In Press as of October 4, 2021. To be published as a chapter in the book series, Adaptive Environments (Springer).

Self-Organizing Robot Team (SORT): A Multi-Robot, Wall Climbing Organizer-and-Delivery System for Living Spaces

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Abstract Maintaining an organized lifestyle, especially during the COVID-19 pandemic lockdown, is an important domestic routine that reduces the effects of poor mental and physical health associated with clutter. We propose a multi-agent system of wall climbing robots, the "Self-Organizing Robot Team" (SORT), supporting independent living by 1) helping people organize domestic belongings on walls rather than strewn across tables or desks, and 2) storing items and delivering them to users as needed or wanted. Here we report on the design and fabrication of a working prototype, the results of early lab experiments, a household belongings inventory, and two online user studies with a storyboard illustrating how SORT's group behaviors can work with the ambient environment for various interactions. The results provided early validation of our concept and insights for future wall-based interaction designs. As interactive systems support and augment domestic routines, SORT offers a design exemplar of a multi-robot system that improves life quality by leveraging and enhancing the home environments.

1.1 Introduction

As we spend more time indoors (Klepeis et al. 2001), especially during the COVID-19 pandemic lockdown, maintaining an organized lifestyle by actively sorting and organizing personal belongings becomes an important daily activity. Traditionally, we rely on horizontal surfaces such as tables, desks, cabinets and shelves for storage and display. When poorly managed, domestic items can be difficult to find, causing unnecessary cluttering. This paper introduces a multi-agent system, the "Self-Organizing Robot Team" (SORT), supporting independent living at home (Fig. 1.1).

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Fig. 1.1 Photo collage illustrating a SORT prototype delivering a medication bottle to user at scheduled time with prompt reminder**.**

A messy environment is associated with poor physical and mental health, including a reduction in working memory (Gaspar et al. 2016), an increase in stress (Saxbe and Repetti 2009), and difficulty in object identification (Whitney and Levi 2011). When living in a disorderly space, our diminished attachment to and perception of our homes can lead to a lowered level of subjective well-being (Roster et al. 2016). A cluttered home may also reduce a person's ability to recognize others' facial expressions (Cutting and Armstrong 2016), and significantly impact relationships by inducing negative emotions (Shaw 2015). Moreover, there is evidence that clutter and its associated, perceived sense of being out-of-control can lead to overconsumption of food (Vartanian et al. 2016) and obesity (Raines et al. 2015). For older adults, especially, clutter may lead to a reduction in sleep quality (Davidson et al. 2019), further inhibiting mobility and potentially causing falls (Sattin et al. 2015). Clearly, an organized home environment is critical to maintaining a healthy lifestyle.

To aid in organization, SORT is designed to serve a broad range of users, such as older adults with mild cognitive or mobility impairment, college students living in confined dorm rooms for extended periods of time and ambulatory patients recovering from illness (such as COVID-19) who need medication management. The inclusion of the latter group was motived by the direct experience of an author of this paper who was recovering from COVID-19 at home, managing with much frustration, and at different hours of the day, combinations of medications, inhalers and lung exercise devices that were kept on a side table (Fig. 1.2).

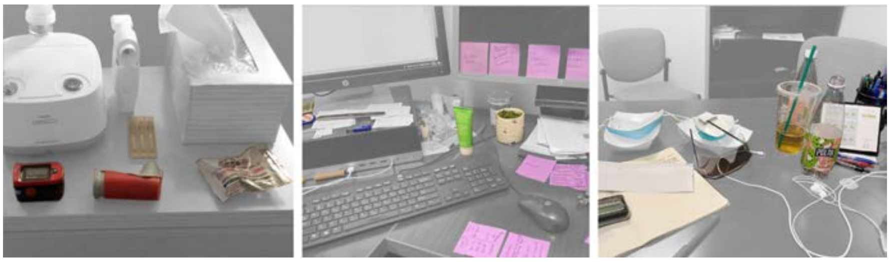

Fig. 1.2 Photographs taken by the authors: (left) an author's side table with COVID-19 treatment items; (right) authors' personal desks. Highlighted objects are candidates for sorting.

In this paper, we report on the design and fabrication of various prototypes of SORT, an early lab locomotion experiment, along with an object inventory study, two interviews with older adults and college students, and a summary storyboard illustrating the potential robot group behaviors. SORT aims to help users declutter their domestic environments by arranging personal items on wall surfaces and delivering them at pre-scheduled times or when desired. When not actively delivering items to users, the system organizes itself in visually pleasing arrays, these group level behaviors may serve as novel modes of interaction and communication by activating and working with the ambient environment. We expect SORT to help users control their physical surroundings, increasing perceptions of self-control over their lives which, as already noted, are directly correlated with better quality of life (Wirtz et al. 2015, Mallers et al. 2013).

1.2 Related Works

Robots supporting healthcare and wellbeing are an important focus in the assistive technology and interaction design community. A variety of home-based robots have been introduced to support elderly users (Daniel et al. 2009, Boumpa et al. 2017). Standalone robotic furnishings, surfaces, and other robotic devices are also developed to provide a range of assistive care to users (Verma et al. 2018). However, there remains a gap in care that could be filled by robotic assistance at home, that is easy to use, practical (e.g., requiring no modifications to the home), and affordable (Dahl and Boulos 2013) as SORT aims to be. Previous Human Robot Interaction (HRI) studies suggest that a non-anthropomorphic robot (like SORT) is a viable approach to assistive care (Kuchenbrandt et al. 2014) even when social robots have been shown by some researchers (Boladeras et al. 2013, Lehmann et al. 2013) to be effective. As a means for communication, gesture can help forming social connections between a user and a non-anthropomorphic robot (Saez-Pons et al. 2014). For example, Vyo has been used successfully to facilitate communication with a smart home system and to help form a social, human-machine connection (Luria et al. 2016). Initial lab investigations have shown that small swarms of non-anthropomorphic robots can also communicate abstract information to a user (Kim and Follmer 2017). However, it is unclear how this type of interaction may occur and contribute to a user's wellbeing, and how such interventions may fit into a person's home environment.

There are a few previous efforts in HRI more closely related to SORT in purpose. One of these studies provided valuable insights in social dynamics between users and delivery robots integrated in healthcare settings (Mutlu and Forlizzi 2008). Another robot organizer system was created for homes but required the installation of tracks above the ceiling—a physically disruptive and costly implementation (Fukui et al. 2008). Also, this system was designed for able-bodied users and it lacked a reminder function for delivering important items at scheduled times such as medication. Other related research includes studies focusing on robots tasked with tidying up spaces (Abdo et al. 2015, Zeng et al. 2018) that specifically investigate, respectively, user preferences for sorting items and the image recognition of objects. In these cases, the robot itself tends to rely on conventional designs such as robotic arms and hence the system as whole is immobile. These are the gaps SORT aims to fill. In addition, in order to effectively help older adults organizing their belongings at home, an ideal robotic assistant would need to be tuned to users' organizational styles (Mohammadi 2008, Pantofaru et al. 2012). Simple algorithms carried out by an autonomous robot (Cha et al. 2015) suggest a way to match a user's expectation of how objects should be organized by a robot like SORT.

