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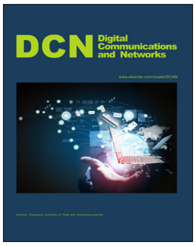

Designing the robot inclusive space challenge

Rajesh Elara Mohan[a], **Ning Tan**[b,*], **Katrine Tjoelsen**[c], **Ricardo Sosa**[d]

[a]*Engineering Product Development Pillar, Singapore University of Technology and Design, Singapore*
[b]*SUTD-MIT International Design Centre, Singapore University of Technology and Design, Singapore*
[c]*MIT Predictics Lab, Massachusetts Institute of Technology, USA*
[d]*Faculty of Design and Creative Technologies, Auckland University of Technology, Auckland, New Zealand*

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Abstract

A novel robotic challenge, namely the robot inclusive spaces (RIS) challenge, is proposed in this paper, which is a cross disciplinary and design focused initiative. It aims to foster the roboticists, architects, and designers towards realizing robot friendly social spaces. Contrary to conventional robotics competitions focusing on designing robots and its component technologies, robot inclusive spaces challenge adopts an interdisciplinary "design for robots" strategy to overcome the traditional research problem in real world deployments of social robots. In order to realize the RIS, various architectural elements must be adapted including: design principles for inclusive spaces, lighting schemes, furniture choices and arrangement, wall and floor surfaces, pathways among others. This paper introduces the format and design principles of RIS challenge, presents a first run of the challenge, and gives the corresponding analysis.

1. Introduction

Despite the great colonization of industrial robots over the last five decades, it is expected that industrial robotics will be soon surpassed by resulting markets from the so-called service robotics in the coming decades. In fact, there are currently more service robots than industrial ones, in a ratio of 5:1 by 2008 [1], but the market value of the latter is a little more than twice that of the first [2]. Service robotics deals with robotic applications in, for instance, rehabilitation and health care, logistics, defense, agriculture and forestry, construction, search and rescue, transport, homecare, and education. In fact, several developed countries have already started national and multi-national plans, such as the National Robotics Initiative (NRI) in the US or the Cognitive Systems and Robotics projects in the EU, for supporting basic and applied research that ensures their leadership in the future robotic industry. The potential of the social and economic relevance of these robots is evident.

Service robotics research is very challenging and complex because such robots must be able to work cooperatively and

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*Corresponding author.

E-mail addresses: rajeshelara@sutd.edu.sg (R.E. Mohan), ning_tan@sutd.edu.sg (N. Tan), ktjolsen@mit.edu (K. Tjoelsen), rsosa@aut.ac.nz (R. Sosa).

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safely with people in changing indoor and/or outdoor environments. This is an inalienable objective that has encouraged roboticists to constantly improve the performance and abilities of robots, especially, since late 1980s. Relevant examples of commercial success stories include, the Paro, a robotic seal developed by AIST, Japan for companionship and therapeutic purposes in a home setting; the iRobot Roomba, the famous autonomous indoor robotic vacuum cleaner; and Kiva, the mobile robot used in the novel automated material handling system by Kiva Systems. There are many other service robotic platforms that are being researched and under development by a variety of research institutes and universities around the world: Willow Garage's PR2, a wheeled robot with two 7-DOF arms and several sensors [3]; the mobile manipulation robot Care-o-bot, a robotic system with a 7-DOF lightweight arm and a 3-Finger gripping hand [4]; REEM-B of PAL Robotics, a 140 cm tall humanoid that can walk up to 1.5 km per hour and transport loads weighting 20%–25% of his own body weight [5]; the world-famous ASIMO by Honda [6]; Cosero developed in University of Bonn, a platform composed of an omnidirectional base, a 2-DOF movable trunk, two 7-DOF anthropomorphic arms, and several sensors [7]; DFKI's AILA, a mobile robot with movable torso and two 7-DOF arms designed for supporting astronauts on the international space station [8]; the mobile humanoid Justin with compliant controlled lightweight arms by DLR [9]; among others. Nevertheless, in spite of these important practical results and the tremendous advances in artificial intelligence, mechanics, sensing, actuation, and control in the past two decades, multi-purpose service robots are still far away of working autonomously in fully dynamic human-related environments. Success of real world deployments of service robots has been generally limited and at times disappointing.

