateness of the touch needs to be considered. Some body parts are more socially appropriate to touch such as the arm and the shoulder [64]. Thus, developers will have to carefully select the location of the haptic stimuli based on the application.

Tactile vs. Kinesthetic. Depending on the contact location and the motion of the robot, the robot can provide either tactile or kinesthetic stimuli. The stimuli will be kinesthetic when the magnitudes of the forces are great enough to move the joint angles in the body whereas they will be tactile if the forces are weak and thus only stimulate the skin. For example with our system, even a single robot is sufficient to move a single finger but at least seven robots are needed for an entire arm. Thus, we need to ensure that the contact location, magnitude of force, and type of motion are properly selected to produce the desired haptic effect.

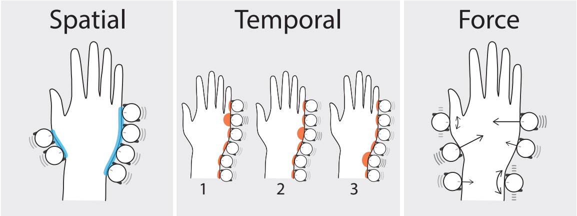


Figure 3: Types of coordinations possible among a swarm of robots: we can coordinate where the robots provide haptic stimuli, when they apply the forces, and which forces in terms of force type, frequency and amplitude they generate.

Size and Texture. Size or form factor of the robot is another important parameter that could impact the interaction experience. Prior works have shown that people perceive telepresence robots differently even when just the height is changed [55]. Similarly, any significant change in other form factor such as size and shape is highly likely to influence user's perception. On the other hand, contact material and softness have been shown to have significant effect on perceived pleasantness [23]. Thus, even with the same force type, frequency, and other haptic parameters, changing the texture of the robot will most likely effect user's perception.

Haptic Parameters for a Swarm of Robots

Number of Robots. The most basic parameter for swarm robots is the number of robots. As people behave differently based on the number of people they interact with [38], we conjecture that the number of robots will change how people perceive, behave, and interact with them. Also, more robots increase the degrees of freedom for haptic expressivity.

Coordination. A more complex design parameter for a swarm of robots is the coordination between them. With more robots, it becomes not only difficult to control them [36], but also it is uncertain how to best coordinate them for different applications. As shown in Fig. 3, we propose three ways to coordinate the robots: spatial, temporal, and force.

Spatial distribution: With many robots, we need to determine how to spatially distribute them. There are many factors to consider such as the desired resulting force and the users' comfort. With multiple robots, it is possible to combine their forces to create different haptic patterns. For instance, with one robot, it is impossible to provide "squeeze" sensation to the user's forearm.With many robots, we can distribute the robots to both sides of the forearm and command normal forces to generate the "squeeze" sensation. At

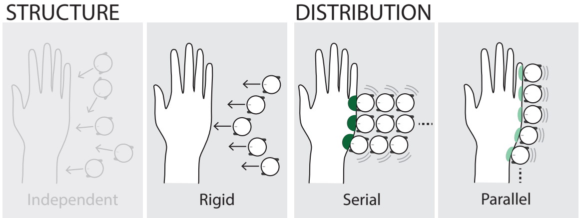


Figure 4: Spatial parameters: Structure between the robots, from independent robots to robots in rigid formation, affects user perception. Distribution of them either serial or parallel, determines contact area size and resulting forces.

the same time, we need to consider users' comfort when touching multiple locations with the robots. Users may not be comfortable with being surrounded by the robots or being touched in particular areas [64].

Independent motion vs. Rigid structure: In addition to the robots' relative positions to the user, the relative positions between the robots need to be considered. Inter-robot interaction can affect how the users perceive haptic stimuli from the robots. For example, haptic stimuli from a group of robots in rigid formation can feel different than one from a group of robots that move independently. This inter-robot relation has proven to have significant effect on human perception for abstract motion [35] but needs to be studied for haptic display with swarm robots.

Serial vs. Parallel distribution: With many robots, there are different ways of distributing the robots. To maximize the contact area, we can distribute the robots in a parallel fashion; while to reduce the contact area with the same number of robots, we can place them in series as shown in Figure 4. We can imagine the robots as representing forces, and for higher combined force at a point, one would put the forces in serial while to spread the forces to a larger area, one would use the parallel formation. An appropriate method should be chosen based on the context. For instance, to rotate a user's forearm about her elbow, it is ideal to provide the resulting force near the wrist, the furthest point from the elbow. Then, we should distribute the robots in serial near the wrist rather than placing them in parallel across the forearm.

Spatial & temporal patterns: To further enrich the range of expressivity, one can combine spatial and temporal coordination. A simple example is a line of robots that apply normal forces to the user's arm in a sequential manner from top to bottom as shown in Figure 3 which could be used to provide directional cues to the user for navigation.