Various wall-climbing robots have also informed the development of SORT, including bio-inspired (Garcıa-Cardenas et al. 2019) and industrial-purposed robots (Eto and Asada 2020). Significant developments have also occurred in suction cup-based wall-climbing robots including passive suction cup climbers (Yoshida and Ma 2010, Ge et al. 2016) and suction cups using vacuum pressure (Papadakis et al. 2020, Qian et al. 2006). However, these robot designs are tethered and tend to rely on a steady supply of power and pneumatic vacuum air. Moreover, none of these previous examples are meant to operate in a multi-robot group for domestic use; and no suction-based wall-climbing robots have been applied to assisting users in organizing the home environment. Another major concern with wall-climbing robots is noise. SORT will be designed to operate quietly with non-continuous usage of vacuum motors. While multi-agent systems of organizing robots have been deployed across enormous industrial floors, such as the Xanthus and Pegasus system at Amazon Warehouses (Ackerman 2019), no such system has been adapted at a smaller scale to domestic environments.

SORT is also inspired by studies on ways in which the built environment improves users' quality of life. For instance, numerous studies have shown that exposure to art and nature have positive therapeutic effects on people's mental and physical health, such as reduction of stress (Laursen et al. 2014), and shortened post-operative hospitalization (Ulrich 1984). While music, paintings and views to outdoor green spaces have been made a part of healthcare facilities, there has emerged a range of embedded and embodied interactions that offer multi-sensory experiences allied with assistive and social robots in HRI domains. Two such cases are ScreenPlay, a contactless interactive media display installed in a hospital waiting room to provide engaging experiences among patients, family and staff (Biddiss 2013), and LUMES, a light-emitting wood wall at Cabrini Hospital in Australia designed to improve mood (LUMES 2016). The logic behind using interactive environment to promote wellness is rooted in supportive design principles of interior architecture, which include providing positive distraction, fostering social support and granting users more control over the environment (Ulrich 1991, Ulrich 2001). The SORT system, an assemblage of light and sound emitting robots, has the potential to offer some benefits of these multi-sensory interventions at home through robot group behaviors to achieve the supportive design agenda.

1.3 Inventory study

To better understand what objects can be organized by SORT, we conducted an inventory study of various domestic items, which were gathered and weighed on a tabletop scale. They were then built as 3D models where a bounding box was fitted on each to record the dimension. The longest side was noted as the critical dimension that needed to be satisfied when designing container receptables. For items that the authors did not have at hand, specification information was obtained from similar products found on Amazon. The inventory list is summarized in Table 1.1, and the corresponding objects' weight to critical dimension relationships are shown in Fig 1.3. Based on items assembled so far, the critical length needed to be satisfied by the robot and container ranged from 5.2cm to 20.5cm. While the final design may not accommodate the entire list, it will be designed for the majority of the objects identified.

Table 1.1 Inventory list of potential household objects for sorting.

	Item	Weight (g)	Bounding dimension (cm)
1	Eye glass	30	13.8 x 4.4 x 3.7
2	Cell phone	150	16.8 x 9 x 1.2
3	Wallet	75*	12 x 10.6 x 2
4	Keys	90*	19.8 x 5 x 2.6
5	Remote	110	20 x 6 x 2.5
6	Inhaler	50	8.5 x 6 x 3
7	Nebulizer med.	5*	10 x 9 x 5
8	Cough drop	85*	12.5 x 10 x 3.5
9	Ibuprofen	30*	7.5 x 4 x 4
10	Thermometer	25	10 x 1.5 x 0.5
11	O2 monitor	60	6 x 4 x 4
12	Pen / pencil	8(x6)*	10 x 4 x 1.2
13	Digital screen	73	10 x 6 x 0.5
14	Med. bottle	20	10 x 5 x 5

15	Med. organizer	70	20.5 x 3.4 x 2.2
16	Picture frame	113*	15 x 10 x 10
17	Alert device	56	8.1 x 5.5 x 5.5
18	Sticker note	60*	9.4 x 9.4 x 8.4
19	Paper clip	34*	5.2 x 5.2 x 3.2
20	Deodorant	130*	14.6 x 5.4 x 5.4
21	Nail clipper	45	7 x 4 x 1.6
22	Breathing device	100	9.5 x 5 x 3.6

* Items have greater weight variability
Note: list to be expanded based on feedback from user studies

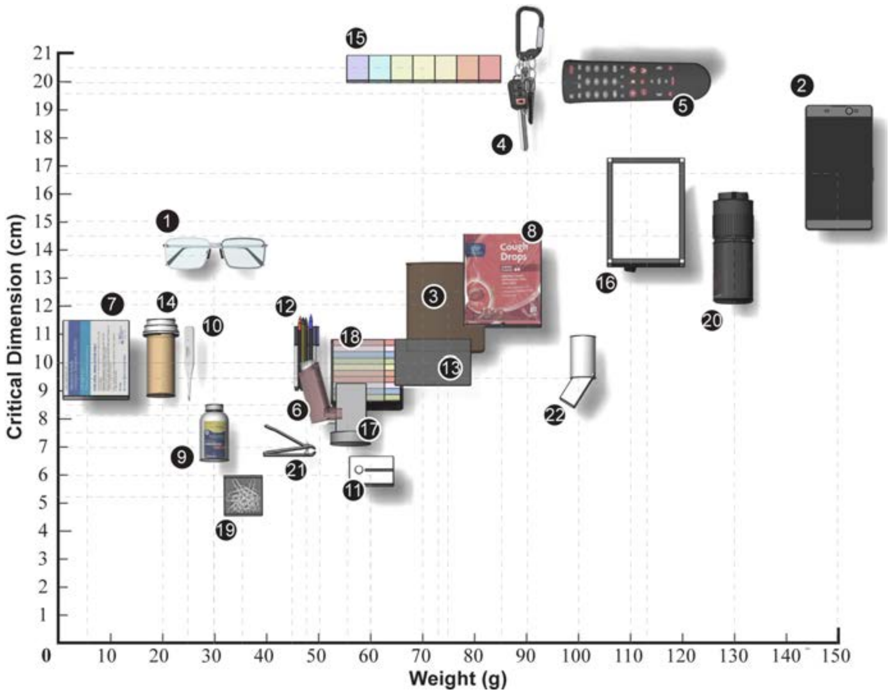

Fig. 1.3 Plotting of the inventory study, showing relationship between object weight and critical length. Object identification number corresponds to list in Table 1.1.

