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DESIGN PRINCIPLES FOR ROBOT INCLUSIVE SPACES

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ABSTRACT

Social and service robotics deals with robot applications in, for instance, rehabilitation and health care, logistics, search and rescue, and homecare. The civil and economic relevance of these robots is more than evident. However, in spite of the tremendous advances in artificial intelligence, control, and sensing in the past decades; social and service robots are still far away of working autonomously in dynamic human-related spaces. Given this scenario, instead of developing robots with complex skills using a full suite of sensors to solve issues appearing in a real environment, the norm in robotics, we propose an augmentative approach that aims at designing social spaces of service robots through uncomplicated actions that would enable robots to overcome their limitations, and accomplish their missions with ease. In particular, we present a set of design principles namely, observability, accessibility, manipulability, activity, and safety for urban spaces involving sociable robots living and working alongside humans. The suggested principles are defined and analyzed using as case study a commercial mobile robot platform that performs a logistics task in a Singaporean hospital.

Keywords: robot inclusive spaces, design for X, service design, design principles, robotics

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1 INTRODUCTION

The design of robots and the design of everyday living spaces are largely disconnected. This represents a major challenge for service robotics research because such robots must efficiently and safely work beside people in dynamic and highly unpredictable built environments such as hospitals, homes, offices, schools and public places. This design goal has motivated experts to constantly improve the performance and abilities of robots. Relevant examples of recent achievements include BigDog, a robotic pack mule by Boston Dynamics, the autonomous robotic vacuum cleaner iRobot Roomba, and Kiva, an automated material handling robot by Kiva Systems. In spite of these important results and the significant advances in artificial intelligence, mechanics, sensing, actuation, and control, service robots are still far from working autonomously and meaningfully in realistic human-related environments. The uncontested assumption in technology has been to equip robots with increasingly complex skills using a full site of sensors to solve issues appearing in real environments. Designing robots that adapt to a world that is not designed for them, is a key reason why service robots remain an unmet promise. This paper characterizes cross-disciplinary opportunities for collaboration between architects, designers and roboticians in order to design everyday spaces and products that address the requirements of all stakeholders, including robots.

The design of new spaces and devices such as lighting and furniture traditionally responded to the needs of healthy adult populations until appropriate design principles were introduced in response to special segments including elderly, children and user groups with physical disabilities. For example, Robinson et al. (1984) propose guidelines for housing severely and profoundly retard adults, Regnier (1993) discusses principles in housing for the elderly, Mäyrä and Vadén (2004) present rules for proactive home environments, Richards et al. (2007) show a framework for the achievement of survivable system architecture, and Bergen et al. (2001) identify elements to guide those practicing ecological engineering. Moreover, the Center for Universal Design (1997) promotes seven principles widely used in the design of products and environments to be usable by all. In contrast, architects and designers are largely unaware of the efforts by the robotics community to create robots for a home/office in the near future, and the ensuing challenges that exist ahead due to the complex nature of the built environment and the dynamic nature of the people living within it.

This paper formulates the need for relevant principles and guidelines that support the design of robot-friendly places and products to enable their introduction in everyday life and thus reap their numerous potential benefits. Numerous works have targeted adaptations to living spaces through the use of wall embedded RFID sensors (Gueaieb, 2008) indoor GPS (Hada, 2001), and visual markers (Becarri, 1997, Cassinis, 2005). Such solutions lack a holistic approach to robot inclusive design often ignoring the aesthetic needs of the human users, requiring expensive complex sensors and its maintenance, and dedicated space allocated for robots to function preferably with clear segregation from humans. In the robotics community, the work has mainly focused on specifying key elements for better robot systems. For instance, Brugali et al. (2010) determine principles for system openness and flexibility as these are quality factors of a robotic system and Krichmar (2012), based on the eight methodologies for intelligent agents proposed by Pfeifer and Bongard (2007), presents design elements for biologically inspired cognitive robotics. Kawamura et al. (1996) puts forward a design philosophy for service robots that emphasizes compromise and practicality in design. Although the challenges have been identified elsewhere (Soroka et al, 2012), systemic design principles that aim for seamless integration of service robots and humans in everyday environments have not been previously discussed.