Force coordination: Finally, we can coordinate the forces that each robot generates. For instance, when providing directional cues, we can modulate the magnitude of the force in addition to the frequency to enhance the fluency of the directional cue similar to how Israr et al. used an amplitude modulation algorithm for a vibrotactile array [32]. In addition, we can vary the force type that each robot provides: normal or shear. For example, we can have some of the robots output normal force while the others produce shear force as shown in Figure 3. While it is still unclear how human would perceive such a combination, this flexibility adds another degree of freedom for conveying information.

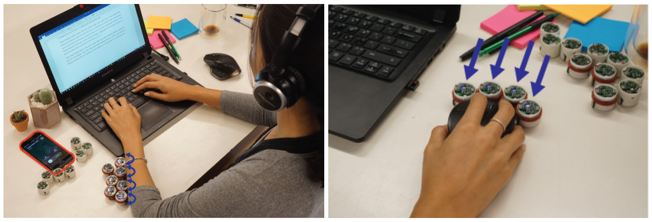


Figure 5: (a) Notification: She doesn't notice her phone (in red) is ringing because her eyes and ears are occupied. The robots approach and apply shear forces to alert her. (b) Directional Cue: the robots guide the user's mouse motion.

Mediated Display In addition to displaying haptics directly to the skin, the robots can provide haptic sensations indirectly through external objects. Instead of augmenting each device on the desktop like LivingDesktop [5], we can provide haptic sensations through SwarmHaptics. For instance, to help a user maintain focus, robots could push the mouse that the user is holding away from links of a distracting video. By indirectly pushing on the mouse instead, this could potentially reduce the discomfort that the users may feel from a swarm of robots touching them directly.

Visual Effects of Robots' Motion As the robots move to produce haptic sensations, there are inherently visible motions that accompany the haptic stimuli. For instance, when the robots are providing wave-like haptic stimuli, users would also see the wave-like motion. This visual may help complement the haptic stimuli to enhance the salience of the haptic stimuli. Also, their paths and motions could help users understand the robots' intents and internal states [19].

4 EXAMPLE SCENARIOS

Here we demonstrate several example scenarios of how SwarmHaptics can be used in real life situations.

Notification. SwarmHaptics can be used to notify users through touch. This can be especially useful when the other primary senses, visual and audio, are occupied by other mediums. For example, imagine Tia is writing a paper on her laptop while listening to her favorite music through her headphones. When her collaborator calls her to discuss details about the paper, she doesn't notice even though her phone is ringing. The robots then take action and approach her forearm to provide tactile notification through shear forces.

Directional Cues SwarmHaptics can be used to convey directional cues to the user. For instance, imagine Lauren is studying for final exams but is continuously tempted to watch entertaining videos instead. However, whenever she tries to move her cursor to click the link, the robots push her

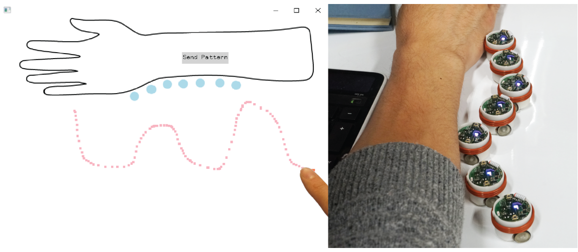
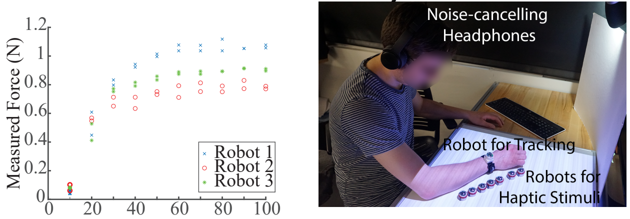


Figure 6: Remote Social Touch: Different haptic patterns can be drawn on a touch screen to convey remote social touch.



(a) Normal Force Evaluation. (b) Perception Study Setup.

Figure 7: Implementation: (a) normal force evaluation for three robots. (b) perception study setup with robots for haptics/tracking and a user with noise-cancelling headphones.

mouse away as shown in Fig. 5. After a few failed attempts, she finally gives in and studies for her final.

Remote Social Touch SwarmHaptics can be used to convey social touch to a remote person. For instance, imagine that Joanne is trying to condole a friend who is having a tough time. Unfortunately, she cannot physically be there for him as they are far apart. As a way to provide comforting touch, she draws a sinusoidal wave on her phone to convey a soothing wavy haptic and visual stimuli with the robots.

5 IMPLEMENTATION

We used the robots in UbiSwarm [35] which are modified version of the Zooids robots [39]. These robots communicate with a centralized computer and move in 2-D space via two, wheeled motors. To track the robots, we used the same projector-based tracking [40] as in Zooids [39].