1.4 Robot Design and Fabrication

To conceptualize the SORT robot, a morphological chart was first created to document potential candidates for each of the robot's components (Fig. 1.4). Because the robots are expected to move on walls while holding various items, a circular body shape was selected to minimize accidental corner collision and maximize the container volume. As mentioned, current wall-climbing robots that focus on heavy industrial use tend to require high levels of steady supply in power and vacuum air. Since the household items SORT aims to organize have lighter weights, a different design was created with simpler hardware by linking two cylindrical units together with a fulcrum arm. Locomotion can then be achieved by having the two units swing around each other in a path pattern similar to that described in a self-contained wall-climbing robot (Yano et al. 1998). For SORT, the suction cup option was selected for its availability and low cost.

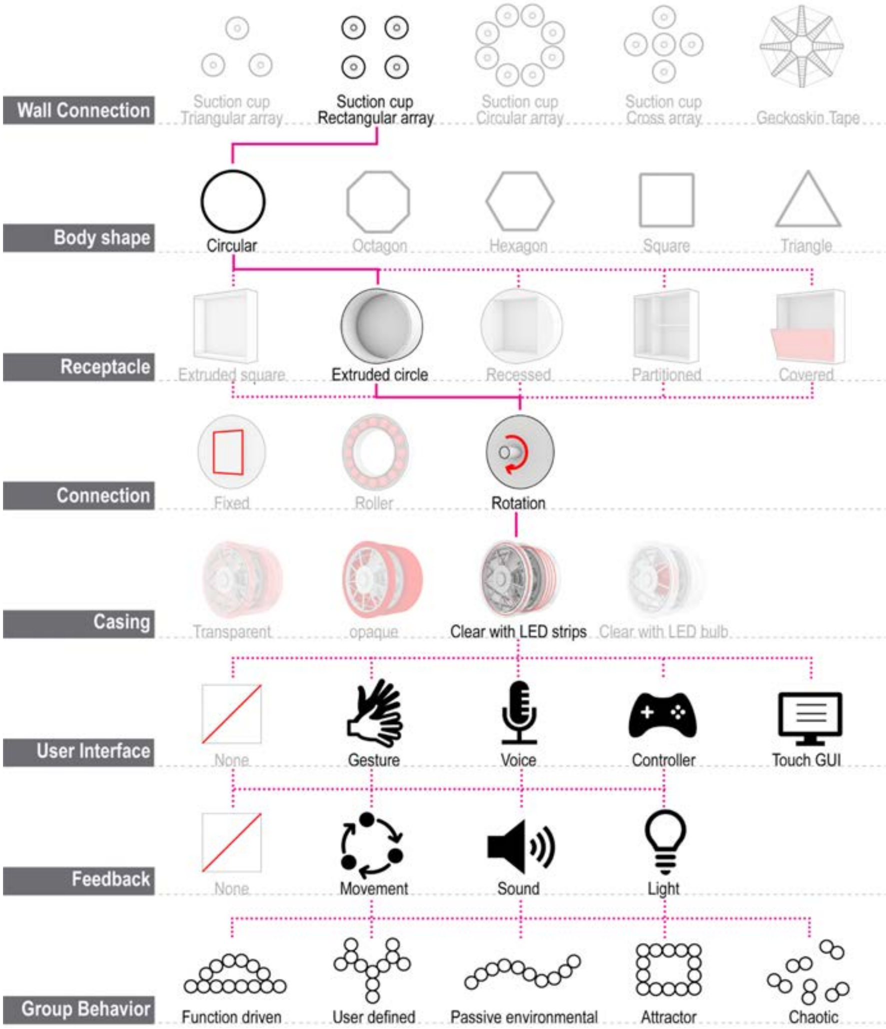

Fig. 1.4 Morphological chart documenting component variations for designing the SORT robots. Solid magenta lines indicate options included for prototyping. Dotted magenta lines indicate potential alternatives to be explored.

1.4.1 Prototype-1

Utilizing the morphological chart, a series of prototypes were developed. The first prototype was built to test the suction cups with tubes. Running a 3.3V micro vacuum pump for only one second with a check valve to prevent backflow was enough to have the prototype successfully adhere to a glass window and a smooth white board wall. The pumps can remain off so the whole system is quiet. A cardboard shell was then added with a receptacle container clipped on via magnets. Engaging the release valve will allow air into the tubing and the prototype can be detached from the wall. These steps are shown in Fig 1.5. There were some limitations, such as leakage, an unstable connection bridge, and a bulky shell chamber. A servo was installed but did not successfully create locomotion and the suction cups work only on smooth surfaces.

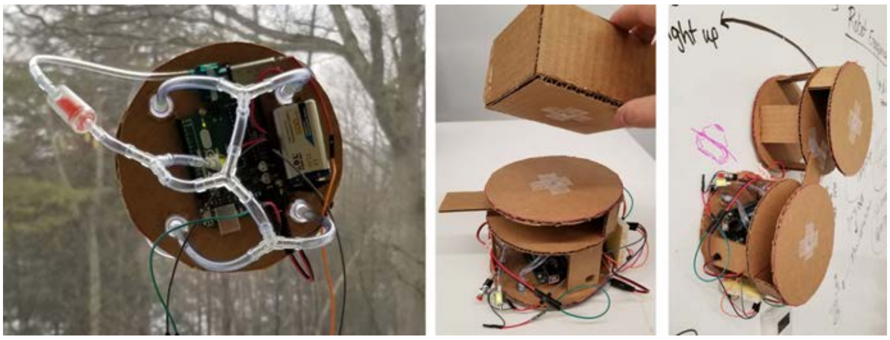

Fig 1.5 Left: the first prototype's base adhered to a window with 4 suction cups controlled by a micro vacuum pump connected to a check valve and release valve. Center: one robot unit with detachable container via magnets. Right: prototype adhered to a whiteboard wall.

1.4.2 Prototype-2

Improvements were made for the second prototype. integrated channels were created in lieu of plastic tubing to connect the vacuum pump, check valve, and release valve. A new base was 3D-printed to better organize the components inside. The new robot successfully adhered to a white board on the wall via Bluetooth controlled by a cellphone; but due to power and torque issue, the servo provided limited range of motion. As a result, a tethered controller with external power was used for testing (Fig 1.6).

