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Bridging the Ambient Environment and HRI: Using Site-Specific Robots to Create Context-Conscious Interaction

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Abstract — We propose a concept of context-conscious interaction—an intermediate level knowledge in bridging the ambient environment and Human-Robot Interaction (HRI) as an extension of context awareness in ubiquitous computing and embodied interaction. Incorporating the ambient environment in the HRI design process, we argue, can augment the impacts of HRI and expand the research field. We explore this promise by focusing on a case study, a multi-agent robotic system we call Self Organizing Robot Team (SORT), created to provide assistance in independent living environments to various users. We here describe the design and fabrication process of SORT as an HRI design exemplary and present results as early validation of the system's capacity. As HRI research continues, and is more frequently examined in the context of the home, we believe it is imperative for the research community to understand the HRI design process as a function of its context instead of independent from it.

Keywords —Human robot interaction, Ambient environment, Architectural robotics, Assistive technology, Multi-agent system

1. INTRODUCTION

The concept of context has been an integral part of the field of HCI and HRI. Various theories had been proposed to frame context within the realm of interaction, such as Gibson's environmental "Affordance" in 1966 [23], Weiser's "Ubiquitous Computing" in 1991 [25], Schilit's "Context-Awareness" in 1994 [27], Ishii's "Tangible Bits" in 1998 [26], and Dourish's "Embodied Interaction" in 2001 [24], who has initially linked the concept to Heidegger's 1927 comparison of "present-at-hand" and "ready-to-hand" to lay the foundation of phenomenology in context-awareness [24]. While these theories have pushed interaction beyond the human scale to consider identity and location, we believe that architectural design and corresponding theories and methods pertaining to the spatial dimensions of interaction extend the discussion.

The design of the ambient environment has historically been the charge of architecture, which is a product of an iterative design process—a "middle ground"—between artistic creation (theory) and engineered code compliance (instance). We see this middle ground to be congruent with the "intermediate level knowledge" (or "Strong concepts") proposed by Höök and Löwgren [1], which is not only characteristic of architecture but, arguably, of other much younger design fields, particularly HRI. An example of this intermediate level connection, within the academic discourse of architecture, would be when designers refer to doors as thresholds. By removing the elements' utilitarian identities through typological abstraction [28], the designers are afforded new opportunities to gauge alternative or derivative options—to expand the designer's "repertoire of partial solutions" [1]. This process echoes the "present-at-hand" (theory) and "ready-to-hand" (use of theory) relationship where oscillating between the abstract and the concrete, meaning can arise out of action.

As a confounding variable, the ambient environment may play a role in altering interaction outcomes. All human activities (including those that might be characterized by HRI) inevitably occur within some forms of context. Therefore, the study of HRI should also be contextualized to reflect and accommodate the different scales of interactivities within specific architectural spaces or against specific building elements. We call this *context-conscious interaction*, which should be an integral part of the design process (Figure 1), augmenting the impact of interaction and expanding the field of HRI by exploring and integrating architectural design and corresponding theories to create site-specific robots. The purpose is to extend the current framework in ubiquitous computing and embodied interaction and explore the role of context in HCI and HRI, such that context-conscious takes a step further from context-aware in leveraging the ambient environment and architectural features to proactively cue, anticipate and guide users' needs and responses.

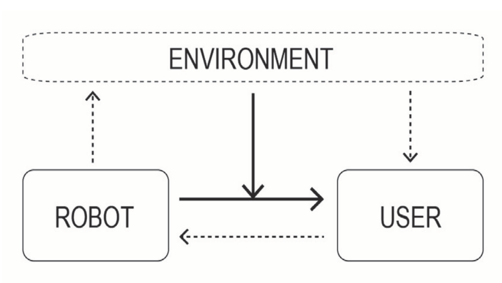

Figure 1. A concept model showing the environment as an additional element in the HRI process. Solid arrows represent direct impact, dashed arrows represent passive impact.