There are several challenges with using swarm robots for a haptic display. For haptic stimuli, force amplitude is one of the most important parameters. At the minimum, it needs to be detectable by the users. To further expand the range of haptic stimuli possible, a larger range of force amplitudes is desired. The current Zooids do not output such forces, and even the modified version with stronger motors used for UbiSwarm fail to produce significantly greater forces due to the low friction between the wheels and the driving surface. To overcome this, we attached magnets to the bottoms of the robots and used a ferromagnetic surface to increase the normal force, and thus the wheel traction. This by itself increased the force output of the modified Zooids robots by a factor of 9 from 0.1 N per robot on non-ferromagnetic surfaces to approximately 0.92 N per robot on ferromagnetic surfaces as shown in Figure 7a. The same could be achieved by increasing the mass of the robot by a factor of 9 or by using gecko-adhesives/microspines as used in [4, 14]. For this paper, we decided to use the ferromagnetic surface for quicker implementation and to keep the volume of the robots to a minimum allowing more robots to simultaneously interact with users' forearm. Due to cost and complexity of integrating a force sensor in a small robot, we didn't include a force sensor and the force outputs were provided in open-loop.

In addition to the friction between the robots and the ground, we need to consider the friction between the users and the robots as it determines the shear forces that users would feel. The current robots are 3D-printed plastic and thus doesn't have good traction with human skin. Studies have shown that softer materials are more pleasant than rough materials [23]. Thus, to increase friction without causing any discomfort, we added soft silicone rings around the robots.

We programmed the applications, motions, and haptic stimuli in C++ in Visual Studio using the Zooids API [39]. To track the participant's forearm, we used the position of a robot that is mounted on the participant's wrist through a wristband as shown in Figure 7b. Based on the location of the wrist, we estimated the location of the forearm. For more details about the Zooids system, refer to [39].

6 USER PERCEPTION OF SWARMHAPTICS

To properly design the haptic patterns from SwarmHaptics, we first need to understand how people perceive different haptic stimuli from the robots. We first begin by studying the effects of the fundamental parameters such as force type, frequency, and amplitude with varying number of robots. Other elements of our design space such as spatial, temporal, and force coordinations build on the fundamental parameters and we plan on investigating them in the future.

Hypotheses

The first parameter we studied was the number of robots touching the participant. No research to our knowledge has explored and tested the idea of multiple robots touching a human. We expect similarities with what Podevijn et al. has found for people observing motion of different number of robots [54]. They found increasing the number of robots in motion increased the subjects' heart rate, skin conductance level, arousal, and valence [54], we hypothesize that increasing the number of robots in contact will also increase the perceived arousal, urgency, valence, and likability.

Based on pilot testing, there seems to be significant effects from the force type. In particular, we conjecture that shear forces are more pleasant and likable than normal forces. Thus, we hypothesize that shear forces will be rated higher in valence and likability than normal forces.

Frequency is an important haptic parameter for both detectability [46] and user perception. However, the trend for perception has been unclear in prior works for vibration

[43, 58] and mid-air haptics [49].Based on the commonalities of the prior works, we hypothesize that higher frequency will elicit higher perception of arousal and urgency.

For haptic devices, controlling the force amplitude is critical not only to overcome the absolute threshold but also to mediate the users' perception. For instance, with both belt-compression and electrovibration haptic devices, higher amplitude for force or vibration has been rated lower in valence [8, 68]. Thus, we also hypothesize that the higher force amplitude will lead to lower valence and likability.

Method

To evaluate the human perception of haptic display with swarm robots, we provided various haptic stimuli to the users, on the dorsal side of their forearm. We chose it for three reasons. First, it is one of the more socially accepted areas for other people to make contact [64]. People typically rest their forearm on a flat table which is one of the ideal locations for the robots. Lastly, the forearm provides ample room for a swarm of robots to provide direct haptic sensations.

Independent Variables. We varied four independent variables: number of robots, force type, frequency, and amplitude. To limit the total experiment time to less than 50 min, we only used one repetition for a total of 24 trials per participant.

Number of Robots: For the study, we explored three values for the number of robots: n = 1, 3, and 7. The maximum number was limited to seven as only seven robots could touch a user's arm simultaneously in a parallel configuration.

Force Type: We also looked at the effect of different force types: normal and shear. Normal forces are generated by applying the same torque to both motors in the same direction while for shear forces, the directions are reversed.

Frequency: Binary values were used for the frequency: 1 Hz or 10 Hz. 10 Hz was the highest that the robots could render without reducing the force amplitude significantly.

Amplitude: We explored the effect of binary values of the amplitude: a low value (0.8 N per robot) that we felt were just detectable and a high value (0.92N per robot) that is the maximum amplitude possible with the current robots.

Dependent Variables. Emotion: For any experience, it is important to account for user's perceived emotion as emotion influences physiological, cognitive, and behavioral states of the users. Thus, we studied the effect of different haptic stimuli on users' affect. To measure, we used a seven-point scale of SAM [10], a visual scale of parameters in the PAD model [44]: valence, arousal, and dominance. Due to its use of pictures, SAM is a widely used to assess emotion in both user experience and HRI research across different regions.

Measures for Human-Robot Interaction (HRI): Many HRI researchers have used the questionnaire designed by Bartneck et al. that is specific to measuring perception of robots [7]. Out of the five categories of the questionnaire, we asked the participants to rate seven-point semantic differential scales on the three most relevant ones: anthropomorphism, likeability, and perceived safety. We included anthropomorphism as generating human-like touch will be meaningful and useful especially in the context of social touch. We excluded perceived intelligence and animacy as a pilot study showed these two did not vary with different haptic stimuli.

Urgency: Lastly, we envision that SwarmHaptics can be used to notify people of events with varying urgency. We adopted the method used in [53] to measure urgency. Through a seven-point semantic differential, we asked the participants to rate their perceived urgency of the haptic stimuli and their intention to either dismiss or attend to them.

Participants. Twelve participants (5 M, 7 W, Age: 21-29) were recruited. Participants had various previous haptic experiences ranging from none to extensive. None had neurological disorders, injuries to the hand/arm, or any other conditions that may have affected their performance in this experiment. They were compensated $15 for their time (~ 40 min) and the study was approved by the University's Institutional Review Board with subjects providing informed consent.

Procedure. Before the study, we informed the participants that they would be given various touch stimuli from the robots and would be asked to rate their perception. To track their arm, they were asked to wear a tracking wristband. They also wore a noise-canceling headphone to isolate the audio cues from the robots. For each trial, participants placed their arm on a designated location. Once ready, they pressed a button to start. The robots initially positioned 10 cm away from the arm, moved forward and made contact with their arm. After a second, the robots would provide the touch stimulus (500 ms) three times with a 500 ms break in-between for a total of 3 seconds. Once completed, they would move back to their initial positions. Participants would then complete a survey on a tablet and repeat for a total of 27 fully randomized trials (3 training trials + 24 conditions).

Analysis. To examine the effects of the four independent variables including interaction, a Mauchly's Test of Sphericity and a 4-way repeated measures ANOVA were performed for each dependent variable. If Mauchly's Test of Sphericity was violated, we used a Greenhouse-Geisser correction for F and p values from ANOVA indicated by F^* and p^*. If any independent variable or combinations had statistically significant effects ($p < 0.05$), Bonferroni-corrected post-hoc tests were used to determine which pairs were significantly different.

Results

Figures 8-10 report the means of all dependent variables for each haptic parameter along with their standard errors. (*: $0.01 < p < 0.05$, **: $0.001 < p < 0.01$, ***: $p < 0.001$)

Emotion. All independent variables except force type had a significant effect on at least one parameter of emotion, as

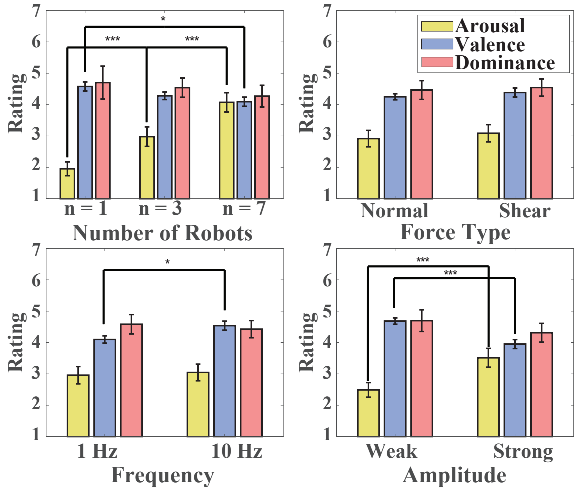


Figure 8: Effect of haptic parameters on emotion.

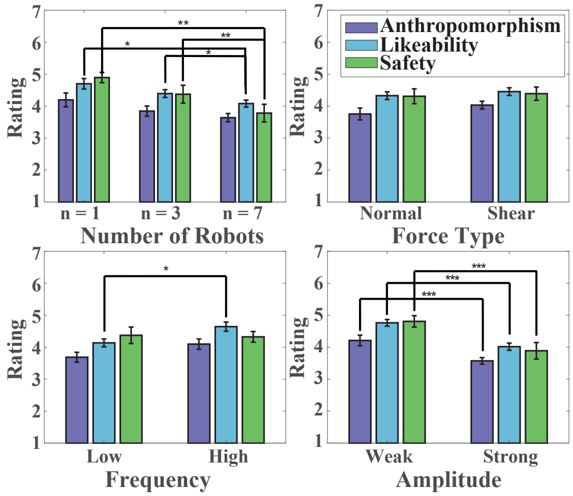


Figure 9: Effect of haptic parameters on HRI metrics.

