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THE HOUSE THAT ROOMBA BUILT

Creative spatial and furniture designs by a cleaning robot

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Abstract. The "Roomba House" (RH) is a novel generative design approach based on robotic interaction with the physical environment in order to inductively identify design opportunities for improving the design of future robot-inclusive spaces and furniture. The paper presents the theoretical and technological details of this approach, an empirical study of a cleaning robot and sample results from an evolutionary system inspired by heuristics inductively derived from the study. RH is an informed provocation based on the recognition that increasingly widespread domestic robots that roam our living spaces will infer key features and help produce creative design solutions that maintain or improve user requirements while improving their inclusiveness in everyday life.

Keywords. Robots, evolutionary creativity, computational creativity.

1. Introduction

This paper presents the first results of 'Roomba House' (RH), part of an ongoing multi-disciplinary research project with a comprehensive Robot-Inclusive design philosophy (Elara et al., 2013). In RH, off-the-shelf robots are deployed and interact with realistic conditions. Design heuristics inductively derived from this systematic interaction are used to improve the adaptability of future robot-inclusive spaces.

Robot-inclusiveness remains a marginal area in design, despite the growth in adoption of companion and cleaning robots. Recent studies have shown that robots' compatibility with the environment can be an important factor in adoption or rejection of cleaning robots as well as in long-term usability and product attachment (Sung et al 2010).

Designing *for* robots acknowledges the new inhabitants of our everyday spaces similar to how designers address the needs of special populations (ageing, disabled) and their interaction with other users. Increasingly complex robots are developed to cope with pre-defined environments to complete everyday tasks that depend on seemingly simple capabilities such as turning a handle to open a door. Bridging the decision-making in robot and spatial design would carry a twofold advantage: designers would see service robots as target stakeholders and users, and roboticians would build upon the environment's features to make future robots capable at manageable costs.

Designing *by* robots takes advantage of the close physical interaction that robots have with our everyday spaces, and seeks to build upon 'robotic post-occupancy' experiences to systematically evaluate existing designs and derive creative directions for improvement. Designing *with* robots opens this process for collaboration between robots and designers. This paper shows one approach to this multi-disciplinary collaboration. It presents the theoretical and technological details of this approach, followed by sample results from an evolutionary implementation.

2. Background

While generative design systems are usually built for optimisation tasks, a number of systems explore the role of computational generators in creativity. These systems vary from fully automated combinations or transformations of an existing corpus to human-in-the-loop systems where humans intervene to guide the process (i.e., the selection operator of evolutionary systems) (Bentley, 1999). Our approach explores a 'robot-in-the-loop' design process where the robot interacts with the built environment to assess design features and inductively extract insights, which are used to produce novel, more suitable and in some instances unexpected (i.e., creative) designs.

The Roomba robot is selected because of its relative autonomy, its commercial success in the market, and its extensive use as a viable foundation for classroom and lab activities (Jones, 2006; Tribelhorn and Dodds, 2007). Roomba uses mechanical and infrared sensors including a light-touch bumper to detect obstacles, follow walls, avoid falling off stairs, and differentiate between hard and soft barriers such as skirts and curtains.

Beyond the economic and cultural impacts of the increasing adoption trend of service robots, there are good reasons for designers to be interested in domestic robots. Recent ethnographic studies target the complex relationship between humans, robots and the physical and social spaces that they share (Fink et al., 2013). A study found that when cleaning robots were run in environments "that had not yet been modified to accommodate them, they encountered several accidents, such as breaking a full-sized mirror, eating toys, and damaging furniture" (Sung et al., 2010). As a result, users make adaptations such as placing "a book under a lamp so that Roomba would not get stuck while trying to climb on it" and "changing furniture layout". As such, this type of robots "become a mediating factor for householders to make changes in their homes".

This ‘Roombarization’ effect of domestic spaces has been documented elsewhere such as a user "placing his coffee table on his couch to let Roomba vacuum optimally" noting that one of the main barriers to adoption is that it is "not usable across a wide variety of physical environments" (Bauwens and Fink, 2012; Fink et al., 2013). Some users see "robots as social agents after the initial interaction", they ascribe "lifelike qualities, such as Roomba’s intention to go to a certain place" and a large number give "names to Roomba within the first two weeks of usage" and engage "in conversations with it" (Sung et al., 2010). The incompatibility between robots and environments is a cross-disciplinary design problem that will become more complex given the massive adoption and the emergence of new robots on top of other social trends such as ageing in place. In addition to improving functional performance, designing robot-inclusive spaces also addresses the long-term users’ interaction and acceptance of these products and guarantees that the designed environment supports a safe and satisfying experience.