To demonstrate our phenomenological approach to embodiment—context-conscious interaction—we offer our designerly HRI process of developing a multi-agent system we call "Self Organizing Robot Team" (SORT) supporting independent living at home and work. In so doing, we offer three scenarios corresponding to the context-conscious agenda by considering healthcare architecture principles in supportive design set by Ulrich [2] [3]. The scenarios include: (1) provide stress reduction through positive distraction, (2) provide social support via novel human-swarm interactions [4] [5] [6], and (3) help the user become more organized to instill a sense of control. In addition, each scenario will be tailored to specific populations: 1) elderly people with mild cognitive impairment, 2) high functioning young adults with Autism Spectrum Disorder, and 3) individuals living at home with debilitating illnesses like COVID-19.

2. RELATED WORK

With the rise of assistive technology where context plays an important role, it has been identified that there exists a gap in health care at home that could be filled by robotic assistance or telemedicine [11]. Standalone robotic furnishings, surfaces, and devices have been created that "cohabitate" with humans [7], [8]. Interactive spaces are also used to support occupational therapy [9] and to assist rehabilitation by incorporating video games [10]. Domestic assistance robots have been designed which interact with users non-intrusively, reacting only when interpreting the user's intention to initiate an interaction [12]. It has been shown that robotic controls developed to anticipate a user's needs significantly streamline HRI and help the user complete tasks faster [13]. This presents an opportunity for developing an anticipatory robotic system to promote health and wellbeing in the domestic environment.

Work in domestic robots which provide assistive care to specific groups such as children on the Autism Spectrum has seen increased interest in the HRI field [14], [15]. Moreover, it has been indicated that movement or gesturing can provide a means of socialization between a human user and a non-anthropomorphic robot, and that tuning of these gestures can successfully allow for human-robot communication [16]. In practice, the non-anthropomorphic robot Vyo has been used to successfully facilitate communication between a user and a smart home system as well as provide socialization [17]. However, it has not been determined how a user may socialize with a multi-agent swarm of such robots.

It is clear that such interaction would vary in character based on the specific individuals involved. Studies on women living alone have shown that there is a desire for companionship that could be filled by a socially aware robot, but that it must be intelligent, problem solving, and have a distinctive personality [18]. Domestic robots supporting elderly users have been shown to require the development of a social relationship in order to be effective at providing assistive care [19], [20]. In children or young adults on the Autism Spectrum robots have been shown to provoke development of social skills. However, these are often static robots that do not move autonomously and that are designed to be introduced into the user's home only for a short, pre-determined period of time [21].

3. METHODS

To conceptualize the SORT robot, a morphological chart was created (Figure 2) documenting possible candidates for each of SORT agent's components and functionalities. The chart's categories include wall connection types, base geometries, receptacle shapes, body-receptacle connections, interfaces, feedback types, and casing and swarm arrangements. Informed by this chart, our current prototype (Figure 3) was fabricated consisting of two circular units of 5-inch diameter coupled rigidly with a rotating arm. The robot achieves wall adhesion through negative pressure via vacuum pumps. Each unit contains four suction cups joined together with plastic tubing and custom 3D printed connectors, one high-torque servo, one vacuum pump, one check valve, and one release valve.

To move on the wall, the two circular units take turns to swing each other around through an alternating sequence of engaging and releasing their suction cups, until one of the units arrives at a destination.

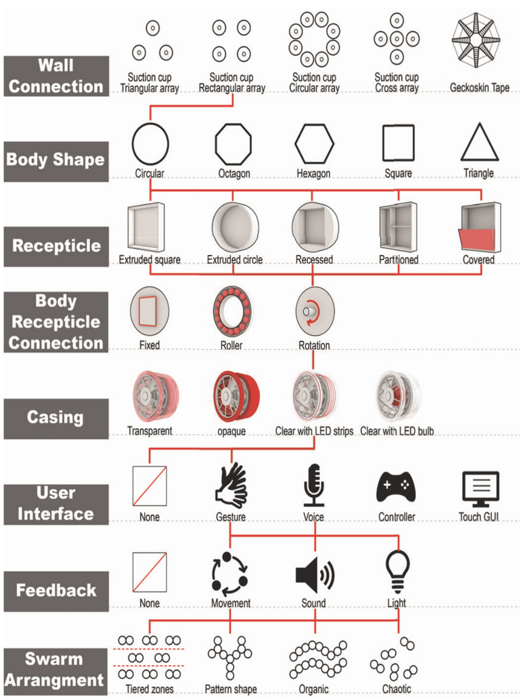

Figure 2. Morphological chart showing the variations of key design elements. The logic flow indicates those that have been selected for the prototype.