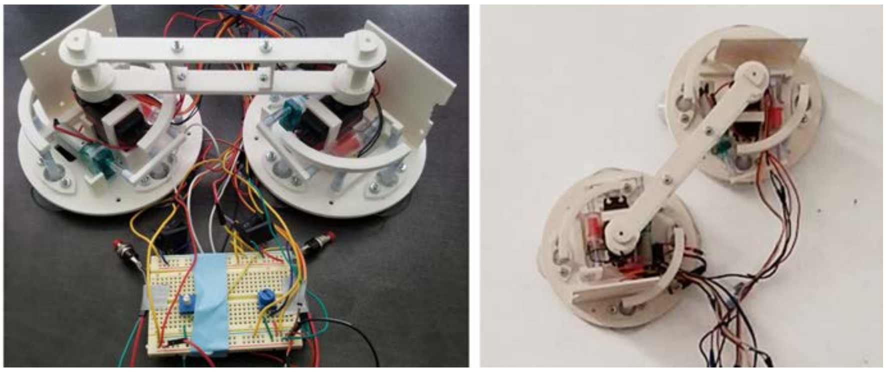

Fig. 1.6 Photos of the second prototype. Left: 3D-printed base with air channels that connect release valves, check valves and vacuum pumps. Right: one SORT robot on a white board.

1.4.3 Robot Locomotion

An experiment on locomotion with the second prototype served as early proof-of-concept. As mentioned earlier, the robot moves on the wall by having one cylindrical unit ("unit-A") swing the other cylindrical unit ("unit-B") around it, following the sequence shown in Fig. 1.7.

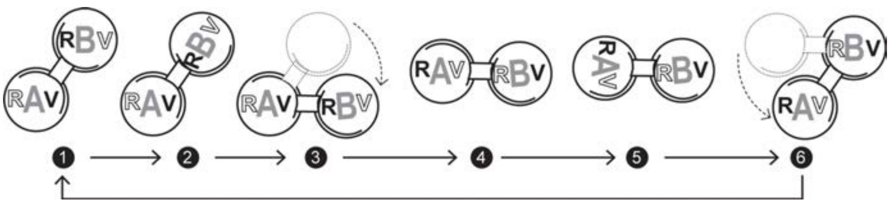

Fig. 1.7 Locomotion sequence: 1) Unit-A's vacuum engages; unit-B's release valve activated. 2) Unit-B self-rotates. 3) Unit-A swings unit-B to position. 4) Unit-B's vacuum engages; unit-A's release valve activated. 5) Unit-A self-rotates. 6) Unit-B swings unit-A to position. Then the sequence repeats. Note: **V** represents vacuum on, 𝕍 represents vacuum off, **R** represents release valve on, ℝ represents release valve off.

A tethered controller was used for the above process with two switches for the vacuum pumps, two buttons for release valves, and two knobs for the servos. The locomotion test was performed manually on a whiteboard wall. In 3 minutes, 30 seconds, the robot moved 40 inches horizontally (Fig. 1.8) – the distance from an armchair to a table in a studio apartment.

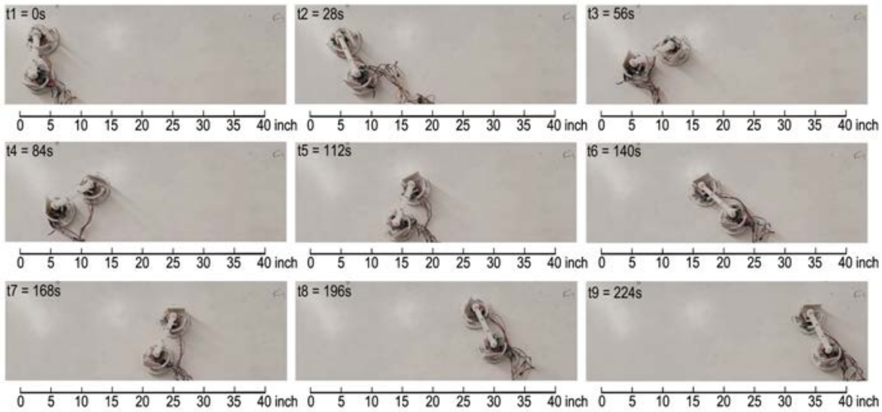

Fig. 1.8 Image captures from recorded video showing the manually controlled movement of the second prototype on a white board wall.

1.4.4 Prototype-3.

The third prototype (Fig. 1.9, 1.10) included a base with integrated channels connecting vacuum pumps with suction cups to further eliminate leaks. An inner-frame structure was created with non-rigid connection bridges accommodating vertical slippage. A ball bearing was inserted at the top center of each cylinder unit's frame, supporting a magnet connector. The receptacle container and display disk can be snapped onto or easily pulled off the base via the magnet connections. In addition, a semi-circular rail was introduced at the base where the bridges can slide along anchor points; this will prevent the rotation from swinging the other cylinder unit out of plane. The vacuum pumps and valves had not been installed and only one prototype was fabricated. This iteration was instead used during the user studies for Wizard of Oz demonstrations.

Fig. 1.9. Left: exploded isometric showing the robot components: 1) Receptacle container, 2) Display, 3) Magnetic connector with ball bearing, 4) Interior frame, 5) Connector bridge, 6) Micro-controller, 7) High torque servo, 8) Check valve + release valve, 9) Micro vacuum pump, 10) Base with integrated channels, 11) Bridge rails, 12) Suction cup anchor, 13) Suction cup. Right: 3D printed parts for constructing the prototype.

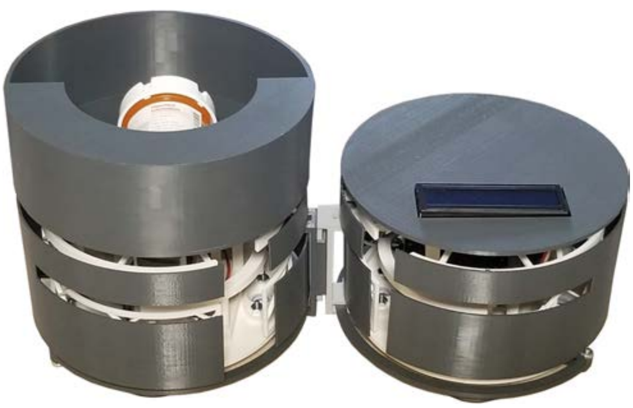

Fig. 1.10 Prototype-3 configured with a container on the left and a display screen on the right.