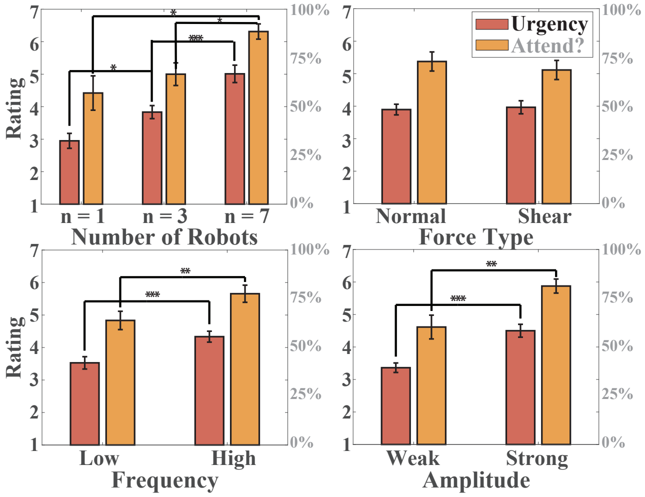


Figure 10: Effect of haptic parameters on perceived urgency and willingness to attend.

shown in Figure 8. For the arousal axis, number of robots (F(2,22)=69.4, p=3.1E-10) and force amplitude (F(1,11)=96.0, p=9E-7) had positive relation whereas they both had negative correlation with the perceived valence (F(2,22)=4.64, p=.021), (F(1,11)=26.6, p=.0003). Finally, force frequency (F(1,11)=14.2, p=.022) had positive correlation with the valence axis.

HRI. All independent variables except force type had significant effect on at least one of the three HRI categories explored as shown in Figure 9. Number of robots and force amplitude had negative correlation with perceived anthropomorphism(F(2,22)=3.6, p=.044), (F(1,11)=19.3, p=3.5E-4), likeability (F(2,22)=6.8, p=.014), (F(1,11)=43.7, p=3.8E-5), and safety (F*(2,22)=11.2, p*=.002), (F(1,11)=36.1, p=9E-5). On the other hand, force frequency had positive correlation with perceived likeability (F(1,11)=7.0, p=.023).

For likeability (F(2,22)=5.8, p=.009) and perceived safety (F(2,22)=7.4, p=.003), there was an interaction effect among number of robots, force type, and frequency. While higher frequency usually increases likability, when there is one robot applying normal force, the frequency doesn't affect the likability. For perceived safety, when there is one robot generating normal force, lower frequency stimulus is perceived significantly safer than higher frequency one.

Urgency. All independent variables except force type had significant effect on urgency and willingness to attend as shown in Figure 10. Number of robots [(F*(2,22)=24.4, p*=7.2E-5), (F(2,22)=7.4, p=.004)], force frequency [(F(1,11) = 25.9, p=3.5E-4), (F(1,11)=13.3, p=.004)], and force amplitude [(F(1,11) = 69.9, p=4E-6), (F(1,11) = 16.0, p=0.002)] all had positive correlations with perceived urgency and willingness to attend.

There was an interaction effect for urgency (F(1,11)=7.2, p=.021) and willingness to attend (F(1,11)=7.3, p=.021) between force type and force amplitude. While stronger amplitude is generally perceived as more urgent and has higher willingness to attend, when the robot(s) are applying shear forces, the amplitude doesn't affect the perceived urgency or the willingness to attend to the robots.

Discussions

Number of Robots. From the results, we can easily see the significant effects that the number of robots has on user perception. The number of robots had positive correlation with arousal, urgency, and willingness to attend while having negative correlation with valence, likability, and perceived safety. These results imply that when deciding the number of robots for haptic display, there is a tradeoff between the perceived arousal or urgency and the pleasantness or likeability of the haptic stimuli. More robots can provide more arousing and urgent sensation but at the cost of pleasantness, safety, and likeablility. Thus, we would recommend limiting the number of robots used for haptic display when conveying positive, safe or pleasant information whereas using more robots for important and urgent circumstances.

Force Type. Force type had surprisingly weak effect on user perception. There was no dependent variable which force type alone had statistically significant effect. However, interaction effects were observed for likeability, perceived safety, urgency, and willingness to attend. The results suggest that force type has complicated relationship with human perception and thus will need to be carefully combined with other parameters to elicit desired effect.