Currently, a tethered controller is used for the above process with two switches for the vacuum pumps, two buttons for release valves, and two knobs for the servos. Swarm behaviors are, for now, simulated in the design software Rhinoceros with Grasshopper. In order to alter the ambient environment, the system can translate a pixel-based image into a vector geometry by finding the medial axes through Voronoi divisions which are then broken into five-inch long line fragments. By extracting and using the lines' control points as attractors, the agents swing themselves sequentially toward the destinations and eventually recreate the input image on the wall. This can organize users' belongings by providing identifiers or reduce stress with a pleasant ambient distraction. Also, each robot has a receptacle to hold items such as medications, glasses, wallet or keys. The system can sort items by fetch-and-carry when needed and provide ambient cues through movement, lighting, and audio output.

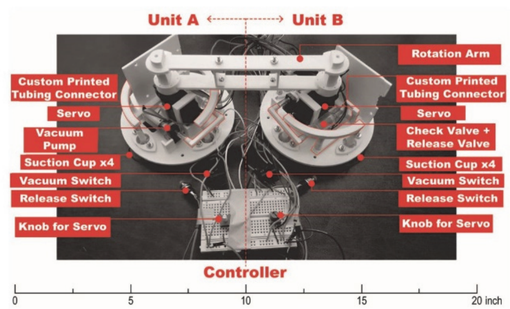

Figure 3. Physical prototype showing one robot agent, which is composed of two circular units, each at 5-inch diameter and 4-inch depth, linked together with a rotation arm.

4. RESULTS

An experiment on motion control with the physical prototype served as our proof of concept. The locomotion test was performed on a whiteboard wall. In 3 minutes, 30 seconds, the agent moved 40 inches horizontally (Figure 4) by manual control – the distance from an armchair to a table in a studio apartment. A few limitations emerged during the experiment, which can be addressed in the next design iteration. For example, the suction cups worked only on smooth wall surfaces, the peak carrying capacities of the servos have not been tested, and the receptacles as designed may cause content spillage.

The simulation and illustration demonstrate two main design goals where the SORT system (1) recreated an image of a tree (Figure 5) as a means for stress reduction through pleasant, ambient distraction; and (2) demonstrated medication management for an aging patient with COVID-19 by fetching the correct treatments at designated times and providing reminders on an integrated LCD screen (Figure 6).

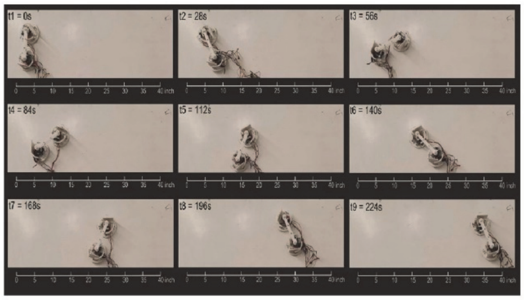

Figure 4. Images from recorded video showing the movement of one agent. (Full video has been uploaded to an anonymous account: https://www.youtube.com/watch?v=gb4llrErnP0)

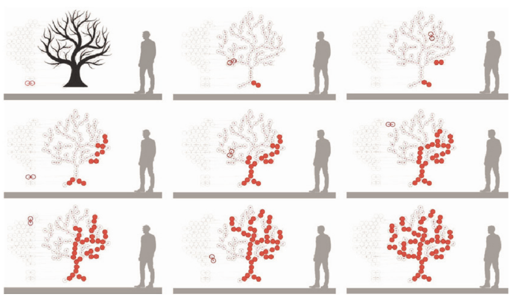

Figure 5. Stepped images from sample simulation showing agents creating a graph on the wall. (Full animation has been uploaded to an anonymous account: https://www.youtube.com/watch?v=4iustu3USTw)