Our long-term objective is to define and test design principles adopting a Design for X (DfX) approach that supports the successful incorporation of autonomous robotic systems in both indoor and outdoor spaces at minimum cost. These principles and associated methodologies must be useful for planning new architectural projects as well as for adapting existing designs. However, defining and measuring the intelligence of a robot is one of the most controversial topics in robotics (Cheok, 2006). Some researchers consider that a robot whose control schemes have been constructed and written by humans is not intelligent (Miura, 1994; Miura et al., 1996); others reduce the measure of a robot's intelligence to how humans assess their usefulness (Crandall and Goodrich, 2003) –a kind of Turing test. In this work, the intelligence of a service robot is defined generally by its capacity to perform its target duties autonomously. Thus, robot intelligence here is a systemic characteristic that can be modeled as a multivariable function depending on intrinsic characteristics of the robot such as its sensing capacity or its location and control algorithms, as well as contextual conditions that support its capacities, for example to navigate and exhibit reliable interactions with humans in its workspace. Therefore, service robotics is seen here from a distributed cognition perspective (Dror and Harnad, 2008).

In this paper we propose a set of principles inspired by universal design methods, namely: observability, accessibility, manipulability, activity, and safety for spaces involving sociable robots living and working alongside humans. A well designed robot-friendly space would allow for easy robot perception of obstacles, landmarks and artifacts of interests (observability). A well-functioning space in this context would also offer convenient navigation across the terrain and the obstacles for a given mobility mechanism of the robot (accessibility). An inclusive space design would maximize the ability of the robot to reach for, handle and interact with artifacts within that space (manipulability). Lastly, it would optimize greater human-robot interaction (activity) as well as guarantee the safety of human users and robots. These five principles are extracted inductively from a case study presented in the next section. The suggested rules aim to overcome unsolved research challenges in the robotics community when placing robots in human environments. In order to simplify the discussion on the design principles, we limit the multivariable function of robot intelligence to a single dimension in this paper: the robot's hardware cost. Future works should extend the presented ideas to more complex performance indicators. The results discussed herein are tested following a deductive approach based on the robotics literature. As suggested in (Singh et al., 2009), a combination of inductive and deductive reasoning is useful for testing the veracity and validity of the resulting methodologies.

In the remainder of the paper, the proposed design principles are defined and analyzed. To this end, a commercial mobile robot platform, performing a logistics task in a Singaporean hospital, is used as case study. The paper closes with a discussion of contributions, limitations, and prospects for further research.

2 DESIGN PRINCIPLES

2.1 Case study

Our case study involves a Singapore based hospital aiming to incorporate automated mobile bases for handling laboratory logistics such as specimen delivery to improve the workflow of healthcare staff. In the current set up, the laboratory samples are delivered to different stations manually as a part of the laboratory diagnostics process. Such stations may be located in various parts of the hospital due to the nature of the analysis required. The staff conducting these tests must stop their immediate task to collect and deliver the samples. It is a tedious, unproductive and time consuming job that can be easily done by an autonomous service robot. The deployment of mobile robot platforms will help to improve the productivity in the hospitals, by relieving the laboratory staff of this time consuming and menial work and allowing them to focus on other more important health service tasks to better serve the community. In order to fulfil the requirements of the aforementioned project, the autonomous service robot must ensure a safe navigation of samples and people. However, given the dynamic presence of humans and obstacles in a building, the autonomous navigation from one station to another is not a trivial problem. Figure 1 presents a feasibility study performed at a Singapore based hospital interested and collaborating in this project. The robot platform deployed corresponds to a slightly modified Adept PeopleBot, a differential-drive robot for service and human-robot interaction projects. This platform has 10 bumper elements and lower and upper SONAR arrays to detect objects, a full datasheet of this robot can be found in (Adept, 2012). The laboratory for which the delivery robot is being developed is one of the major health centres in Singapore; it provides services such as renal chemistry, lipids, endocrinology, and tumour markers.

2.2 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 (HHMI, 1995). 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. Depending on the task, robots are provided with different sensors, 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 proposed guidelines:

O.1: Maximize robot perception through the appropriate selection of colors, 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 (light, sound, etc.).

O.4: Put in place mechanisms that minimize environmental noises that would interfere with the robot's sensors.

Figure 1. Feasibility study involving the service robot for specimen delivery task at Singapore based hospital. The robot platform is an Adept PeopleBot.

The question is: how do we apply these guidelines? Let's take one of the basic senses as example: sight. The first step in our design process is to identify the limitations of the corresponding robot vision system for detecting, for instance, colors, texture and patterns. In robots, visual information is the most important data to model spaces and to detect changes in dynamic environments (Konno et al., 1996). Such system is composed of several algorithms (e.g. feature extraction, matching process, estimation procedures) that depend on the information given by vision sensors (Christensen and Hager, 2008). These sensors can be passive or active, depending on whether they emit energy into the environment or do not. Typical vision sensors in robotics include: Time-of-Flight (ToF) cameras (Foix et al. 2011), monocular (Royer, 2007) and stereo cameras (Adorni, 2003), and laser range scanners (Blais, 2004); each of them with its own advantages and drawbacks.

In our case study at the Singapore based hospital, PeopleBot does not have a vision sensor, that is, a light-based device. The robot is only provided with two set of SONAR arrays to interact with its world by emitting pulses of sounds and then listening to the resulting echoes. The principle of this technique, used in nature by some animals to locate and identify objects, is very simple but it is widely known that some practical problems emerge when the technique is implemented in robots. The most prominent of these issues is that related with specular reflections. When these mirror-like reflections occur, the robot loses the object, for example, a wall or a chair. The critical angle where specular reflections occur depends on the object material and its surface (Marshall, 2005).

Given the described limitation of SONAR systems; for the case at hand, instead of investing in more sophisticated sensors or developing more complex algorithms, we take an augmentative approach by adapting the spaces to overcome the defective design features. Figure 2 shows some examples of defective design features in our case study wherein specular reflection is expected to be a major problem for robot navigation. In this case, we recommend non-reflective finish for the texture of wall, window panels, and doors or colors of the artifacts placed in the environment. Simple indicators like this may be applied on horizontal (floor, ceiling) or vertical (wall) surfaces, and may be built-in or adhered. In any case, they should be discreetly applied and integrated with the architecture or interior, such as along the edges of the floor or wall or ceiling. These basic set of instructions for observability can be extended for other robot senses like visual, auditory, odor, etc.

Figure 2. Observability centered defective design feature identified in the case study at the Singapore based hospital using the observability principle.

2.3 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 (Usability First, 2012). The Americans with Disabilities Act of 1991 (ADA, 1991), that was revised by the US Department of Justice in 2010 (ADA, 2010), establishes several requirements that different spaces must fulfill 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 allows appropriate space for the robot to maneuver and manipulate the knob.

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 with a push, easier to grasp, or touchless interfaces.

Av.5: Floor surface material should be non-slippery, non-reflective, level and even.

2.4 Manipulability

In robotics, manipulation refers to the process of moving or rearranging objects in the environment by grasping, carrying, pushing, dropping, or throwing them using end effectors –e.g. robot hands or grippers-- (Mason, 2001). Autonomous skillful manipulation is essential for social and service robots. However, to date, robots can only perform successful and useful manipulations involved in complex tasks in simulation and controlled environments, or when a human tele-operates them in dynamic spaces. Kemp et al. (2007) list the characteristics that make human environments very challenging for robot manipulation. Given those characteristics, roboticians have focused on different approaches to overcome the current limitations of autonomous robot manipulation. These approaches have been categorized as perception, learning, human robot co-operation, platform design, and control (Kemp et al., 2007). However, all of these research paths follow a bottom-up approach wherein the focus is on developing robots that fit the space. However, the challenges identified for robot manipulation can be easily addressed following a top-down approach that involves spaces designed for robots. For example, "Sensory variation, noise and clutter" (Kemp et al., 2007), which refers to lighting variation, occluding objects, background sounds, and unclean surfaces in human environments, can be handled following the design guideline O.4. Next, we define a set of design guidelines for helping service robots in their manipulation tasks:

M.1: Human-hand-operated or electronically controlled fixtures or, in general, objects that may be manipulated by a robot must have a shape, mass and material that is easy to reach, grasp, move, arrange, operate, or control.

M.2: Artifacts that require robot manipulation should be installed at reachable and consistent heights and ranges.

M.3: Allow for manipulation with only single-end effector that does not require wrist or fine dexterity.

In our case study at the Singapore based hospital, the robot does not have to directly manipulate objects in order to meet its tasks. However, for example, some handles or locks on accessible doors, as the one presented in Fig. 2(left), would pose a serious problem as it requires complex and fine manipulation skills. We recommend the use of sensor enabled automatic doors that would detect the presence of a passerby including the specimen carrying robot at a predefined range and automatically open or close. Such an automatic door would eliminate the need for the robot to engage in a complex manipulation task as well as the tremendous developmental efforts, time and cost associated with it.

2.5 Activity

Hospital laboratories as in our case study are characterized by the highly dynamic pulsating flow of people and objects like trolleys through the space. The particular laboratory of interest is accessed by over hundred healthcare and supporting personnel every single day. In such scenarios, it is critical to ensure smooth flow of people and objects in order to avoid cumulative queues. This fluctuation and the amount of people as well as objects in transit from one test station to another give rise to a complex dynamic crowded scenario that is more than a challenge for robotics researchers. The delivery 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 (Morales et al. 2009), human robot interaction (Hatfield, 2005), obstacle avoidance (Huang et al, 2006), goal recognition (Welke et al, 2010) and path planning (Valero et al, 2006) 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 (auto walkways, elevators, one way paths, etc.), their dimensions, and placing them appropriately. Next, following the ideas discussed about the activity principle, some design guidelines are proposed:

Ac.1: Provide design features to aid robots in recognizing spaces for social interaction and separation, and to distinguish between public and private areas. 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 when people's activity differs from that of robots. If not possible, supply people with identifiers that robots can easily distinguish but are transparent for humans.

Ac.4: Warn people, especially crowds, about the presence of robots using warning signs and posters.

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.

For instance, Fig. 3 presents some of the defective design features that were identified in our case study.

Figure 3 shows three cases of special adaptations to flooring namely, tactile surface indicators, rain water drainage cover, and a thick entrance floor mat that intercepts the pathway of the robot with potential negative consequences including risk of fall, and obstruction as well as conflict between the two dynamic user groups in the case of accessing tactile surface. In this case, we recommend proper segregation of tactile surface indicators from the pathway of the robot. In order to assure the successful integration of services robots; all spaces, routes and fixtures or objects have to be accessible to facilitate the movement of robots and their roles as companions or helpers. For example, for the case of robots with a role as companions to elderly, bathrooms should be provided with roll-in shower and controls at side walls instead of under the shower head. We indeed envisage contributing to an extension of ADA to set specific requirements of public and private spaces for the accessibility of robots in the next few years.

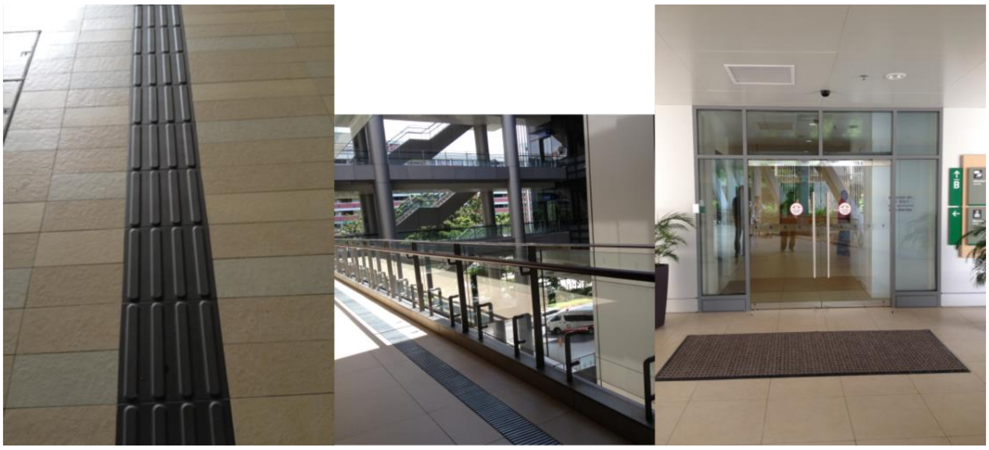

Figure 3. Activity centered defective design feature identified in the case study at the Singapore based hospital using the activity principle.

The proposed design principles minimize the intersection between the workspace of people and that of robots whenever humans do not require the assistance of robots, and they maximize the intersection between the two when people and robot activities do match. The supposed situation at the hospital involving the delivery robot directly hinders the mobility of people as both use the same pathways, in other words, the intersection between human and robot workspaces is very high with minimal overlapping goals. Our recommendation is to establish specific passages for the robot in at least the crowded corridors as observed from the people circulation studies, just as bicycle lanes are designed in urban planning.

2.6 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 (MBIE, 1987; OSHA, 1987; ISO, 2011). 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 proposed:

S.1: Use 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 projections to avoid obstruction of pathways.

3 CONCLUSIONS

Given the current limitations of social and service robots of performing reliable autonomous works in dynamic human environments, we suggest here a top-down approach to overcome the multiple research challenges identified by roboticians. The approach suggests designing and adapting spaces to be suitable for the deployment of robots, a perspective that departs from the usual bottom-up approach followed in robotics where robots must fit the existing environments. In particular, we propose five exemplary design principles, namely, observability, accessibility, manipulability, activity, and safety that support the successful incorporation of autonomous robotic systems in indoor and outdoor spaces. This work is the first step towards our long-term objective: to define design methodologies of minimum cost and useful for planning new civil and architectural projects as well as for modifying existing spaces for a real human-robot integration in indoor and outdoor conditions.

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, real experiments comparing scenarios before and after applying changes according to the five design principles have to be performed in order to validate the proposed approach.

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REFERENCES

ADA (1991) *'1991 ADA standards for accessible design'*, US Department of Justice, Americans with Disabilities Act.

ADA (2010) *'2010 ADA standards for accessible design'*, US Department of Justice, Americans with Disabilities Act.

Adept (2011) *'PeopleBot*, http://www.mobilerobots.com/Libraries/Downloads/PeopleBot-PPLB-RevA.sflb.ashx (20 December 2012).

Adorni, G., Mordonini, M., Cagnoni, S., and Sgorbissa, A. (2003, June). Omnidirectional stereo systems for robot navigation. *In Computer Vision and Pattern Recognition Workshop, 2003. CVPRW'03*. Conference on (Vol. 7, pp. 79-79). IEEE.

Beccari, G., Caselli, S., Zanichelli, F., and Calafiore, A. (1997, July). Vision-based line tracking and navigation in structured environments. *In Computational Intelligence in Robotics and Automation, 1997. CIRA'97., Proceedings., 1997 IEEE International Symposium on* (pp. 406-411). IEEE.

Bergen, S.D., Bolton, S.M., and Fridley, J.L (2001) 'Design principles for ecological engineering', *Ecological Engineering*, vol. 18, no. 2, pp. 201-210.

Blais, F. (2004) 'Review of 20 years of range sensor development', *Journal of Electronic Imaging*, vol. 13, no. 1, pp. 231-243.

Broggi, A., Zelinsky, A., Parent, M., and Thorpe, C.E. (2008) 'Intelligent vehicles', in Siciliano, B. and Oussama, K. (eds.) (2008) *Handbook of Robotics*, Springer, pp. 1175-1198.

Brugali, D., Scandurra, P., Gargantini, A., Gherardi, L., Luzzana, A, and Pedroni, M. (2010) 'Design principles, implementation guidelines, evaluation criteria for system openness and flexibility and use case implementations', *Best Practice in Robotics (BRICS) - Deliverable D7.1*, The European Union's Seventh Framework Programme.

Cassinis, R., Tampalini, F., and Fedrigotti, R. (2005). Active markers for outdoor and indoor robot localization. *Proceedings of TAROS*, 27-34.

Center for universal Design (1997) *'Principles of universal design'*, Center for Universal Design, North Carolina State University.

Cheok, K.C. (2006) 'Gauging Intelligence of Mobile Robots', in *Mobile Robotics, Moving Intelligence*, Buchli, J. (Ed.), InTech.

Christensen, H. and Hager, G. (2008) 'Sensing and estimation', in Siciliano, B. and Oussama, K. (eds.) (2008) *Handbook of Robotics*, Springer, pp. 87-107.

Crandall, J.W., and Goodrich, M.A. (2003) 'Measuring the intelligence of a robot and its interface', *Proceedings of the 2003 Performance Metrics for Intelligent Systems Workshop (PerMIS'03)*, September 16-18, Washington, DC.

Dror, I. E., & Harnad, S. R. (2008). Cognition distributed: How cognitive technology extends our minds (Vol. 16). John Benjamins Publishing Company.
Foix, S., Alenya, G., and Torras, C. (2011) 'Lock-in Time-of-Flight (ToF) Cameras: A Survey', *IEEE Sensors Journal*, vol.11, no.9, pp.1917-1926.
Gueaieb, W., and Miah, M. S. (2008). An intelligent mobile robot navigation technique using RFID technology. *Instrumentation and Measurement, IEEE Transactions on, 57(9), 1908-1917.*
Hada, Y., and Takase, K. (2001). Multiple mobile robot navigation using the indoor global positioning system (iGPS). *In Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on* (Vol. 2, pp. 1005-1010). IEEE
Hatfield, U. K. (2005). Companions: Hard Problems and Open Challenges in Robot-Human Interaction.
HHMI (1995) *'Seeing, Hearing, and Smelling the World'*, Biomedical Research Reports, Howard Hughes Medical Institute.
Huang, W. H., Fajen, B. R., Fink, J. R., and Warren, W. H. (2006). Visual navigation and obstacle avoidance using a steering potential function. *Robotics and Autonomous Systems*, 54(4), 288-299.
ISO (2011) *'ISO 10218-1:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots*, International Standards Organization.
Katabira, K., Zhao, H., Nakagawa, Y., and Shibasaki, R. (2008) 'Real-Time Monitoring of People Flows and Indoor Temperature Distribution for Advanced Air-Conditioning Control', *11th International IEEE Conference on Intelligent Transportation Systems*, pp.664-668.
Kawamura, K., Pack, R. T., Bishay, M., and Iskarous, M. (1996). Design philosophy for service robots. *Robotics and Autonomous Systems*, 18(1), 109-116.
Kemp, C.C., Edsinger, A., Torres-Jara, E. (2007) 'Challenges for robot manipulation in human environments', *IEEE Robotics & Automation Magazine*, vol.14, no.1, pp.20-29.
Konno, A., Uchikura, R., Ishihara, T., Tsujita, T., Sugimura, T., Deguchi, J., Koyanagi, M., and Uchiyama, M. (2006) 'Development of a High Speed Vision System for Mobile Robots', *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.1372-1377.
Krichmar, J.L. (2012) 'Design principles for biologically inspired cognitive robotics', *Biologically Inspired Cognitive Architectures*, vol. 1, July, pp. 73-81.
Marshall, B. (2005) *'An Introduction to Robot Sonar*, http://www.robotbuilder.co.uk/Resources/ Articles/138.aspx (20 December 2012).
Mason, M.T. (2001) *'Mechanics of Robotic Manipulation'*, MIT Press
Mäyrä, F. and Vadén, T. (2004) 'Ethics of living technology: design principles for proactive home environments', *HumanIT: Journal for Information Technology Studies as a Human Science*, vol. 7, no. 2, pp. 171 – 196.
MBIE (1987) *'Robot safety'*, Ministry of Business, Innovation, and Employment, New Zealand.
Miura, H. (1994) 'What is robot intelligence', *IEEE Symposium on Emerging Technologies and Factory Automation*, pp.2-9.
Miura, H., Yasuda, T., Fujisawa, Y.K., Kuwana, Y., