2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Design Principles for Robot Inclusive Spaces: A Case Study with Roomba*

Mohan Rajesh Elara, Nicolas Rojas, Adrian Chua

Abstract— Research focus on service robots that deals with applications related to healthcare, logistics, residential, search and rescue are gaining significant momentum in the recent years. Their social and economic relevance is more than evident. Yet, while much has been researched about “designing robots” focusing on sensing, actuation, mobility and control of service robots, little work has been done on “design for robots” that looks at designing preferred artefacts or environments for such robots. In this work, we propose a new philosophy of robot inclusive spaces, a cross disciplinary approach that brings together roboticians, architects and designers to solve numerous unsettled research problems in robotics community through design of inclusive interior spaces for robots where the latter live and operate. With a residential floor cleaning robot as a case study, we inductively derived a set of four design principles namely observability, accessibility, activity and safety that guides the realization of an inclusive space for these service robots. Also, the suggested principles are further defined, analysed and validated for their merits in this paper.

I. Introduction

In the past, design of contemporary new spaces and devices such as lighting and furniture conventionally target the majority of well able-bodied healthy person until recently apposite design principles were introduced in response to a special group of people such as children, elderly and user groups with physical disabilities. For example, Robinson et al. proposed guidelines for housing severely and profoundly retarded adults [1], Regnier discussed principles in housing for the elderly [2], Richards et al. showed a framework for the achievement of survivable system architecture [3], Mäyrä and Vadén presented rules for proactive home environments [4], Bergen, Bolton and Fridley identified elements to guide those practicing ecological engineering [5] and the Center for Universal Design promoted seven principles widely used in the design of products and environments to be usable by all people [6]–[7].

*Research supported by SUTD-MIT International Design Centre.

Mohan Rajesh Elara is with the Engineering Product Development Pillar, Singapore University of Technology and Design, 20 Dover Drive, Singapore 138682 (E-mail: rajeshelara@sutd.edu.sg)

Nicolas Rojas is with the Department of Mechanical Engineering and Materials Science, Yale University, New Haven, CT USA (Email: nicolas.rojas@yale.edu)

Adrian Chua is with the School of Science and Technology, Singapore Institute of Management University, 461 Clementi road, Singapore 599491 (Email: adrianchua001@unisim.edu.sg)

With an increasing drive for productivity and recent advent in ICT, an emerging category of service robots are expected to be an additional stakeholder in social spaces aiding humans in day to day activities. There are two arguments that substantiate this claim. Firstly at workplaces, most countries would face tremendous shortfall in the number of blue collared workers with people preferring to work on higher value jobs. Secondly within a home, most people would have lesser time to handle household chores that are often tiresome, and repetitive. Such service robots are expected to engage in psychological (relaxation, and motivation), physical (support for basic skills like mobility, housekeeping, eating, grooming among others), and social (stimulation of communication) activities with people. Pertinent example of modern success stories consist of BigDog, a robotic pack mule by Boston Dynamics; Kiva an automated material handling robot by Kiva Systems and the intelligently sharp autonomous robotic vacuum cleaner iRobot, Roomba which was designed, fabricated and tested to help user clean the house.

Designing a service robot capable of performing a plentiful of functions to acclimatize to the present world is still not yet possible. Service robotics research has been challenging and convoluted. Such robots must be able to work competently and safely along people in highly dynamic and unpredictable built environments in homes and public places (for example offices, hospitals and schools). Even with the most cutting-edge technology, artificial intelligence, sensing, actuation, mechanics and control, service robots are still far from the ideal robot that it able to function autonomously and interact openly with human being in realistic human-related environments.

The perceived assumption in technology has been to invent and create service robots, its component technologies with largely sophisticated algorithms so as to perform simple and multilevel complex skills that a human requires. Given the boundaries of service robots and its capabilities at present time, the most logical approach would be to examine ways at designing social spaces and optimizing its architectural characteristics that would allow such service robots to overcome their limitations and achieve tasks easily at low costs. Some studies that have looked into how this has been done include work targeted adaptations to living spaces through the use of wall embedded RFID sensors [8], indoor GPS [9], and visual markers [10]–[11]. Even though such solution offers some answers, they often emphasize on overcoming a specific problem in an application context such as obstacles avoidance, navigation, manipulation and localization lacking a holistic approach. There is a clear absence of any work both in robotics and architectural communities that focuses on design methods, tools, best practices and principles to be used by roboticians, architects and designers in realizing robot-friendly residential spaces.