In this paper, we propose an unconventional robotic challenge that fosters roboticists, architects, and designers towards achieving robot inclusive spaces wherein participating teams iteratively design spatial characteristics aimed at overcoming traditional problems associated with sensing, actuation, control, human–robot interaction and artificial intelligence for real world deployment of service robots. In order to realize robot inclusive spaces, various architectural elements must be adapted including: design principles for inclusive spaces, lighting schemes, furniture choices and arrangement, wall and floor surfaces, pathways among others. Contrary to conventional robotics competitions, which are focused on designing robots and its component technologies, Robot Inclusive Spaces (RIS) challenge adopts an interdisciplinary "design for robots" strategy to contribute to a solid set of principles, best practices and methods for designing social spaces that accounts for robots as a stakeholder on top of conventional considerations including average humans, people with special needs like elderly, children and disabled as well as other artifacts. We foresee that this challenge is expected to be a game changer in successful deployment of service robots in a variety of applications from healthcare to domestic and transport to security.

The rest of the paper is organized as follows. Section 2 presents the motivations of our research. A design initiative is proposed in Section 3. Section 4 briefly introduces the design principles. Section 5 is the core of the paper where the first run of RIS challenge is presented in detail. The challenge is evaluated and discussed in Section 6. Finally Section 7 concludes the paper and gives some outlook.

2. Motivations

Given the described limit of current service robots, a simple natural option emerges to improve, accelerate and facilitate the incorporation of such systems in society at low cost. The norm in robotics is to develop robots with complex skills using a full suite of sensors, mechanisms and computation to solve issues appearing in a real environment. Currently, these efforts are totally segregated and independent to the design of the spaces where robots live, work and rest. The variables considered while designing any new spaces are based on normal healthy adult with special adaptations for elderly, disabled and children. The designers, architects as well as the end users are simply unaware of the tremendous efforts by the robotics community to put one robot for a home/office in the near future.

However, huge barriers lie ahead due to the complex nature of the built environments and the dynamic nature of the people living within it. Therefore, there is an urgent need to design barrier free built environments for the robot to allow for their full participation and reap numerous benefits for the mankind. In the related literature, design principles have been proposed for multiple concerns. For example, Robinson et al. proposed guidelines for housing severely and profoundly retard adults [10]; Regnier discussed principles in housing for the elderly [11]; Mäyrä et al. presented rules for proactive home environments [12]; Richards et al. showed a framework for the achievement of survivable system architecture [13]; and Bergen et al. identified elements to guide those practicing ecological engineering [14]. Moreover, the Center for Universal Design at NC State University developed seven principles for the design of products and environments to be usable by all people [15].

Even though, numerous works have been done that involve structural changes to the living space of robots through the use of wall embedded RFID sensors [16], indoor GPS [17], and visual markers [18,19]. In the robotics community, the works about design principles have focused on the determination of key elements for better robot systems. For instance, Brugali et al. determined principles for system openness and flexibility as these are quality factors of a robotic system [20]. Krichmar presented design elements for biologically inspired cognitive robotics [21]. Pfeifer et al. proposed eight principles for intelligent agent design [22]. Mohan et al. defined metrics for human robot interactions in service-oriented missions [23]. Kawamura et al. put forward a design philosophy for service robots that emphasizes compromise and practicality in design [24]. However, such solutions lack holistic consideration of space design which often lead to specific problems like obstacle avoidance, navigation, and in some cases ignoring the esthetic needs of the human co-users, requiring expensive complex sensors and their maintenance, and dedicated space allocated for robots to function with clear segregation from humans.

Meanwhile, robotic competitions is very popular stages for developing and benchmarking technologies and skills. RoboCup is the largest robotics competition attended by thousands of researchers every year comprising of individual focused leagues namely: (i) RoboCup@Home, for developing domestic service robots using a so-called 'system benchmarking' that evaluates robot performances in a realistic, complex and dynamic environment whose design focuses on exhibiting a high degree of uncertainty [25], (ii) RoboCup Soccer for developing and benchmarking co-operative multi-robot and multi-agent systems in dynamic adversarial environments with the ultimate goal of building a humanoid soccer team that defeats the human World Cup Champion team by mid-century [26], and (iii) RoboCup Rescue for developing and benchmarking physical/virtual robotic agents, information infrastructures and strategies for search and rescue missions with the purpose of helping mitigate the suffering of people from disasters [27]. The AAAI Grand Challenge comprises of a benchmarking competition for human robot interaction that involves paper presentation by participating robots and a second benchmarking competition for search and rescue robots. The DARPA Grand Challenge aims at developing and benchmarking autonomous robotic cars with a larger objective of minimizing traffic fatalities, participants normally implemented solutions based on GPS navigation together with multimodal sensor fusion to tackle the uncertainties of the real-world scenarios. However, the complexities of such environments were limited by simplifying the cognition tasks, e.g., contextual information was provided in predefined maps [25]. Eurobot is an annual robot challenge that involves development and benchmarking of autonomous robots that collect artifacts on a defined playing arena with an evolving set of rules [28]. The DARwIn-OP Humanoid Application Challenge, held in conjunction with IEEE ICRA 2012 and 2013, was a competition that focused on development and benchmarking of vision-aided humanoid robots. Other robot challenges that have been carried out during ICRA conferences include: the Mobile Manipulation Challenge, a competition to show off the state of the art in integrated perception and manipulation; the Humanitarian Robotics and Automation Technology Challenge, a competition to benchmark applied robotics and automation technologies in solving problems related to humanitarian causes; and the Mobile Microrobotics Challenge, a competition focusses on testing the autonomy and mobility of robots of a size in the order of the diameter of a human hair.

Despite the high number of challenges available for benchmarking robot systems, all existing competitions focus on developing robotic platforms, mechanisms, perception approaches, actuation strategies, control phenomenon, human–robot interaction, and integration issues. There are no robotic challenge that focuses on competitive design, development and benchmarking of robot inclusive spaces essential for successful deployment of service robots. While there exist numerous architectural design competitions that target elderly [29], sustainability [30], developing/undeveloped worlds [31], tropical architecture [32], schools [33], residential spaces [34] and many other themes. But, none of them considers inclusion of robots as a stakeholder or a variable in space design.

We envisage, however, that developing a set of complete design principles, best practices and their corresponding guidelines for robot inclusive spaces through a challenge requires a continuous effort over a long period from a multi-disciplinary pack of researchers from several countries. This is the principal driving force for the RIS challenge proposal.

3. A design initiative

RIS challenge [35] is a novel robotic competition that focuses on designing robots and spaces by incorporating architectural and design features that optimize the performance of service robots. It aims to (1) foster collaboration between roboticists and designers closer in brining robots ever closer to human societies, (2) develop complementary solutions that remain unexplored in conventional competitions, and (3) solidify the fundamental design principles for realizing robot friendly spaces. The RIS challenge consists of three leagues: (1) RIS-Simulation, (2) RIS-Physical space, and (3) RIS-Coadaptation. Fig. 1 shows visually the RIS challenge (the middle circle), its component leagues, and its relevance to the traditional robotics (the left circle) and design competitions (the right circle). On the whole, the RIS challenge first is deployed independently with another two sets of competitions, and then interact intimately with them in coadaptation competitions.

The RIS-Simulation league contributes to development of a new class of holistic simulators that enables architects, designers and roboticists to conceive, configure, operate and evaluate robot friendly spaces with a large set of autonomous, semi-autonomous and tele-operated robots. The RIS-Physical space synthesis league contributes to the development of tools, processes and infrastructures needed for physical realization of robot friendly spaces. There are two kinds of contests in the RIS-Simulation league. The first one is called RIS-Simulation Adaptation where the competitors use a common open-source simulation platform and a specific set of robot tasks to modify a given social space to fit it to the characteristics and limitations of an undisclosed commercial available robot. In the second kind which is called RIS-Simulation Environment, the competitors propose modifications to the current software platform, or present an entirely new one, for pushing forward the scope of simulation. The winning proposal of such competition becomes the standard platform for the next year of RIS-Simulation Adaptation. The RIS-Physical league is the physical counterpart of this last competition.