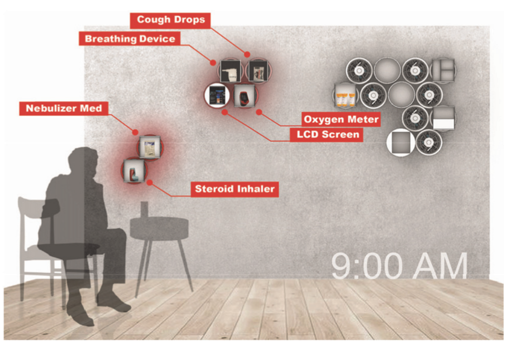

Figure 6. Rendering showing one scenario of medication management for a patient recovering from COVID-19. In the morning, SORT brings the user a steroid inhaler with Nebulizer medication. The agents move closer to the person while emitting a stronger red glow by wall reflection to attract attention. Other devices to be used in the day are lined up in agents on the wall. (Full animation has been uploaded to an anonymous account: https://www.youtube.com/watch?v=X1eZLluq-kA)

The robots interact with users through changes in lighting, sounds, and movements within a specific site such as the living room wall. We envision SORT distinguishing itself from other context-aware interaction design approaches by incorporating emergent behavior and self organization of a swarm [21], by providing practical assistance and utility functions, by activating under-utilized architectural elements such as the wall, and by using the ambient environment to augment its interaction effects such as light diffusion.

5. DISCUSSION

As an on-going project, SORT represents the concept of context-conscious interaction as an intermediate level knowledge and contributes to the field of HRI in the following ways.

SORT can be approached from two levels: one at an agent scale where each robot is designed to deliver or retrieve an item, the other at an environmental scale where the robots interact with users in passive ways. The concept of context-conscious interaction provides a generative design basis at both levels. For example, from the designer perspective, each robot agent must be situated into the environment, resulting in variations of wall adhesion designs shown in the morphological chart. From a user perspective, the emergent behavior of the swarm can form a tree as demonstrated, which may come from a user specified image. It can also create a slow-moving wave mimicking the ocean to reduce stress, or a gentle sunrise to wake the user in the morning. These semi-abstract yet site-specific behaviors compose the "repertoire of partial solutions" [1].

SORT interactivity provides two modes: a "present-at-hand" state where each robot agent (design element) retreats back into the ambient environment and becomes part of the performative swarm formation (artifact) when no commands are issued or functions scheduled, and a "ready-to-hand" mode to engage the user for sorting tasks. Switching between these two modes allows SORT to continuously influence users' behaviors over time. It is both the initiator and receiver of interactions at a room scale. We believe this design approach, where both active (task driven) and passive (environment driven) interactions are built into the same robot system, can benefit HRI by expediting the familiarization process between users and robots.

SORT aims to help re-organize user belongings from horizontal surfaces (tables) onto vertical surfaces (walls), which traditionally have been an underutilized architectural element. Site specificities are also considered during the design process so the robot not only fits but also uses the environment to its advantage. For example, sorting tasks in a bedroom would be different from those in a living room. We believe the continuous exploration of architectural spaces where robots are situated and tailoring interaction tasks to site-specific user needs can benefit HRI by allowing the design to expand its application domains.

6. CONCLUSION

In this paper, we presented a concept of context-conscious interaction as an extension in the realm of ubiquitous computing and embodied interaction by showing a preliminary design example of SORT, which is a system of wall climbing robots that provide assistance by working with or changing the ambient environment. Experiments with physical and simulated prototypes provided early validation of our stated design goals.

We predict significant advances in the field of smart robotic devices for assisted and independent living. Such devices must be site-specific and designed to adapt to user groups of wide-ranging capacities to ensure beneficial human-robot interactions. We believe that architectural design and corresponding theories and methods pertaining to the spatial dimensions of interaction will advance the promise of Designerly HRI.

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