To date, work in the robotic community has mainly focused on specifying key elements for design of better robot systems. For instance, Brugali et al. determined principles for system openness and flexibility as these are quality factors of a robotic system [12] and Krichmar [13], based on the eight methodologies for intelligent agents proposed by Pfeifer and Bongard [14], presented design elements for biologically inspired cognitive robotics. Kawamura et al. puts forward a design philosophy for service robots that emphasizes compromise and practicality in design [15]. Although Soroka et al. have identified some of these challenges [16], systemic design principles that aim for seamless integration of service robots and humans in everyday environments still have yet to be discussed.

Our ongoing *Robot Inclusive Spaces* project, a novel design initiative puts forward a "design for robot" approach to complement the conventional "designing robot" strategy. Such an approach brings together roboticians, architects and designers in realizing friendlier spaces for robots where component systems of the robot such as sensors, actuators, mechanism etc as well as the component variables of the space such as lighting scheme, floor surface, furniture choices etc are both optimized. The role of service robots and the concept of designing robot inclusive space will be of significant importance for smart cities of the near future. However, research emphasising design of friendlier spaces with optimal flooring, wall structures, lighting schemes, furniture choices and placement, doors, windows, among others to fit service robots is still lacking. In this paper, we put forward and validate a set of design principles for robot inclusive spaces with a residential floor cleaning robot as a case study. The design principles are extracted by inductive analysis with the robot under test. The design principles presented in this paper can be applied for both planning new civil and architectural projects as well as for adapting existing spaces. This paper closes with a discussion of the proposed design principles and the future prospect of this research.

II. DESIGN PRINCIPLES

A. Case study

Over the past decades, human beings have been using technology to help improve their lives. From computers to smart phones, the use of technology has become an integral part of human life. In the household environment, machines such as vacuum cleaners, washing machines and clothes dryer have become necessities in helping improve the standards of living. The use of service robots has been picking up in trend albeit slowly. These service robots can assist human beings in many ways including household chores. With the help of service robots, household chores can now be taken care of when they reach home. One such tedious, time consuming, and repetitive but essential job is that of cleaning in any household. To automate the job, there are many brands of cleaning robots that are available in the market such as Roomba, Neato XV-21, CleanMate QQ2-T Plus, Iclebo, and Samsung NaviBot SR8980 among other platforms. The deployment of robot platform will help to improve productivity within home, by relieving the humans of this time consuming and menial work allowing them to focus on other important familial tasks that improves quality of life. However, given the nature of the task and environment, the autonomous cleaning task for the entire residence is not a trivial task. Our case study in this paper involves iRobot Roomba, a popular floor cleaning robot. Since its launch in 2002, iRobot has sold over 7.5 million Roomba cleaning home robots so far and is currently selling in over 45 countries around the world and expanding [17]–[18]. Fig. 1 presents Roomba robot in action during our feasibility study performed in a residential space.

Figure 1. *Roomba robot in action during our feasibility study performed in a residential space*

Roomba's mobility system consists primarily of two motor-driven and tracked wheels. Roomba steers by alternating the power supplied to each wheel. A behaviour based strategy is adopted for control of Roomba that achieves automatic detection and avoidance of stairs and other drop-offs, detection of dirtier areas, spending more time cleaning the particular area and automatically adjusting from carpet to hard floors. Some of the important components that allow Roomba to function include an infrared "cliff sensor", an acoustic-based dirt sensor and a forward-looking infrared sensor in its bumper to detect obstacles. The cliff sensor constantly sends out infrared signals and if is obstructed by dust or debris, the infrared- sensor is weakened. This will allow the Roomba to detect obstacles such as stairs or ledges, which will not allow Roomba to manoeuvre over such places. The acoustic-based dirt sensors are located under the two main brushes and are able to detect hard and small particles like sand. The sensor will then steer the Roomba towards the area where there is a higher concentration of dirt. The forward looking sensors are located at the bumper to detect obstacles. It will then perform and repeat a sequential of actions such as sensing the obstacles in front and slowing it down when it is nearing obstacles to reduce the force of impact. In terms of hardware design, it has an improved filter to capture more dust and allergens, faster counter-rotating brushes that will allow more hair and debris to be picked up and removed, an anti-tangle technology that prevents the Roomba from getting stuck on cords, carpet fringe and tassels, and an improved side brush to allow Roomba to clean edges and corners. For software design, it has implemented a virtual wall where users can set the area that they do not want the Roomba to access and the Roomba will automatically return to its self-charging Home Base to dock and recharge between cleaning.