Lastly, the RIS-Coadaptation league contributes to the integration of the best practices and/or technologies from robot-centered and design-centered approaches for successful deployment of service robots in social environments. In the RIS-Coadaptation league, competitors use state-of-the-art results from robot-centered and design-centered competitions, or new inventions, for designing the robot inclusive spaces from scratch.

Every run of the competition focuses on a unique theme that centers on a specific space such as home, office, hospital, school, airport, park, mall, etc. Within a given theme, a series of tests are administered. For instance, a RIS-Home challenge includes component tests that focus on specific stakeholders, regions and activities within a home. The five design principles, namely observability, accessibility, activity, manipulability and safety discussed earlier in Section III form the core of the evaluation and scoring system for the RIS challenge. We expect the design principles, components and assessment criteria to evolve over time resulting in a rigorous set of design guidelines for industry and academic

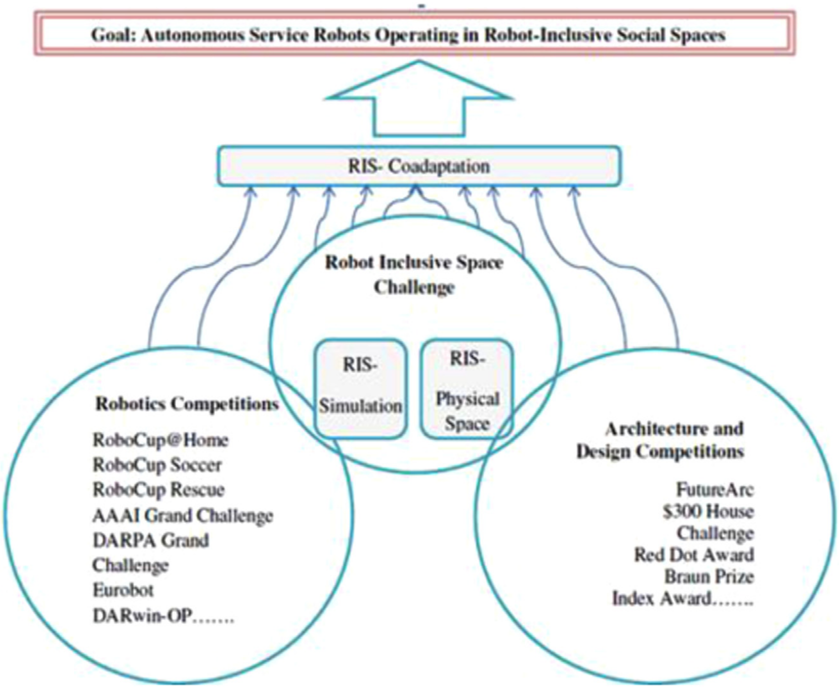


Fig. 1 Topology of the robot-related competitions. Contributions from the RIS-Simulation and RIS-Physical space leagues complement the contributions from existing robotics, architecture and design competitions in order to integrate and assess best practices for successful service robots in social environments.

practitioners. Considering the logistics efforts associated, the focus of the RIS challenge in the initial years may be on a limited set of spatial regions within a theme such as RIS-kitchen for a home theme and expand with time.

4. Design principles

In our previous works [36,37], a hybrid inductive-deductive approach had been used to derive a set of robot inclusive principles, namely: observability, accessibility, manipulability, activity, and safety for spaces involving sociable robots living and working alongside humans. We also have validated the usefulness of the principles in improving the performance of robots across two service tasks. These principles were handed to the participating teams to be used as guiding principles for adapting the given social space to be more inclusive for deployment of robots. Furthermore, these principles allow for analysis of team performances and evolution of the competition in a systematic way. Still, there needs to be an international, cross-disciplinary effort to apply, complete, evaluate, adapt and redesign these principles and their guidelines considering variety of tasks, environmental settings, cultures and socio-political structures. We recognize that an international robot centered competition offers a unique opportunity to adapt and strengthen the laid design principles for robot friendly spaces. A well designed robot friendly urban space would allow for easy perception of the obstacles, landmarks and artifacts of interests. It would optimize activity to deliver greater human robot interaction as well as the safety of the humans, robot and any artifacts in the living space. A well-functioning urban space in this context would offer convenient navigation across the terrain and obstacles for a given mobility mechanism of the robot. Also, an inclusive space design would maximize the ability of the robot to reach for, handle and interact with artifacts within that space.