Frequency. Frequency of the haptic stimuli had positive correlation on valence, likeability, urgency, and willingness to attend. This is intriguing as some of the results correlate with previous work while some provides clarification. Specifically, the trend for perceived urgency and willingness to attend is aligned with what others found, in that higher frequency is more alarming, and arousing [43, 49, 58]. On the other hand, the results for valence and likeability provides some clarification as other works had found mixed results. However, as the values of frequency tested here (1-10Hz) are drastically different than the ones used in previous work for vibrations and ultrasonic transducers (16-175Hz), more studies are needed for further clarification.

Amplitude. Increasing the amplitude of the haptic stimuli increased the arousal, urgency, and willingness to attend but decreased valence, anthropomorphism, likeability, and perceived safety, similar to the effect of increasing the number of robots. This result is consistent with what Valenza et al. found in which higher force amplitude led to higher arousal and lower valence [68] and with Bau et al. which found higher amplitude for electrovibration was rated less pleasant [8]. Along with the number of robots, force amplitude was found to be the more influential parameter and thus will need to carefully controlled to elicit desired perception.

7 ELICITATION STUDY FOR SOCIAL TOUCH

In the earlier study, we evaluated human perception of various simple haptic patterns. To generate more expressive patterns specifically for social touch with different spatial, temporal, and force coordinations, we had the participants brainstorm haptic patterns through an elicitation study. Elicitation studies with novice users have been shown to be beneficial in terms of understanding users' preferences [27, 47, 71].

Method

As SwarmHaptics is a novel system, we wanted to ensure there was a feedback loop in which participants could feel the haptic patterns they created and modify them as needed. Thus, we had participants use their own non-dominant arm for feedback and the dominant arm to generate the pattern.

Referents. There exists a wide range of social touch that varies in its intent and affect. Prior work has identified six categories for symbolic meanings of touch: positive affection, control, ritualistic, playful, and task-related [34], while there are six widely accepted basic emotions (happiness, sadness, fear, anger, disgust and surprise) [22]. Based on these two concepts, we generated a list of referents, shown in Table 1.

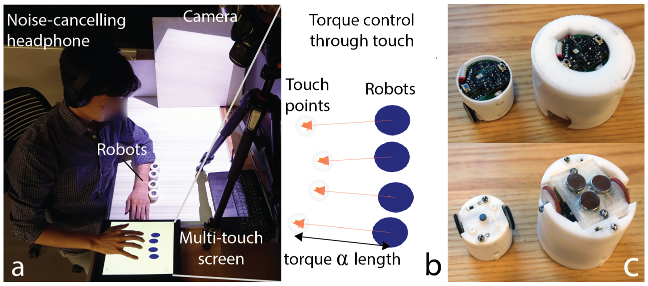


Figure 11: Elicitation study setup (a) with a close-up view of the multi-touch screen (b). (c) The robots for the elicitation study (right) compared to the one used in first study (left).

Data Collection. For analysis, we videotaped participants' movements and recorded positions/velocities of the robots and touch. To understand participants' perception, we asked them to complete a questionnaire after each trial rating the clarity, ease of control, anthropomorphism, and likability of the haptic pattern they just created. We included anthropomorphism as generating human-like touch is important and relevant especially for social touch. They also wrote a textual description what they were trying to do with the robots. After the trials, they filled out a questionnaire and had short interviews about the overall experience of using SwarmHaptics for remote social touch.

Implementation. For the study, we used a set of four robots controlled by the user's finger movements on a multi-touch screen as shown in Fig 11a. We initially started with five robots but preliminary testing revealed that controlling five fingers independently without losing contact with the screen is uncomfortable and do not increase the expressiveness substantially. Users control the torque of the robots by dragging the blue circles with their fingers. The distance and direction of the drag controlled the torque and heading of the robot (Fig 11b). The sizes of the control points and spatial map were adjusted for each user to accommodate their hand sizes.

As our previous study demonstrated the importance of force amplitude, we redesigned the robots to increase force output (up to 3.6 N compared to 0.92N) with a larger size (45 mm diameter) as shown in Fig. 11c. The existing motors are replaced with higher torque motor (Pololu Micro Metal Gearmotor #2365) and additional battery (850 mAh, 1C) is added to power them. Stronger magnets are added on the bottom to increase the normal force, thus the traction.

Procedure. Twelve participants (6M/6W, age: 20-33) were recruited. None had injuries, fatigue, or disorders that could impact their performance. They were compensated $15 for

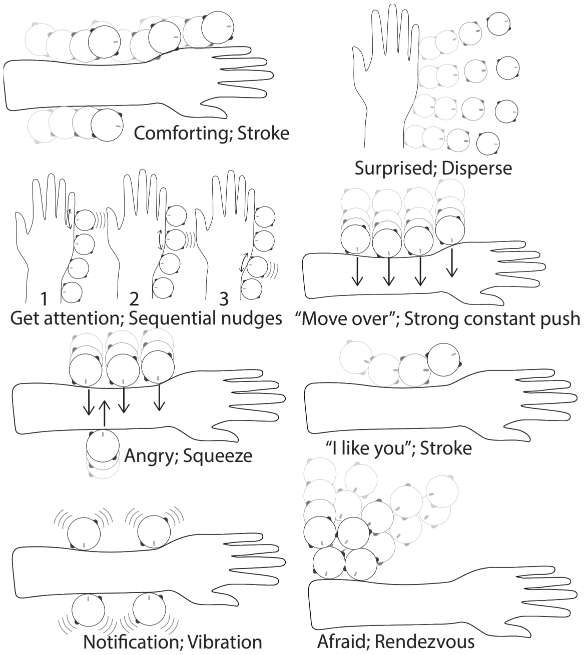


Figure 12: Example interactions from the elicitation study for social touch. A non-conflicting set for ten referents which may not be the most representative one is shown.

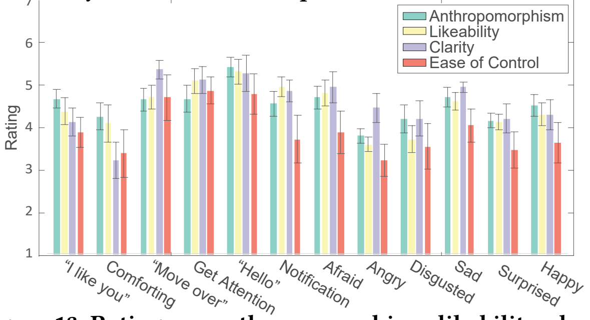


Figure 13: Ratings on anthropomorphism, likability, clarity, and ease of control of the robots for each referent.

their time (~45 min) and the experiment was approved by the University's Institutional Review Board.

Before the study, participants were informed that they would be given a set of referents for each of which they would create a haptic pattern using the robots and answer a questionnaire. After the instructions, three minutes were allotted for to familiarization with the interface and exploration of the range of possible haptic patterns. Then, for each referent, the participants were told to try out different patterns on themselves, decide on the best one, and record it. Participants were told to use as many robots as necessary and wore noise-canceling headphone to isolate audio cues.

Results & Discussions

In Table 1, the interactions with the number of robots used for each referent are listed. Only interactions with frequency greater than 2 are shown due to space constraints. Some of the example interactions are shown in Fig. 12.

Category	Referent (Agreement)	Interaction	# robots	#
Positive Affection	"I like you" (0.39)	Stroke	1	5
		Hug	2+	3
		Touch & draw heart	1	2
	Comforting (0.31)	Stroke on both sides	2+	5
		Stroke	1	3
		Hug	2+	2
Control	"Move over" (0.25)	Strong constant push	2+	5
		Sequential push	2+	2
		Tap	1	2
	Get attention of someone (0.13)	Sequential nudges	2+	2
		Hard collide	1	2
		Sporadic taps around arm	1	2
Ritualistic	"Hello" (0.32)	Tap	1	5
		Tap	2+	2
		Fist Bump	1	2
Task-related	Notification (0.22)	Tap repeatedly	1	4
		Vibration	2+	3
		Strong Push	2+	2
Emotion	Afraid (0.13)	Nudge for long period	1	2
		Strong push back & forth	2+	2
		Touch & rendezvous	2+	2
	Angry (0.25)	Strong push	2+	5
		Squeeze	2+	2
		Strong push back & forth	2+	2
	Disgusted (0.24)	Tap & run away	2+	5
		Poke repeatedly	1	2
	Sad (0.14)	Gentle push	1	3
		Slow Stroke	1	2
	Surprised (0.17)	Strong push back & forth	2+	3
		Disperse	2+	3
	Happy (0.15)	Move/jump back & forth	2+	3
		Touch & draw smiley face	1	2
		Dancing	2+	2

Table 1: Set of referents for social touch elicitation study and their corresponding interactions (# indicates the frequency of each interaction)

Agreement. For each referent, we calculated the agreement score [71] as in Table. 1. It's interesting to note that having higher self-reported clarity rating doesn't necessarily translate to higher agreement score (Spearman's correlation p-value = 0.29). For instance, referents such as sad, afraid, and get attention of someone have high clarity ratings (>5) but have agreement scores on the lower half (<.15). On the other hand, the referent with lowest clarity rating (comforting) had one of the highest agreement score.