1.5 User Studies

A previous study (Ferrari and Roster 2018) has shown correlations between procrastination and clutter, where such relationship tends to strengthen as the population age increases. For older adults, clutter may lead to a reduction in sleep quality (Davidson et al. 2019), further inhibiting mobility and potentially causing falls (Sattin et al. 2015). According to research on the impact of visual clutter, both young and older adults were found to be negatively affected by on-screen clutter, with older adults being affected more (McCarley et al. 2012). Another study on young adults and college students found that indecision or decisional procrastination was related to self-reported clutteredness (Ferrari et al. 2018). For our user studies, older adults and college students, whom tend to live in small spaces such as nursing home rooms and college dorms were first identified as potential participants. Due to on-going pandemic lockdown, user studies were conducted online via Zoom.

1.5.1 User study 1 – Older Adults

We conducted the first user study to determine if older adults were receptive to the SORT concept and how they would envision themselves or someone close to them using it at home. Nine individuals who currently use or have used a walker completed our study. The participants (seven females and two males) ranged in age from 51 to 80 years with a mean of 64.8 years (SD = 8.2 years). All participants live in their own home and have access to a computer. eight of the participants had used a web-based video conferencing program or Facetime, and all have cell phones. Ethical approval was obtained through the university review board.

A semi-structured user interview was conducted via Zoom with participants in their own home. The participants were given an overview of the concept while viewing a rendered image of SORT (Fig 1.11). Four questions pertaining to SORT were asked: 1. “What do you think about this idea?”; 2. “How do you think you could potentially use this?”, and 3. “Can you think of friends or loved ones who would benefit from something like this? How? Why?”. Each session lasted a maximum of ten minutes.

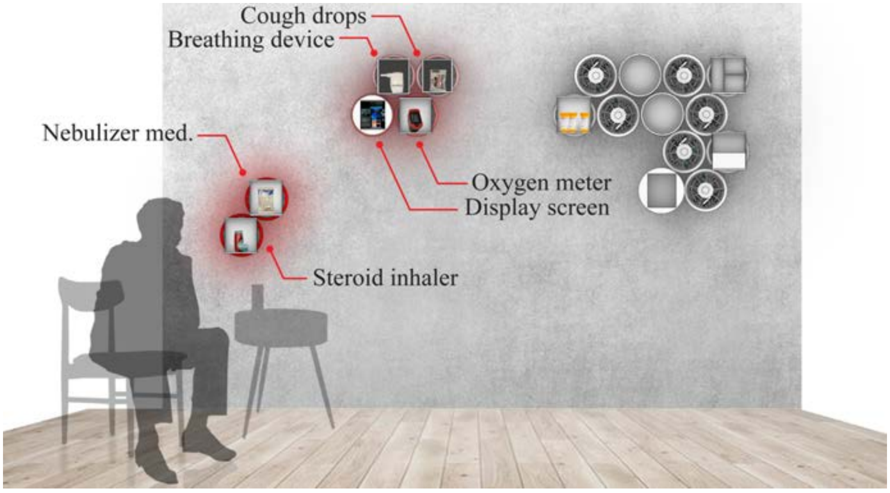

Fig. 1.11 Concept rendering used during the interviews to show SORT managing a user's COVID-19 treatments by delivering an inhaler and nebulizer medicine

For the first question, "What do you think about this idea?", two individuals had unfavorable comments including "I don't see much use for that" and "We don't have any open wall so no way to get from one place to the next, (moving) tables would work better". Seven participants had favorable responses to the concept of SORT, with comments such as "Very helpful", "It's a good idea", "I would give it an 8 out of 10" and "…like the idea for people to remember medications". The feedback also contained suggestions for items to store that the team had not previously considered including sewing needles and decks of playing cards. Participants wanted to know how they would "call" it to them and who would program it. The greatest concern was a lack of open walls due to pictures and artwork or an open floorplan; this was mentioned by three of our nine participants.

For the second question, "How do you think you could potentially use this?", four expressed interest in using SORT for medications, with one individual in specific need for organizing various eye drops after cataract surgery. That individual also suggested having pictures of each medication with reminder alarms when it is time to use them. One participant would use SORT for a variety of important personal belongings, such as holy cards, jewelry and "special things". Novel items to store include lip balm, a mirror, dental floss and ointments. One participant commented on potentially using another robotic arm to retrieve items from SORT.

When asked, "Can you think of friends or loved ones who would benefit from this?", all participants responded favorably. The suggested potential users include: someone who was paraplegic, people with poor eyesight, people with arthritis, parents of small kids, anyone who has confusion using medications or someone who takes medication infrequently, patients recovering from surgery, family members with special personal belongings and specific instances such as "when my mom had MS (Multiple Sclerosis) she would have greatly benefited from this and it would give more independence".

When asked "How?" or "Why" as a follow up question, the responses varied from gaining more independence, feeling more self-reliant, to serving as a reminder for medication or other tasks, to feeling less overwhelmed. One person asked if the user would need one "good hand to use the system". Another who used to work in long term care felt "if people could just do a few things for themselves, it could be super!". Some others commented SORT could be used for daily calendars and care plans, goal setting, and declutter over-the-bed tables.

1.5.2 User Study 2 – College Students

After receiving positive reactions from the first study, a second online user study was conducted with 10 college students (six females and four males) ranging in age from 20 to 27 years with a mean age of 22.9 years (SD=2.1). All participants live in their own rooms either in a house or an apartment. When asked to rate the clutteredness of their personal spaces from 1(tidy) to 5(cluttered), participants' responses were neutral with a mean of 3.05 (SD=0.76). A four-part semi-structured interview was conducted via Zoom. First, participants were shown images and videos of how SORT works (as presented earlier), followed by nine open-ended questions. Then six robot demonstrations were performed to better understand user preferences and reactions. The researchers then walked the participants through eight Likert scale questions. Finally, renderings and animations of robot group behaviors were shown followed by open ended questions. Each interview session lasted one hour. Each participant was compensated with a $15 Amazon gift card. Ethical approval was obtained through university review board.

Open Ended Questions

The first question "What do you think SORT is trying to do?", and the second question "Can you describe to others what SORT does?" aim to understand if participants' perceptions of the robots align with the design intention. All participants were able to describe SORT both in functional goals and physical appearances. Some interesting reactions include, "SORT moves like a toddler or penguin.", "They are very cute.", and "My cat would like watching it move."

For the third question, "Would you have SORT in your home?", seven participants responded positively, three would use SORT but under certain conditions. Some participants feedback include, "My concern is that it is hard to reach (over furniture).", "The sound level would have an impact on whether I would want it.", and "I wonder if there will be some damage to the wall."

For the fourth question, “Do you have an empty wall at home for SORT?”, nine participants responded positively.

For the fifth question, “Where would you put SORT in your home?”, the spaces mentioned include: kitchen (six times), bedroom (five times), laundry room (once), living room (four times), bathroom (four times), workspace (once).