Unlike ‘architectural robotics’ where modular adaptive environments are augmented with smart sensing and control (Weller and Do 2007), our goal is to produce creative and low-cost passive designs (spaces, artefacts) taking robotic inputs in the design process as well as targeting service robots as direct users. The resulting designs respond to the robots’ requirements, support their functionality, and their interaction with humans.

3. Roomba as a design robot

3.1. STUDY OF ROBOT-INCLUSIVE HEURISTICS

An iRobot Roomba® 500 series is selected for this study with a twofold aim: to empirically characterise the impact of environmental changes in the performance defined as the ratio of clean area in a time period, and to inductively derive design heuristics based on the observed behaviours. The test area is a square of $4m^2$ delimited by small walls. A time of 8 minutes is estimated as sufficient to clean this area (Vaussard et al., 2013; Palleja et al., 2010). In order to assess cleaning efficiency, a Java-based image processing program

(Goldstein, 2011) is used to automatically calculate the percentage of clean area. Various materials were tested to evaluate the reliability of this automated visual analysis method across flooring materials and lighting conditions. Sesame seeds were chosen because of high contrast under control illumination levels and easiness to be spread evenly and to be removed between trials. At the start of each trial, 20g of sesame seed is spread evenly across the floor and photographs of the full test area are taken from a fixed bird's eye view. Roomba is then placed in the top left hand corner of the test area and allowed to run for 8 minutes. Photographs of the test area are captured again, with the difference in contrast levels between the set of pre and post-images used as an indicator of performance (O'Connell 2002).

Figure 1 shows the test furniture area: a square cabinet of 400x400mm (#1), a round dustbin (#2) of radius 120mm, a four-legged stool (#3) and a plastic chair (#4). The stool and chair were selected so that the distance between their legs would prevent (#3, stool), and enable (#4, chair) Roomba to fit underneath the furniture (#4, chair) –Roomba's radius is 175mm.

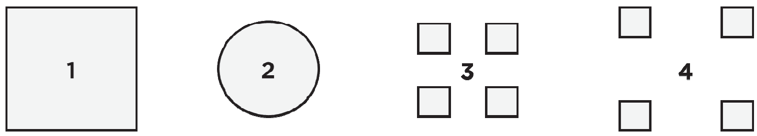

Figure 1. Test furniture area: cabinet (#1), dustbin (#2), stool (#3) and chair (#4). Roomba does not fit between the legs of the stool (#3), and it fits between the legs of the chair (#4).

Five test settings capture the effects in performance comparing what was hypothesised to be a less Roomba-inclusive set {#1,#3} and a more Roomba-inclusive set {#2,#4}. The overall area covered by the furniture in both cases is equivalent (0.25m2). Three trials were conducted for each experimental setting with minimum variance recorded between trials. Results (shown in Table 1) demonstrate that Roomba's cleaning performance varies up to 8.3% even in a small area of $4m^2$. Similar effects were obtained across lighting conditions, which are beyond the scope of this paper.

Table 1. Experimental settings used in the study

Setup	Type of furniture	Flooring material	Performance
a	Baseline, empty space (no furniture)	Short-pile carpet and laminate	95% to 96%
b	Set {#1,#3}: cabinet and stool	Short-pile carpet	85.2%
c	Set {#2,#4}: bin and chair	Short-pile carpet	93.5%
d	Set {#1,#3}: cabinet and stool	Laminate	86.2%
e	Set {#2,#4}: bin and chair	Laminate	90.6%

Based on these results, the following design heuristics are extracted: 1) Round corners are preferred over sharp corners; 2) Leg number and configuration can have a significant effect in performance; 3) Furniture placement is important, ‘nesting’ effects occur by the proximity of legs from different furniture; 4) High contrast is important, enhanced by light-colour materials and reduced by darker as well as transparent materials.

In order to validate these effects, we replicate the study in a furnished office space of $12m^2$ to test Roomba’s performance over a period of 25 minutes following the same procedure. The existing office arrangement is compared against a modified "Roomba-inclusive" version which consists of: rounding sharp corners with 15 cm strips of cardboard (heuristic #1), placing wood blocks of 10cm to the base of all furniture (heuristic #2), clearing the space between furniture (closest legs) beyond 300mm (heuristic #3), and covering dark and glass materials with 15cm strips of white paper (heuristic #4). As a result, average cleaning efficiency in three experimental trials jumps from 71% to 93% with these robot-inclusive adaptations.

These results inspire the creation of a proof-of-concept evolutionary system that generates creative designs applying robot-inclusive heuristics allowing exploration of a wide range of scenarios which would be costly and time consuming with real furniture in real spaces. The aim of this system is to assist in developing a deeper understanding of the effects in order to fine-tune the experimental requirements to deploy Roomba in realistic domestic environments to evaluate furniture sampled from international furniture stores.