In addition, Welch's t-test revealed that the self-reported clarity ratings of interactions that are members of larger groups of identical gestures (#>=3) are not significantly different (p = 0.37) from those that are not. In fact, the average rating of the former interactions was lower. This is different from what Wobbrock et al. [71] found for surface computing gestures possibly due to the fact that we are investigating interactions for affective communication, which can be very context dependent [41] rather than to achieve a specific task.

Visual Complement. One interesting trend is that many interactions relied on visual components with varying degrees.

For instance, participants partially relied on the paths or motions of the robots to convey more context especially for abstract referents such as afraid (touch & rendezvous) and surprised (disperse). Others relied mostly on the visual aspects by drawing heart ("I like you") or dancing (Happy). As swarm robots inherently provide both visual and haptic cues, more studies should be done to investigate the trade offs between them and which is better for different applications.

Contact Location. Another unexpected feature was the use of contact locations. For some interactions, participants used contact location to provide more context. For instance, to convey "Hello", two participants made a robot bump toward their fist to create a "fist bump". For the "afraid" referent, one participant had a robot "hide" under the arm while another had a robot nudge between the thumb and index finger.

Metaphors. From the post-study interview and qualitative feedback after each referent, we have gathered multiple metaphors that the participants used for the robots. They mentioned that depending on the referent, they pictured the robots as being either extensions of their hand, minion/pet/living creature that delivers their message, or parts of an emoji. Though we did not measure social appropriateness, these positive metaphors suggest that people were comfortable interacting and using the robots for social touch.

Trends between Ratings of Referents. In Fig. 13, average ratings of perceived anthropomorphism, likability, clarity of the message, and ease of control are shown for each referent. A Welch's t-test reveals that the self-reported clarity for functional referents (i.e. control, ritualistic, and task-related referents) is significantly higher than those for affective ones (i.e. positive affection and emotion referents) (p=.0032). This is consistent with the qualitative feedback from participants as many of them spoke about the difficulty of creating haptic patterns for abstract and emotional referents. Thus, they sometimes had to rely on the visual aspects of the robots' motions to convey the appropriate context.

8 LIMITATIONS & FUTURE WORK

There are a number of considerations with regards to the generalizability of our study results. First, the studies can only be generalized to systems comparable to our swarm robot platform. With systems of drastically different parameters such as size, form factor, force outputs, and contact material, the current study results may not hold. In the future, it would be interesting to further investigate the effect of different robot sizes and a wider variety of form factors.

In addition, the trends demonstrated with the current study results may not hold with different values of the parameters. The goal of the current study was to investigate effects of different parameters and their combinations. Thus, we only tested 2 or 3 values of each parameter. With values much greater or smaller, the trends may take unexpected turns as shown in the case of Uncanny valley [45]. In the future, we suggest studies with more values of each parameter to better understand their impact on users' perception.

For the elicitation study, many participants had difficulty controlling 3+ robots simultaneously. This is partially due to the multi-touch screen that requires a constant contact for each finger and the nonholonomic nature of the robots. To alleviate this, a 3D gesture could be adopted using hand tracking sensors like Leap Motion. Also, omni-directional robots could help users express a wider range of messages.

A more fundamental limitation for SwarmHaptics is that it is restricted provide haptic stimuli to body parts that are in close proximity to flat surfaces. As the robots can only move in 2-D plane, they cannot provide haptic stimuli to multiple body parts that are arbitrarily separated in the 3-D space.

In addition unlike visual displays, there are visible motions that always accompany the robots when moving from point A to B. This could be both beneficial or undesirable depending on the context. As supported by the elicitation study, it could serve as a multimodal display and provide more context or unintentionally distract users. Thus, designer will need to take this into account and either minimize the undesirable effect by slowing down the robots or take advantage of it to communicate both visually and haptically.

Finally, the example scenarios shown in this paper are limited to one-directional haptic display such as haptic notifications and social touch. In the future, we would like to study the use of swarm robots to provide real-time multipoint haptic feedback for interactive applications as prior work has mainly focused on using robots to provide single point feedback or as grasped puck-like devices [50].

9 CONCLUSION

In this paper, we investigated how a swarm of robots could provide richer information to users in the context of haptic notifications, directional cues, and remote social touch. To do so, we introduced SwarmHaptics, a new type of visual and haptic display consisting of small mobile robots that can approach the users at will to provide different haptic patterns. We described the design space for SwarmHaptics with parameters for both each individual robots and collections of them, and demonstrated its possibilities with example scenarios. We evaluated how people perceive different haptic patterns and how they create visual and haptic patterns for different social touch. We hope that this paper and our study will spur interests and aid researchers in further exploring a haptic display with a swarm of robots.

10 ACKNOWLEDGEMENTS

This work was supported by Samsung Scholarship for L.K., and by Hasso Plattner Design Thinking Research Program.

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