When asked “How many SORTbots would you have?”, the overall preferred robot numbers range from 1 to 20, with maximum tolerance up to 30. The preference ranges were also room specific - bedroom: 1-6, kitchen: 5-15, bathroom: 2-5, living room: 4-15, workspace: 10-20.

For the next question, “What other items would you want SORT to carry or deliver?”, the responses include: toothbrush, cooking utensil, cups, sanitizer, spices, masks, small plants, electronic parts. Larger items, that cannot fit in current prototypes, include books, cloth, shoes, laptop, camera, hairdryer, speaker, bag, yoga mat. There were also some interesting user feedback: “(it) would be great if SORT could function as a library.”, and “(put) valuables if it has a lock.”

When asked “Would you use SORT for some other purposes?”, the responses range from interactive art with different shapes and lights, sending items to others in the room, a mobile video conferencing platform, to toys for pets, using SORT itself as a pet and as a cooking assistant.

For the last question, “Can you think of friends or loved ones who would benefit from SORT? How and why?”, all participants responded favorably. The suggestions include elderly grandparents, people with disabilities, those living in tiny spaces, people who are forgetful. Some interesting comments are: “I want to have a healthier life...have chocolate inside the robot, it will run away from me if I try to take (the chocolate).”, and “If there are things you don’t want children to get into, raising (SORT) almost to the ceiling level...would be a smart use.”

Scenario demonstrations

Six scenarios were demonstrated to understand users’ preferences on robot group location, movement speed, movement path, interaction mode, feedback mode and meanings of communication gestures. To expedite the process, two cardboard robot mock-ups (Fig. 1.12) were created and operated via a Wizard of Oz method.

Fig. 1.12 Robot mock-up models used during the scenario demonstrations**.** Photo print outs on cardboard base representing the actual robots were mounted together on a sheet of plastic to be moved quickly as a group. One set of the robot container and display screen were mounted on cardboard bases controlled by plastic dowels for Wizard of Oz demonstration.

During the first scenario demonstration, three different height options, measured off of the floor level, were shown by the researcher with the cardboard model group on a wall. The options include 100 cm (at around the standing waist level of the researcher who is 180cm tall), 140 cm (at around the chest level) and 180cm (above head level). The participants were asked to select a preferred option where they would locate SORT at home. Seven participants preferred the middle location (140cm). One favored the higher location. Two expressed no preferences but mentioned that the robot location would depend on specific use cases.

For the second scenario demonstration, three different robot movement speeds were shown by the researcher using the container model on plastic dowels to simulate the swinging locomotion. The manually operated speeds, across a distance of approximately 60cm, include a slow option (approximately 6cm/second), a medium option (approximately 10cm/second), and a fast option (approximately 20cm/second). Participants' preferences were varied depending on robot tasks. In general, the fast speed was associated with efficiency and the slow speed was associated with low obtrusiveness. Some interesting feedback include, "I want SORT to mirror my own pace.", "It would be good if you could choose the speed.", and "Fast speed makes me scared...slow speed makes me feel impatient."

Next, two types of robot paths were demonstrated with the container model on plastic dowels moving either in a straight line or a curved path. Five participants preferred the straight path for efficiency, two chose the non-straight one for it being "lively" and "animated."

Then five types of robot interaction modes were explained and demonstrated to the participants, including hand gesture, voice, a remote controller, a touch screen app and no interaction. Five participants favored using voices to communicate with SORT for convenience and familiarity, two preferred gesture for its "friendliness," one preferred touch screen, one wanted no interactions where robots simply carry out tasks as scheduled, and one chose the controller. Each participant could choose more than one option.

Four types of robot feedback modes were also explained and demonstrated, including a swinging motion as gesture feedback, a bird chirping noise as sound feedback, a pulsing LED as light feedback, and a last option of no feedback. Four participants chose movement, four picked the light, three preferred sound, and one chose no feedback where robots would directly proceed to carry out the task without acknowledging user input. Similarly, each participant could choose more than one option.

For the final scenario, six robot gestures (Fig 1.13) were demonstrated with the container robot on plastic dowels. The gestures include a small wave, a quick jitter, a pacing back-and-forth movement, a large wave, a rotation from up to down position, and a rotation from down to up position. Participants were then asked what they thought SORT was communicating. For the first gesture – small wave, six participants associated the movement with attention seeking; two felt it was a greeting; two thought the robot was in trouble. For the second gesture – quick jitter, five participants perceived the gesture as urgent reminder; two said attention; three thought the robot was in trouble (such as being stuck). For the third gesture – pacing back-and-forth, the responses were diverse: the robot was "bored," "antsy," or "pending," in a "holding pattern." For the fourth gesture – large wave, five participants were unsure; three mentioned attention; one said waiting; one thought it was sleeping. For the fifth gesture – moving from up to down, three participants were unsure; four said the robot was powering off; two said task completion; one said charging. For the last gesture – moving from down to up, four participants were unsure; three said the robot was powering on; three said task completion. Based on the responses, it appeared larger robot movements tend to produce more ambiguous gestures that are difficult for users to interpret.

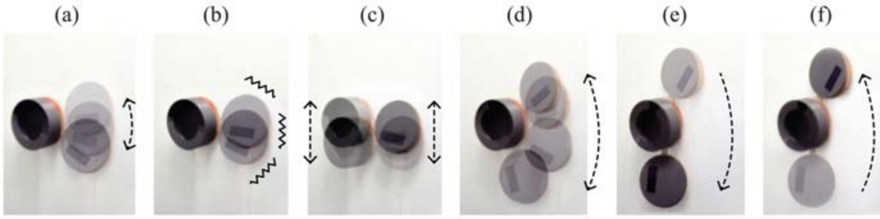

Fig. 1.13 Robot gesture demonstrations. (a) Small wave, (b) Quick jitter, (c) Pacing back-and-forth, (d) Large wave, (e) Moving from up to down, (f) Moving from down to up**.**

Scaled questions

In this section of the interview, the researchers walked the participants through eight questions based on a 5-point Likert scale with 1 being strongly disagree and 5 being strongly agree.

For the first question, "I think I would like to use SORT.", the mean response score was 4.35 (SD=0.67). Participants responded positively toward SORT. Some concerns include container size limitations and a need to have SORT match existing interior design.

For the second question, "I think it is helpful that SORT can move and transport, fetch and deliver things to me.", the mean response was 4.7 (SD=0.48). Participants' responses were very positive. The main concern was that SORT cannot move between rooms.

When asked "I think it is helpful that SORT can remind me of tasks.", the mean response was 4.85 (SD=0.34). Participants' responses were very positive. One asked to pair SORT's reminder with personal cell phone.