5. The first run

As a starting point for what will develop into more advanced competitions with elaborate designs, the first run of the RIS challenge focuses on the theme of designing a robot inclusive residential living room that is most conducive for floor cleaning robots. The participating teams primarily focused on adapting furniture design, and their arrangements within the designated space to achieve better floor coverage area for the given cleaning robot. The scenario and implementation of the first run is detailed in the followings.

5.1. Scenario

Participating teams designed an inclusive residential living room for iRobot Roomba 530 cleaning robot. More than eight million iRobot Roombas have been sold, and this makes the iRobot Roomba the most popular cleaning robot on the market [38]. Other cleaning robot brands include Neato XV-21 [39], CleanMate QQ2 Plus [40], iClebo [41], and NaviBot SR8980 [42]. Cleaning robots are currently the most commercially used platforms among service robots. However, the performance of such robots in cleaning the expected floor area is far from achieving complete coverage. Even though Roomba has been studied extensively over the last decade, previous efforts focused on the improvement of mechanical design [43], control algorithms [44], multi-robot co-operation [45], human robot interaction [46] and autonomy [47] with no attention to designing a friendly space for Roomba to operate and therefore to improve its performance. Given the mass reach of cleaning robots, its market potential and their current technological bottlenecks, we center our theme for the first robot inclusive space challenge towards design of the most conducive space.

5 teams each consisting of 5 members were qualified to participate in the challenge. The members were mix of undergraduate and graduate students in the age group of 19–32 years old. The technical background of the participants was from 4 major disciplines, namely electrical engineering, mechanical engineering, computer engineering and architecture. Each participating team was notified on the details of the theme, and specific Roomba series that will be using for the robot inclusive space challenge. The venue specification of a mock residential living room was also made known to the participants. All participating teams utilized the robot inclusive spaces design principles described in the last section as guidance to making adaptations to the spatial elements. Each team was also given a rulebook and predefined set of resources for planning, designing and realizing the adaptations for the given space within a specific time period. In addition, each team also had access to one A1 sized cardboard and a masking tape per team. They were permitted to purchase any additional resources for up to $30, and would be reimbursed for any such purchases upon submission of the bill of materials. Possibilities include buying materials to elevate furniture or to even out surfaces or corners.

The robot inclusive designs of the participating teams were assessed based on the cleaning efficiency measured by the cleaned floor coverage area in percentage. Such an approach to measuring performances in cleaning robots has been validated in popular robotic competitions such as AHRC Vacuum Contest and the 2002 IROS Cleaning Contest where the emphasis was solely on competitive development of robotic technologies and intelligent strategies towards improving cleaned floor coverage. The winning team would have the highest cleaned floor area among all teams.

5.2. Venue specifications

A mock residential living room was chosen as the venue for the first run with a rectangular geometric morphology of size 3.50 m × 3.90 m. The space was chosen to have an area that is larger than a normal typically room size of 12 m^2. Given the theme of the challenge set in a residential living room, constraints were laid for the team to retain certain functional characteristics of the space. To this end, we enforced the following regulations through the rulebook:

- Include four compulsory items, namely two ottomans, a coffee table, and an office chair.
- Include three more chairs and two more tables from a provided selection of six options. Fig. 2 shows the furniture collection used for the challenge.
- Include an extension cord on the floor.
- Except for the extension cord, no objects may be stacked or placed under or above each other. For example, this implies that no chair can be placed under a table.
- All furniture objects must maintain their functionality. The functionality was defined as follows:

(a) Chairs/ottomans without wheels: There must be access and realistic height to sit on them.
(b) Office chair with wheels: It must be possible to sit on and it must be mobile.
(c) Table: It must have a horizontal surface not elevated any higher than 1.40 m above the ground.
(d) If Roomba is stuck, a time penalty of 5 min will be enforced and participating team can only resume the remaining stipulated time to clean after the time penalty is up.

The design specifications were laid down to ensure fairness and usability of the designs, while also allowing the participants freedom to adapt the furniture to meet the needs of the robots while retaining their core functionalities.

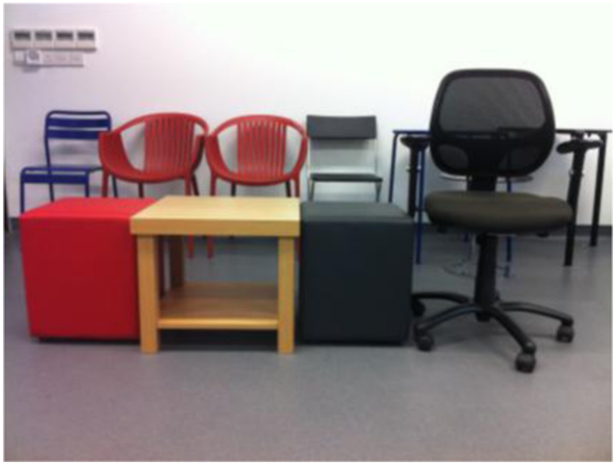
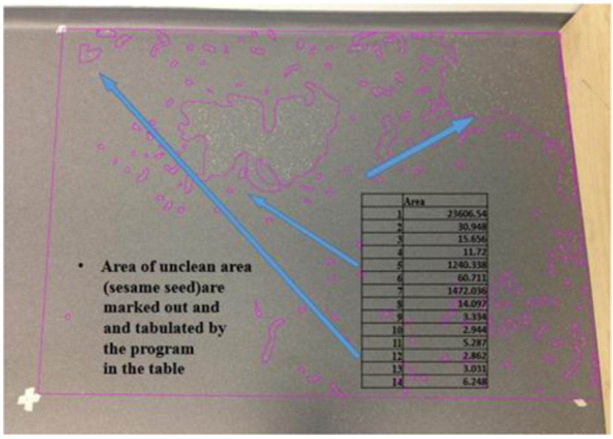


Fig. 2 Furniture collection used for the first run of the robot inclusive spaces challenge; compulsory items (front row): 2 ottomans, a coffee table, and an office chair. Other furniture (back row): furniture that is allowed to choose.

5.3. Challenge implementation

During the actual day of the space challenge, participating team arrived at the given timeslot. Participating team were given 45 min to finalize their designs and proposed spatial adaptations to achieve robot inclusiveness. Once the design has been finalized, no changes were allowed to be made while robot has been deployed or in operation.

Every game started with the removal of all the furniture and other artefacts out of the room leaving it empty and followed by uniform scattering of a pre-prepared dust mixture all over the floor. Later, we allowed the designated team to adapt the space for robot inclusiveness and further deployed the robot for the cleaning mission. Team were not allowed to intervene in any ways during the robot operation. Once the robot finished an operational period of 30 min, the robot was stopped and removed from the venue. We then removed the furniture and other artefacts out of the room again, and this process clearly exposed the unclean areas. We captured bird's view images of the emptied room using a camera mounted on the ceiling. The images were used to compute the percentage of the area cleaned to the entire room area by utilizing image processing tools, ImageJ. The process was repeated for all the teams and their adapted spatial setting. Fig. 3 presents the screenshot from the performance computation procedure using ImageJ software.



- Area of unclean area (sesame seed)are marked out and and tabulated by the program in the table

	Area
1	23606.54
2	30.948
3	15.656
4	11.72
5	1240.338
6	60.711
7	1472.036
8	14.097
9	3.334
10	2.944
11	5.287
12	2.862
13	3.031
14	6.248

Fig. 3 Screenshot from the performance computation procedure using ImageJ software.

We computed the uncleaned and cleaned percentages for the designated space as,

$$\text{Uncleaned percentage} = \frac{\text{Uncleaned area}}{\text{Total area}}$$

$$\text{Cleaned percentage} = 100\% - \text{Uncleaned percentage}$$

Using this procedure yielded quantitative results of the performance of the iRobot Roomba in each run associated with the participating teams. The final scores of the participating teams are presented in Table 1, where Team D achieves the maximum cleaned area and Team D ranks the last.

Table 1 Final scores of the participating teams.

Placement	Team	Cleaned percentage (%)
1	D	87.33
2	E	82.53
3	C	76.56
4	B	75.87
5	A	72.33

6. Evaluation and discussion

The objectives of the space design challenge is to consolidate creative design ideas and best practices for friendlier spaces for sociable robots which designs work, which do not, and why that is. Fig. 4 shows the design layout for all 5 teams. Team A elevated the coffee table and the 2 ottomans. Team B spread the furniture to the greatest degree. Team C creatively attempted to design a tunnel for Roomba. Team D came up with this highest-scoring design. Team E emphasized keeping the middle area open.

It was observed that 2 spatial adaptions yielded particularly good results: (1) allowing the Roomba to access the floor area by aligning furniture along the walls or combining the legs of different pieces of furniture, and (2) elevating the furniture thereby making the area underneath available for the robot to pass through.

Two common, but in hindsight unnecessary, fears influenced several of the designs. First, the teams feared that the Roomba would easily get stuck between the legs of chairs, and combatted this by making the area unavailable to the robot. This seems to have resulted in more uncleaned area, and from other observations the robot does not get stuck so easily. Second, several of the teams overestimated the time that the robot needs to vacuum the area, and made decisions of sacrificing area in order to give the robot more time on the open spaces.

The challenge yielded useful insight into how future competitions can be revised as to better serve the motivation of the event. The benchmarking framework adopted for the first run focused only on the overall performance of cleaning as measured by the cleaned floor area. But, an effective and efficient approach would be to examine not only the overall system performance but also the level of adherence to the defined design principles that must be followed to achieve robot inclusive spaces. The results of the participating teams substantiate the need for extension of benchmarking framework which was found to be close to each other with no systematic capturing of factors affecting their performance. One strategy being considered is to run a series of tests instead of one to score the performance against design principles. For example to run a separate test that measure the interaction between the robot and chair in terms of cleaning efficiency; another test to score the performance of robot to collect the dust from the floor and more tests with respect to lighting, time, safety among others. Uncertainty was not considered in the first run of the competition. A future competition would consider elements of uncertainty like a moving human or dynamically changing lighting condition to make the scenario more closer to real life one. Another benchmarking component being considered is the inclusion of a test for repeatability wherein the robot has to do the task over few rounds and the average is considered for the final score. The furniture set made available to teams was of a smaller set of choices which would be extended for the next runs.

7. Conclusion and outlook

This article presented the Robot Inclusive Spaces challenge as a design initiative that uses competition framework to complement the current focus on "designing robots" approach with a "design for robots" strategy to overall traditional research problems in real world robot deployments. The RIS challenge is the first of its kind bringing together architects, roboticists and designers in developing design principles, methods and best practices for robot inclusive spaces. With the service robotics industry witnessing a rapid growth, a competition platform that offers "design for robots" solutions would significantly impact the integration of these robots into social spaces. The first design challenge is intended to be a starting point of a much larger multi-national competition that cuts across socio-political, cultural and geographical boundaries. The challenge is expected to experience numerous iterations both

Team A Team B

Team C Team D

Team E

Fig. 4 Design layouts for all five participating teams.

on technical and organizational aspects considering development from individual runs, participants, scenarios and tasks. Moreover, as one of the main issues to be addressed in the short term is the implementation of a holistic benchmarking framework that considers both overall system performance as well adherence to design principles. Gradually, we expect the test scenarios to move from mock setting to real world social spaces like corporate office spaces, home and shopping malls. We also hope to see open source standards be developed for users, outlining how they can design their homes in order to benefit the most from service robots. This step would allow the users directly to take control, transform into designers and optimize their experience robots in their lives.

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