3.2. EVOLUTIONARY ROBOT-INCLUSIVE DESIGN SYSTEM

An evolutionary system is implemented to generate creative robot-inclusive designs. A total of eleven furniture types are selected based on the classification of a retailer’s catalogue (Ikea 2013), namely: media console; one, two and three-seat sofas, coffee table, cabinet, bookshelf, side table, chaise longue, chairs, and footstool. For each type of furniture, product measurements are registered (total area) creating a collection of one-hundred products that can be selected to furnish a space. A total of seven possible materials are included in the system to be assigned to products. Since Roomba directly interacts with the bottom 100mm of furniture, eleven configurations based on number and orientation of legs are defined as shown in Figure 2.

For each leg, Figure 3 defines six options available: wheel, round, 3, 4, 5 and 6-sided. A "total area/leg area" ratio (r) is defined generalizing the range of options observed across products. The range for r is defined from 0.7 to 1.2 and represents the percentage covered by the legs or base in relation to the total area of the furniture. As shown in Figure 4, a table with a four-legged table has a low *r* value when the area covered by the legs is smaller than the total area of the furniture; with protruding legs, *r* can exceed 1.0.

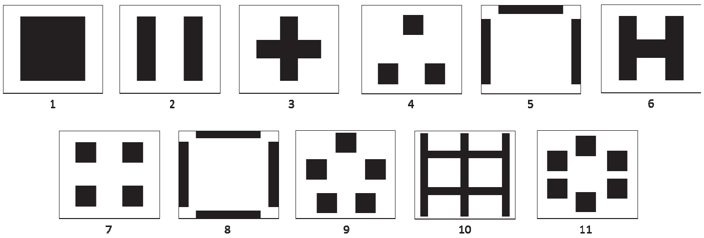

Figure 2. Eleven leg configurations are defined based on number and orientation of legs.

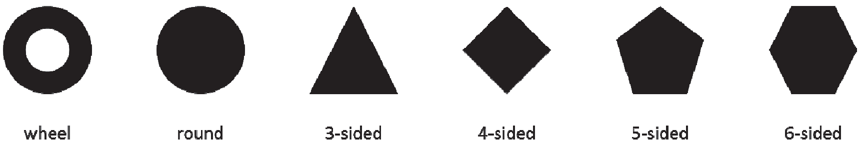

Figure 3. Leg shapes used to capture leg type diversity observed in the product catalogue.

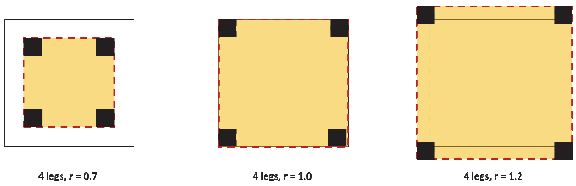

Figure 4. Three 'total area/leg area' ratio (r) values are defined to capture leg coverage.

The process to build virtual room layouts consists of a semi-random sequence where furniture is selected, placed and oriented in relation to the room and to other furniture in a general schema with ranges from which values are selected randomly. At first, a layout is created by placing one of three types of furniture (media console, sofa, bookshelf), which are considered the *anchor* living room furniture. Iteratively, instances from the other furniture categories are placed by random location and orientation values within legal ranges (i.e., sofas must be a minimum of 7 feet from media console, etc.). A complete description of these schemas is beyond this paper's length limit.

A genetic algorithm (GA) is implemented combining semi-random generation (constrained by domain heuristics), crossover, mutation, scoring, and roulette selection (Goldberg and Holland, 1988). In a chromosome, genes cover broad aspects of design factors, including location and orientation of furniture, as well as material, type, number and configuration of legs. A dominant/recessive gene increases the diversity of leg shape. Crossover takes place within the features of individual furniture and also in the location of same-type furniture in different rooms with same layout scheme.

All candidate room designs are scored in the following four criteria: cleaning performance (S_{cp}), furniture function (S_{ff}), materials (S_{mb}) and layout aesthetics (S_{la}). If Roomba is able to access all the available space in the room (unclean area, A_u=0), the maximum S_{cp} score of 0.4 is given. Layouts with furniture combinations that support five functions (seating, entertainment, etc.) get a top S_{ff} score of 0.1. Materials are evaluated for compatibility. Layouts with 3 and 4 different materials receive a maximum S_{mb} score of 0.1. The last score is a composite of four criteria: right-in-room (S_{rir}), widespread (S_{ws}), symmetric-axis (S_{sa}), and symmetric-spread (S_{ss}), each of them with equal contributions to a maximum S_{la} score of 0.4. These criteria are designed to account for qualitative requirements including usability, aesthetics, cultural conventions and personal preferences.

3.3. ANALYSIS OF CREATIVE ROOMBA-INCLUSIVE SOLUTIONS

The following results are extracted by analysing typical high-score solutions from this evolutionary system that draw attention due to the unexpected character of their features. In this version, results are selected as case studies rather than based on statistical testing, an ongoing effort in addition to validating these outcomes in physical settings. While a large number of fit designs present standard furniture and layout features, this section shows three sample non-obvious effects:

H1: Non-uniform scale effects. A large number of good solutions are found where squared-shaped furniture (cabinets, one-seat sofas, footstool) present low *r* values (0.7). In contrast, when rectangular furniture (consoles, three-seat sofas) is found in good solutions, they tend to have high *r* values (1.2). This effect can be explained by an epiphenomenon of Roomba's interaction with its environment, a heuristic that was not explicitly encoded in the system and that designers of Roomba-inclusive furniture could exploit. As Figure 5 shows, when some sides are short as in rectangular furniture, leg distance tend to hamper accessibility with $r < 1$, so Roomba will not fit from some directions and is likely to miss part of a considerable area (grey area). In contrast, furniture with equal leg distance, are resilient to even very small *r* values, since either the missed area is too small, or due to the uniform scaling of leg distance, Roomba can roam under the furniture with easy access from all directions.

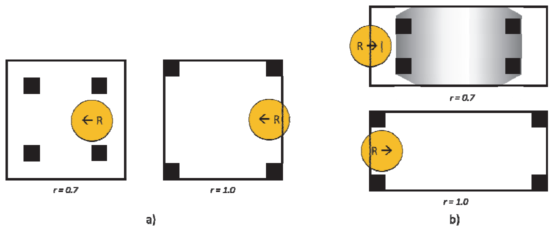

Figure 5. Non-uniform scale effects: a) square-shaped furniture is accessible in r < 1.0, b) rectangular envelopes where r < 1.0, present challenges for accessibility in some directions.

H2: Furniture leg configuration effects. A simplistic view is that furniture with less legs are better for Roomba; however, we find non-obvious results that show that for certain furniture types, specific leg configurations dominate the best fitness solutions. As expected, the best solutions include furniture with the canonical leg configuration of four legs in a square or rectangle (#7 in Figure 2) and similar variations such as #4, #9 and #11. Two parallel legs (#2) are common across the board, while one-legged configurations (#1) are frequent in small-size furniture (coffee tables and chairs). In general, unconnected legs are more common in fit solutions, regardless of the actual number of legs.

H3: Furniture leg shape effects. While the precise effect of leg shape would depend on the specific type of wall-following and collision avoidance strategy of the robot (Palleja et al 2011), this study provides general insights and reveals some points of interest for the design of robot-inclusive furniture and spaces. Namely, round legs are dominant in fit solutions, and this effect is more pronounced in chairs and small tables, and less significant in consoles and large sofas. A possible explanation is that small furniture cover areas that Roomba may miss entirely if it does not fit underneath or if its edge-following behaviour is compromised by sharp edges, whereas media consoles and sofas have large rectangular areas less susceptible to 'edge effects' caused by shaper leg shapes. In other words, if two sharp leg edges are sufficiently close, the likelihood for Roomba of finding the right angle of approach to fit underneath is small; whereas in large size furniture, sharp leg edges will be far enough for Roomba to approach the area without leg interference. The use of round legs in large and small furniture improves access (provided that Roomba fits, see H2) because the robot will wall-follow the round leg without corners that may deviate its course.

4. Discussion

Considering the rapid progress in robotics technologies, and their promise in enhancing our lives (including elderly and physically challenged users), this paper demonstrates how we can better incorporate robotics occupants and agents when designing built environments. Robot-inclusiveness remains a marginal area in design, despite the incompatibility between robots and environments being an important design problem. In addition, robot deployment is an original tool for designers as a type of ‘design surveillance’ passively observing features and user behaviours or actively engaging with the environment in order to inductively extract heuristics, identify problems and test potential solutions.

Through an empirical study of Roomba and an evolutionary design system, this paper presents three design heuristics that can be used by design practitioners to generate robot-inclusive solutions, as well as by researchers to inform future laboratory and ethnographic studies of domestic robots and the type of effects that everyday furniture and spaces have in their performance. Non-uniform scale effects, furniture leg configuration effects and furniture leg shape effects are discussed in this paper.

Future work in our research group includes the deployment of a new type of reconfigurable robots used to autonomously adapt to uncertain and changing environments in order to inform the design of future robots, spaces and artefacts (Elara et al., 2013).

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