Even though Roomba has been studied extensively over the last decade, but previous efforts focuses on the improvement of mechanical design [19], control algorithms [20], multi-robot co-operation [21], human robot interaction [22], and autonomy [23] with no attention on designing a friendly space for Roomba to operate and therefore to improve its performance.

B. Principle Extraction

Robot inclusive spaces and its design principles has not been studied in both architecture and robotics literature. The design principles are expected to be enablers in realizing optimal design parameters for the space including flooring, furniture, lighting, space geometry, and wall surfaces among others. We adopted an inductive reasoning that begins with specific observation and measures, keeping these observations and measures; we detect the patterns and regularities, formulate some tentative hypotheses and finally end up developing the conclusion or theories [24].

1) Inductive Process

An inductive methodology presents a sound research approach [25] wherein design principles are extracted from spatial constraints observed through experimental trials involving Roomba over a variety of spatial settings where the robot performance is a measure of the cleaned floor coverage area. Fig. 2 shows the inductive process adopted for our experiments.

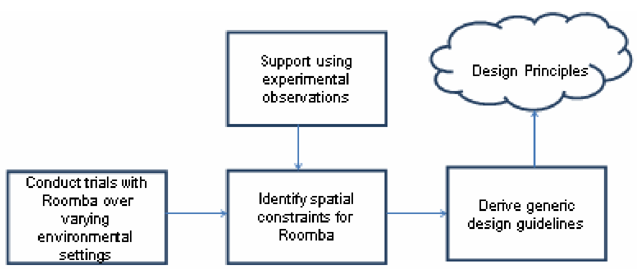

Figure 2. *Inductive Process Adopted for Deriving the Design Principles*

The experiments conducted for this work involved twelve scenarios with three different settings for varying flooring type, furniture choices and their arrangement and lighting schemes. A snapshot of the experimental scenarios is presented in Figure 3. The experimental floor area was 12 square meter. In all the experimental cases, dirt mixture containing sesame seed, rice and hair was sprayed uniformly throughout the floor area before robot operation. The percentage cleaned floor coverage area was determined by capturing a photo of the complete floor area and by computing the ratio of cleaned pixel area after operation by Roomba and pixel area of the entire experimental space including segments of unclean areas. Key spatial constraints observed during our experiments includes,

- Space geometry with square corners was inaccessible by Roomba for cleaning in all experimental cases given the circular morphology of the latter. The performance of the robot was found to be better in the case of space geometry with rounded corners.
- Carpet material was observed to slow down Roomba's mobility. The mobility was much smoother with wooden flooring.
- Furniture with square/rectangular bases was found to have larger uncleaned area in the periphery of the furniture. The uncleaned area in the periphery of the furniture was the least in those with circular bases.
- Dark coloured furniture, walls and other surfaces were less observable by Roomba often resulting in crashes into those cases as compared to light coloured surfaces.
- Uneven surfaces even with rugs and carpets over 1cm are inaccessible for Roomba.
- Dark coloured flooring generates increased false alarms for cliff detection and therefore results in increased uncleaned coverage area.
- Ambient sunlight affects the IR sensors and results in increased collision.
- Increased cluttering of furniture and human mobility results in increased collision and uncleaned floor area.
- Furniture with low vertical ceiling just right for Roomba to pass or if the ceiling funnels down at a narrow angle increases the probability of Roomba to get wedged.
- Furniture arrangements with boundaries converging at narrow angle often results in Roomba being struck in that space
- Electrical cords lying on the floor were unobservable and at times Roomba gets trapped by them.
- Rooms with closed doors are inaccessible for Roomba.
- Orientation and placement location of the furniture were found to affect the way Roomba cleans and the number of collision with the furniture.
- Roomba had difficulty detecting artefacts with transparent or glass surfaces increasing collision in those circumstances.
- Low cliffs were harder for Roomba to detect and avoid in most cases.

Roomba tested over a Cliff with the three flooring types (Tiles, Wood, Carpet)

Roomba experiments involving uneven surface

Roomba experiments involving inaccessible areas

Roomba experiments involving accessible furniture

Roomba experiments involving varied wall surfaces

Roomba experiments involving electrical wirings and infrastructures

Figure 3. *Snapshot of the experimental scenarios*

C. Principle Definition

With the observations made from the experiments, the spatial limitations that impacted robot performance were consolidated and refined to form a set of generic design guidelines. Further categorization of the design guidelines by their characteristics yielded four design principles namely observability, accessibility, activity and safety.

1) Observability

Senses are physiological capacities of organisms designed to perceive external stimuli. In animals, everything that is known about the world is due to their senses. Such sensors have evolved along the time to help them to solve vital problems [26]. In humans, particularly, five senses are traditionally recognized by scientists: vision, hearing, touch, smell, and taste. Service robots are not so different to living systems; sensors in them also play a fundamental role for understanding the environment and making decisions. In general, robots are provided with different sensors based on the task at hand, with their own capabilities and limitations, to emulate at least one of those of humans. Hence, observability principle includes a set of general design guidelines to maximize visibility and perception for a robot navigating in a given landscape. Below are the design guidelines derived from spatial limitations observed during inductive trials with Roomba:

- O.1: Maximize robot perception through the appropriate selection of colours, textures, font/pattern sizes and materials for wall and floor surfaces.
- O.2: Use robot sensing capacities to design observable signage or zoning for major intersections, high human and obstacle density zones, dynamic obstacles areas, uneven terrain, and low visibility regions.
- O.3: Maximize sensory signal strength and contrast as perceived by robots.
- O.4: Put in place mechanisms that minimize environmental noises that would interfere with the robot's sensors.

2) Accessibility

Accessible design normally refers to the design of places of public accommodation and commercial facilities that include the needs of humans with disabilities, that is, people with physical, mental, or environmental conditions that limit their performance [27]. The Americans with Disabilities Act of 1991 [28], that was revised by the US Department of Justice in 2010 [29], establishes several requirements that different spaces must fulfil in order to guarantee the integration of disabled people in all environments. In fact, specific technical requisites are discussed for elements and areas such as, to name a few, doors, drinking fountains and water coolers, toilet rooms, detectable warnings, and dressing and fitting rooms. Service robots, principally those that are mobile, suffer from accessibility related problems as in the case of disabled people when are deployed in a human environment. Hence, accessibility principle includes a set of general design guidelines to provide safe navigation, good connections and access. The scope of the accessibility principle would be limited to the environment access for the robot while ignoring any dynamic agents like humans or other moving agents. Any interaction between humans, other dynamic agents and robots would be dealt in the activity principle. Below are the proposed guidelines:

- Av.1: Ensure barrier free access without steps, thresholds, ramps or kerbs. Where changes in floor levels are unavoidable, the mechanism put in place should allow for effortless accessibility in robots.
- Av.2: Place doors that allow appropriate space for the robot to manoeuvre and manipulate.
- Ac.3: Design recessed spaces in selected areas for the robots to cease work when required.
- Av.4: Install door opening and closing mechanisms that is easier to operate.
- Av.5: Floor surface material should be non-slippery, non-reflective, level and even.

3) *Activity*

Residential houses as in our case study are characterized by the highly dynamic flow of people through the space. In such scenarios, it is critical to ensure smooth flow of people in order to avoid inconveniences. This fluctuation of people in transit moving from one room to another give rise to a complex dynamic crowded scenario that is more than a challenge for robotics researchers. In general, the service robots to be deployed are not only expected to flawlessly detect both the static as well as the dynamic set of people, and other objects but also update its map while planning its future activities based on the traffic information. Robotic researchers have been constantly improving the robotic hardware and software algorithms for better robot navigation [30], human robot interaction [31], obstacle avoidance [32], goal recognition [33] and path planning [34] within a given space. However, numerous challenges remain unsolved due to the complex and dynamic nature of the situation. Activity design involves optimization of traffic flow involving people, goods, and robots achieved through selection of best suitable mechanisms, their dimensions, and placing them appropriately. Below are the design guidelines derived:

- Ac.1: Provide design features to aid robots in recognizing traffic intensity in various regions of the space. Strategies for defining such spaces and routes will use those listed in the observability principle.
- Av.2: Ensure appropriate integration or segregation of accessible routes for robots and artifacts.
- Av.3: Allow for sufficient width, and height for the pathway to accommodate the expected flow of human and robots in order to avoid accidents.
- Ac.3: Reduce the human-robot interaction by scheduling the access to critical spaces.
- Ac.4: Warn people about the presence of robots using appropriate signs.
- Av.5: Any special landmarks/adaptations (like tactile surfaces) for other user groups should be segregated from navigating paths of robots to avoid conflict between user groups.

4) *Safety*

Government policies and international standards have normally associated robotics safety to the analysis of dangerous conditions that threaten human security when working with robots, principally in industrial environments [35]–[37]. We depart from this perspective by extending safety as a principle that ensures the protection of robots against environmental hazards that can cause, for example, fallings, loss of power autonomy, or other irreversible failure situations, and focuses on the prevention of human-robot and robot-robot collisions. In general, safety principle ensures that every human, robot and objects that use a shared space would be able to move and co-exist under least hazards or risks. Some of these objectives are partially handled by other design principles previously discussed, in particular, by the accessibility and activity principles. But, to complement such design criteria and cover the global goals of the safety principle, as it is here understood, the next guidelines are:

- S.1: Use clearly recognizable signs on stairs and steps, or when the surface type or level changes, to prevent robot fallings. Such indications will follow the strategies indicated in the observability principles.
- S.2: Provide self-charging spaces in selected areas to avoid disruptions caused by loss of power.
- S.3: Keep outdoor and indoor areas free from obstacles or slippery elements. Provide indications for robot safety following the activity principles.
- S.4: Supply level platforms at the end of ramps for allowing the robot to perform tasks (e.g. open or close doors that meet the accessibility principle) without rolling backwards.
- S.5: Ensure sufficient protection for the pathway edges to avoid any falls.
- S.6: Select appropriate height and width for wall/furniture projections to avoid obstruction of pathways.

III. Experimental Validation

An office setting within a school was chosen to conduct the experimental validation of the proposed design principles in a real world scenario. The area of the office under study was 9 square meters. In the experiments performed, we compared the performance of Roomba in terms of percentage cleaned floor area for default arrangement of the room to an inclusive arrangement based on the proposed design principles. To achieve that, we removed all the furniture and other artifacts out of the room leaving it empty and then scattered a pre-prepared dust mixture randomly all over the floor. After which we moved in the furniture and other artifacts to their original locations within the room and deployed the robot for the cleaning mission. Once the robot finished operation, we removed the furniture and other artifacts again out of the room which clearly indicated the unclean areas. We captured bird's view images of the emptied room using a camera mounted on the ceiling following which the images were used to compute the percentage of area cleaned of the entire room area using image processing tools. The process was again repeated for a new spatial setting that follows the proposed design principles. Both the test cases involved a constant set of functional artifacts and furniture. In the latter case, spatial parameters including furniture choices and their layout arrangements, lighting scheme, electrical layouts, wall texture and color were adapted based on the design principles with the objective of improving robot performance. While making adaptions for an inclusive space for the robot, efforts were taken to ensure the interest of primary human stakeholder was given due considerations. A dust mixture comprising of sesame seeds, rice and hair was used in both the experimental scenarios that was scattered uniformly over the defined room area.

Our experiments started with the computation of percentage cleaned area in default room setting where robot cleaned the uniformly scattered dust mixture with no changes being made to the spatial layout. Following which, we designed an inclusive setting for the same room using the four design principles proposed in this paper achieved through adaption of the spatial variables. In our experiments, we only considered three spatial variables for adaptation namely lighting, furniture and wall surfaces. Keeping a constant set of functional furniture, we choose the ones that have a height clearance that allow Roomba to access under it and replaced the rest with inclusive ones. Furniture were also arranged in a systematic way that does not block Roomba in accessing corners and to prevent Roomba from wedging in between corners and getting stuck in corner. All the furniture was of a lighter shade colors to have an advantage for Roomba's sensors to detect, avoid and access more space for cleaning. Electrical cords were also arranged properly and placed in a round base box under the table desk. Simple block of decks of about 10 cm each were placed under the table desk to lift the desk table to an appropriate height that allow Roomba to clean under it. Chairs were placed with better accessible spaces around them to allow Roomba to maneuverer. Lighting scheme was altered to be more homogeneous at around 500 lux as verified with the lux meter. Transparent wall surfaces were covered with light colored wall papers. Any unevenness in the floor surfaces was corrected to minimize false alarms in cliff detection. Once realizing the adaptations, the robot was deployed for cleaning mission and percentage cleaned area was computed for the inclusive spatial setting. The experimental setting for default and inclusive scenarios are presented in Figure 4.

Comparison of the results from the experiments clearly indicated that the latter resulted in improved robot's cleaning performance. Roomba covered 92% of the complete room area in an inclusive setting as compared to 71% in the default setting resulting in an improvement of 21% for a robot friendlier spatial arrangement. One major contributor to the poor performance in default setting was the occurrence of false alarms linked to cliff detection wherein the robot left areas of the room unclean as it sensed an obstacle when there was not any. The false alarms were often contributed as a result of the color and texture of the floor and wall as well as the non-homogenous lighting scheme put in place for the default scenario. This result is significant given that the unclean area in the default setting would require additional human efforts to be cleaned even after a dedicated robot was deployed for automating the task. It is therefore evident that a robot inclusive spatial arrangement not only results in an improved robot performance but also minimizes time and efforts for human users. Also, the number of collisions witnessed between the robot and other spatial artifacts including walls were much lesser in the inclusive setting as compared to the default setting. Such increased collision observed in default setting would lead to shorter life time of the bump sensors in the robots as well leading to frequent need for maintenance. Another key outcome from the experiment is that the Roomba robot took a lesser time of 21 minutes to clean the inclusive setting as compared to 33 minutes for the default setting. This was mainly contributed due to the easiness to access and manoeuvre between furniture in an inclusive space as compared to the default one. Such a reduction in time by 57% to complete mission contributes not only to improved effectiveness but also the power efficiency as the robot can operate for longer hours for the same charging cycle.

Default Setting *Inclusive Setting*

Figure 4. *Experimental Cases*

IV. CONCLUSION

Given the current limitations of service robots in performing reliable autonomous works in dynamic human environments, we suggest here a "design for robot" approach to complement the conventional "designing robot" approach with an objective of overcoming the multiple research challenges identified by roboticians. The approach suggests designing and adapting spaces and its component variables such as lighting, furniture, flooring and walls to be suitable for the deployment of robots, a perspective that departs from the usual approach of optimizing the components technologies such as perception, action, and cognition without any inclusive adaptations to the operating environments.

In particular, we derived four exemplary design principles, namely, observability, accessibility, activity, and safety using an inductive research methodology that support the successful deployment of residential floor cleaning robot, the Roomba. Experiments conducted with the floor cleaning robot have clearly validated the efficacy of the proposed robot inclusive approach and design principles. The cleaning performance measured by the floor coverage was found to be

21% higher in an inclusive space as compared to a default arrangement while retaining the interest of the human stakeholders. This work is the first step towards our long-term objective: to develop a handbook of design methods, principles and best practices for designing robot inclusive spaces to be used by roboticians, architects and designers.

The design principles presented here are illustrative rather than exhaustive and have been developed based on a case study and framed within the service robotics literature. Future work will involve validation of these design principles in the field, their application to generic scenarios and exhaustiveness through experimental trials. Since the analysis of design principles herein presented reduces the robot intelligence to a single dimension, the robot's hardware cost, further work should be carried out to extend the proposed directions to more complex performance indicators. Moreover, a simulator is being developed as a part of future work that automatically synthesis robot friendly interior scenes by assigning and optimizing the cost function that represents the design principles defined.

REFERENCES

1. J. W. Robinson et al., "Towards an architectural definition of normalization: design principles for housing severely and profoundly retard adults", Sep 1984.
2. V. Regnier, "Design principles and research issues in housing for the elderly," in *Proc. Life-Span Design for Residential Environment for An Ageing Population*, Washington DC, 1993.
3. M. G. Richards et al., "Design principles for survivable system architecture," In *2007 1st Annual IEEE Syst. Conf.*, Honolulu, HI, 2007, pp.1-9.
4. F. Mäyrä and T. Vadén, "Ethics of living technology," *Environments*, vol. 7, no. 2, pp. 171-196, 2004.
5. S. D. Bergen et al., "Design principles for ecological engineering," *Ecological Eng.*, vol. 18, no. 2, pp. 201-210, 2001.
6. B. R. Connell et al. (1997, Apr 1). *The principles of universal design (2nd ed.)* [Online]. Available: http://www.disabilitymonitor-see.org/documents/dmi2_eng/annex2.pdf
7. M. F. Story, "Maximizing usability: The principle of universal design," *Assistive Technology*, vol. 10, no. 1, pp. 4-12, 1998.
8. W. Gueaieb and M. S. Miah, "An intelligent mobile robot navigation technique using RFID technology," *IEEE Trans. Instrum Meas*., vol. 57, no. 9, pp. 1908-1917, Sep. 2008.
9. Y. Hada and K. Takase, "Multiple mobile robot navigation using the indoor global positioning system (iGPS)," in *Proc. 2001 IEEE/RJS Int. Conf. Intelligent Robots and Systems*, 2001, Maui, HI, pp. 1005-1010.
10. G. Beccari et al., "Vision-based line tracking and navigation in structured environments," in *Proc. 1997 IEEE Int. Symp. Computational Intel. in Robotics and Automation*, Monterey, CA, 1997, pp. 406-411.
11. R. E. Mohan, C. A. Acosta Calderon, C. Zhou, P. K. Yue, L. Hu, and B. Iniya. "An embedded vision system for soccer playing humanoid robot: Robo-Erectus Junior." In *Int. Conf. Signal Processing, Communications and Networking (ISCSN)*. 2008.
12. D. Brugali et al. (2010, Sep. 01). *Best Practice in Robotics (BRICS)* [Online]. Available: http://www.best-of-robotics.org/pages/publications/BRICS_Deliverable_D7.1.pdf.
13. J. L. Krichmar, "Design principles for biologically inspired cognitive robotics," *Biologically Inspired Cognitive Architectures*, vol. 1, pp. 73-81, Jul. 2012.
14. R. Pfeifer and J. Bongard, *How the body shapes the way we think: A new view of intelligence*. Cambridge, MA: MIT press 2007.
15. K. Kawamura et al., "Design philosophy for service robots," *Robotics and Autonomous Syst.*, vol. 18, no. 1, pp. 109-116, Jul. 1996.
16. A. J. Soroka et al., "Challenges for service robots operating in non-industrial environments," in *10th IEEE Int. Conf. Ind. Informatics*, 2012, pp. 1152-1157.
17. iRobot Corporation. (2013, July 10). *Our History* [Online]. Available: http://www.irobot.com/en/us/Company/About/Our_History.aspx
18. iRobot Corporation. (2013, Jan. 15). *Needham Growth Conference* [Online]. Available: https://www.google.com.sg/url?sa=t&rct=j&q=&esrc=s&source=web&cd=8&cad=rja&ved=0CF0QFjAH&url=http%3A%2F%2Fphx.corporate-ir.net%2FExternal.File%3Fitem%3DUGFyZW50SUQ9NDkwMzc0fENoaWxkSUQ9NTI3MzY5fFR5cGU9MQ%3D%3D%26t%3D1&ei=FAbwUc-kEIzirAfv44HQCA&usg=AFQjCNHxUZzhrNII5bMQUdRBNh5MvY2Bvg&sig2=ScXnGMg0iPiHq2c10gZENw
19. J.-Y. Sung et al., "Pimp my Roomba: Designing for personalization" in *Proc. SIGCHI Conf. Human Factors in Computing Syst*., New York, 2009, pp. 193-196.
20. P. Nattharith, "Fuzzy logic based control of mobile robot navigation: A case study on iRobot Roomba platform," *Scientific Research and Essays*, vol. 8, no. 2, pp. 82-94, Jan. 2013.
21. D. Wu and H. Su, "An improved probabilistic approach for collaborative multi-robot localization." in *2008 IEEE Int. Conf. Robotics and Biominetics*, Bangkok, 2009, pp. 1868-1875.
22. P. Saulnier et al., "Using bio-electrical signals to influence the social behaviours of domesticated robots." in *Proc. 4th ACM/IEEE Int. Conf. Human Robot Interaction*, New York, 2009, pp.263-264.
23. P. Kamol et al., "RFID based object localization system using ceiling cameras with particle filter," in *Future Generation Commun. and Networking (FGCN 2007)*, Jeju, 2007, pp. 37-42.
24. W. M. K. Trochim. (2006, Oct. 20). *Research Methods Knowledge Base, Deduction & Induction* [Online]. Available: http://www.socialresearchmethods.net/kb/dedind.php
25. S. Vikramjit, S. M. Skiles, J. E. Krager, K. L. Wood, D. Jensen, and R. Sierakowski. "Innovations in design through transformation: A fundamental study of transformation principles," *Journal of Mechanical Design*, Vol. 131, 2009.
26. A. Y. Saab, *Seeing, Hearing, and Smelling the World*. New York: Infobase Publishing, 2009.
27. Usability First. (2013, Jul. 10). *Principles of Accessible and Universal Design* [Online]. Available: http://www.usabilityfirst.com/about-usability/accessibility/principles-of-accessible-and-universal-design/
28. US Department of Justice. (1991, Jul. 26). *Americans with Disabilities Act: 1991 ADA standards for Accessible Design* [Online]. Available: http://www.ada.gov/reg3a.html#Anchor-Appendix-52467
29. US Department of Justice. (2010, Sep. 15). *Americans with Disabilities Act: 2010 ADA standards for Accessible Design* [Online]. Available: http://www.ada.gov/regs2010/2010ADAStandards/2010ADAstandards.htm
30. Y. Morales et al., "Autonomous robot navigation in outdoor cluttered pedestrian walkways," *J. Field Robotics*, vol. 26, no. 8, pp. 609-635, Aug. 2009.
31. R. E. Mohan, W. S. Wijesoma, C. A. A. Calderon, C. Zhou, "Experimenting false alarm demand for human robot interactions in humanoid soccer robots" *International Journal of Social Robotics*, Vol. 1, No. 2, pages 171-180, 2009.
32. W. H. Huang et al, "Visual navigation and obstacle avoidance using a steering potential function," *Robotics and Autonomous Syst.*, vol. 54, no. 4, pp. 288-299, Apr 2006.
33. K. Welke et al., "Autonomous acquisition of visual multi-view object representations for object recognition on a humanoid robot," in *2010 IEEE Int. Conf. Robotics and Automation (ICRA)*, Anchorage, AK, 2010, pp. 2012-2019.
34. F. Valero et al., "Trajectory planning in workspaces with obstacles taking into account the dynamic robot behaviour," *Mechanism and Mach. Theory*, vol. 41, no. 5, pp. 525-536, May 2006.
35. Ministry of Business, Innovation, and Employment, New Zealand. (2013, Jun. 27). *Robot safety* [Online]. Available: http://www.mbie.govt.nz/what-we-do/mbie-case-studies/mbie-commercialisation-partner-network-%20helps-make-award-winning-robots-reality/

36. US Department of Labor, Occupational Safety and Health Administration, Office of Science and Technology Assessment. (1987, Sep. 21). *Guidelines for robotics safety* [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=1703
37. International Standards Organization (ISO). (2011, Jul. 1). *ISO 10218-1:2011 Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots (2nd ed.)* [Online]. Available: http://www.iso.org/iso/catalogue_detail.htm?csnumber=51330