For the next question, "I think it is helpful to have more than one SORT robot unit.", the mean score was 3.7 (SD=1.2). Responses were varied. Participants had favorable views toward the different functionalities of SORT as a group. Others who preferred fewer robots wanted to test out the product before acquiring more.

For the fifth question, “I think I will feel very confident using SORT.”, the mean response was 4.1 (SD=0.74). The responses were generally positive with a moderate spread. Some concerns include the robustness of the system, the types of surfaces SORT can work on, the weight of items, pets jumping on the robot and a need to provide clear instructions.

For questions six, seven and eight, three photographs (Fig. 1.14) depicting various item organizations on a desk were shown, the participants were then asked to answer a question: “For the following scenes, how organized do they appear to you? (1-least organized, 5-most organized)”, same household belongings were used in each scene. For question six, the mean was 1.85 (SD=0.7). Some judging criteria mentioned were: inability to identify object quickly, presence of unnecessary items and misalignment. For question seven, the mean was 4.35 (SD=0.6), which was significantly higher than the previous question. Some judging criteria mentioned were: grouping of similar items, more open work space and presence of unnecessary items. For question eight, the mean was 4.8 (SD=0.4), slightly higher than the previous one. Some judging criteria mentioned for the score increase were: smaller items were moved into SORT and out of sight, more work space. Overall, participants did not find the SORT presence obtrusive.

Fig. 1.14 Photographs shown to participants depicting three different scenes of item organizations. Left: photo used for question six, showing a disorganized desk. Center: photo used for question seven, showing an organized desk. Right: photo used for question eight, showing an organized desk with SORT on the wall**.**

Robot group behavior

Aside from its functional goal of fetching and sorting household belongings, SORT also considers various group configurations as important means to improve the effects of interaction and augment the ambient environment. These were achieved by creating interactive experiences through human-swarm interaction (Kolling 2016), where the system can form various geometries, such as a user defined tree shape or imitating a sunrise above horizon, combined with lighting effects to convey meaning (Fig. 1.15). For this section of the interview, participants were asked to rank these images (1-most favorite, 5-least favorite) when using SORT as a decorative element at home.

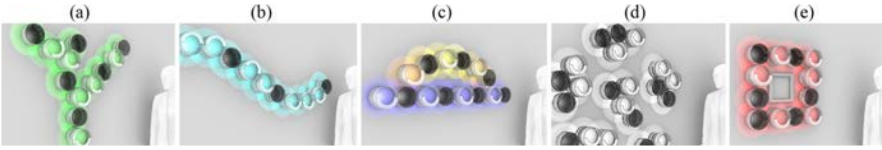

Fig. 1.15 Concept renderings of possible robot group behaviors. (a) tree: a user defined tree shape, (b) wave: an ocean wave, (c) sunrise: imitation of sun rising above horizon, (d) random: robot pairs moving around without a pre-defined pattern, (e) frame: robots surrounding a family photo. These design intentions were not disclosed to participants during interviews.

For the user defined tree shape, the mean score was 2.2 (SD=1.0), it was selected as the most favorite for four times and none chose it as the least favorite. For the wave pattern, the mean score was 2.7 (SD=1.2), it was selected as the most favorite once and least favorite also once. For the sunrise imitation, the mean score was 3.2 (SD=1.3), it ranked as most favorite twice and least favorite once. For the random pattern, the mean score was 3.1 (SD=1.5), it was selected as the most favorite for two times and least favorite for three times. Lastly, the photo frame formation received a mean score of 3.8 (SD=1.4), it was selected only once as the most favorite but five times as the least favorite.

Next, three of the five group behaviors (wave, sunrise and frame) were animated to demonstrate how various lighting effects work and can reinforce the interaction process (Fig. 1.16). After seeing the animations, participants were asked what they thought the robots were trying to communicate (the design intentions were not disclosed).

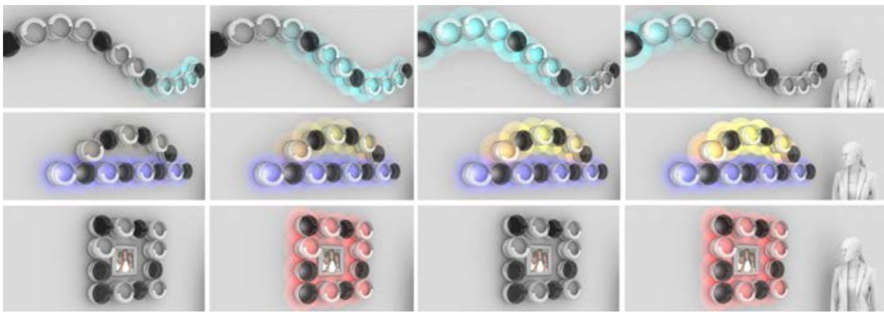

Fig. 1.16 Image capture from animations showing various lighting effects of robot group formations. Top row: light moving in a linear direction to depict wave movement. Center row: lights gradually increase intensity to imitate a sunrise. Bottom row: a blinking light pattern to draw user attention to the framed photo.

For the wave animation, participants' reactions were varied. Five participants felt the behavior made them want to look or move toward the light direction. Three felt "relaxed" or in a "standby" mode. For the sunrise pattern, five participants guessed this group behavior was imitating a sunrise as a way to say “good morning”. One thought it was a weather indicator. One said the robots were charging. For the frame pattern, participants’ reactions were negative. Six participants felt the red color and blinking pattern indicated danger and was not pleasant. Three mentioned phone calls from family.

1.5.3 Storyboard

In developing the interactive scenarios, we created a storyboard (Fig 1.17) informed by the design outcomes and user studies thus far. The persona, John, is a college student living alone in a one-bedroom dorm room. He is recovering from illness such as COVID-19 with non-critical symptoms. Different from the flu, John finds it difficult to manage an assortment of items including various medications, each has a different dosage and use time. In addition, John is trying to stay mentally positive by being productive and is relying on SORT to help him through the recovery. This storyboard served as a recollection moment on the research activities accomplished to date and to capture this reflection in a vision, in pictures and written notations, of what SORT might do for a likely user. This process will aid the authors in designing and structuring future in-person user studies.

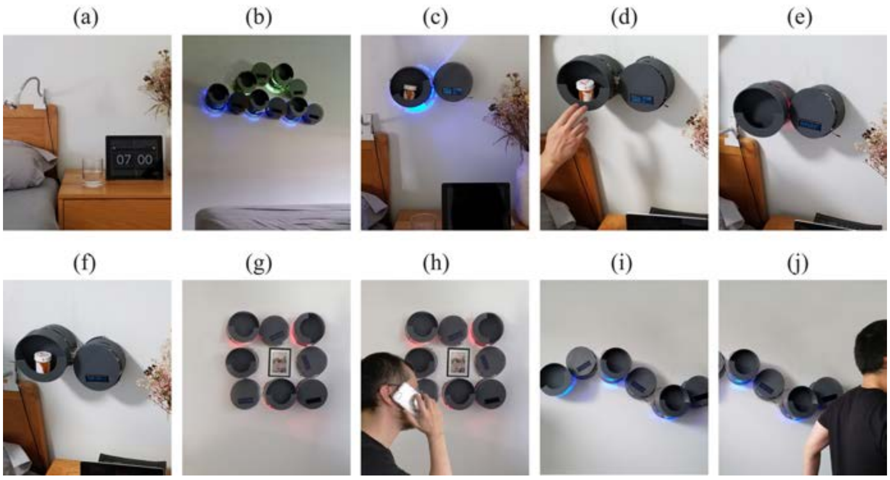

Fig. 1.17 Collaged photos showing the storyboard of how SORT interacts with John and provides assistance through the day. (a) It is 7:00 in the morning. (b) In lieu of conventional alarm, SORT forms and imitates a sunrise coupled with lighting and sound effects to wake up John. (c) One SORT robot that holds the morning medication moves down towards the bed, the screen displays "Pill time, take one." (d) John reaches into the container and takes the medicine. (e) After a while, the robot emits a red color and vibrates, the screen displays "Please return pill bottle." (f) John puts the bottle back into the container, the robot moves back to the upper corner of the wall. (g) Later in the morning, SORT moves to frame around John's family photo. (h) John later notices the robot groups and proceeds to phone home to update family on his conditions. (i) After working for an hour, SORT next to John's desk starts to form a wave pattern with blue lights. (j) John decides to stand up and take a short walk.

1.7 Discussion and Implications

Collectively, the robot design iterations, the locomotion lab experiment, the inventory and configuration summaries, and the potential user interviews have captured our design and evaluation agenda, suggesting the promise of SORT. With roughly an 80% favorable interview response to the concept, it is encouraging to imagine ways in which SORT may improve the life quality for a broad range of users. Participants helped us, as well, identify household items needing organization in addition to what we had envisioned in the inventory study.

Given the intensive focus on assistive technology and smart robots aimed at supporting independent living, there are some interesting findings and lessons learned from SORT. Based on the second user study, participants' willingness to use SORT was unrelated to the self-reported clutteredness of personal spaces. As mentioned during the interviews, robot designs need to fit into user's existing interior architecture style, or the users need to be provided with the option to change robot exteriors, such as color, to fit into personal environments. Compared to older adults, who worried about lack of wall surfaces for the robots, college students were more concerned with the robustness of the system.

One interesting benefit of conducting the online interviews during the pandemic lock-down was the opportunity to let participants answer questions in the room where the robots are meant to be deployed. This, instead of conducting in lab studies, helped participants better imagine and visualize how the robots may work and provide assistance while answering questions such as robots' preferred locations.

As suggested by one participant, in addition to the basic sorting and delivery functions, SORT can also be programmed to help guiding user behaviors. For example, the robot that stores chocolate can "run away" or discourage users from over-eating sweet food.

During the interviews, one concern the researchers had was whether the SORT robots themselves, which declutter the horizontal surfaces, may introduce a new type of clutter on wall surfaces. Based on the results, participants rated item organizations with and without the assistance of SORT almost equally, implying that perceived organization may be less affected by the quantitative presence of objects than on groupings of similar items and placement logic (e.g., long slender objects should be placed pointing in the same direction). Hence, the introduction of organizer robots on walls may not negatively impact users' perceived clutteredness of the space. This finding will need to be further studied.

Furthermore, participants' reactions toward robot group formations were quite varied. For the group behavior where SORT frames around a family photo with blinking red lights, participants reacted negatively. This implies that for multi-robot systems, the group shapes, coupled with lighting effects, may negatively impact participants' mood and perception. Also meaning may be conveyed successfully via robot group behaviors to some participants. For example, without explaining the design intentions, participants were able to identify the tree shape SORT created in the rendering, others viewing the wave pattern mentioned the desire to move toward where the light is pointing, and half of the participants identified the sunrise formation. Lastly, participants in general preferred design options that allow personalization where the robot group can fit better into their existing environment (e.g., container size, robot color, speed, feedback sound and group shape and size).

There are also some limitations. The current robot suction cups work only on smooth wall surfaces and the carrying capacities of the servos have not been tested. There are potential breaking points at the magnetic connectors and the rotating arm bridge. The robot base may also swing out of plane, requiring manual adjustment for adhesion.

1.7 Conclusion and Future Works

In this paper, we introduced a multi-robot, wall-climbing system we call SORT, embedded within the home environment to aid users in organizing personal belongings, an activity associated with improved quality of life. We reported on the ideation process, design iterations of the robots, a lab experiment with a working prototype, an inventory study and results from a preliminary user interview on receptivity. Finally, we shared a storyboard that collected our vision for SORT based on the activities presented here.

As an on-going project, SORT will be improved in many areas. The robots first need to become un-tethered and fully autonomous. A more systematic investigation will be conducted to understand the carrying capacities and potential failures of suction cups. A similar study is also needed for designing the receptacle containers. Insulation materials must be added to further reduce noise from vacuum pumps. We also intend to embed on-board sensors in SORT units and design an associated control algorithm to allow localization and communication between robots and permit the system to orient itself on the wall, assemble in orderly configurations, and locate users. A centralized docking station also needs to be created for recharging batteries. Based on our initial interview feedback, interaction modes need to be further studied to answer questions such as "How should I call SORT for help" and "Should I use gesture or a remote controller to talk to SORT." As a follow up, an in-person study is planned once three robots are fabricated to understand SORT's usability, performance and efficacy.

As demonstrated in this paper, SORT offers inspiration for designing multi-robot systems fulfilling a wellness agenda while leveraging the ambient home environment. For researchers working in the domain of domestic assistive technology, the user study results presented here may provide insights into how people perceive and understand their personal spaces in terms of clutter and item organization. We understand that artifacts like SORT must be designed to adapt to user groups of wide-ranging capabilities to ensure beneficial human-robot interactions. Incorporating principles from fields such as interior architecture and environmental psychology can lead to advancements in interaction design. We encourage future designers and roboticists to consider unconventional domains where robots can live and interactions can occur, such as wall surfaces. Interaction researchers also have a tremendous opportunity to improve users' health and quality of life – a goal that should be in the foreground of the design process.

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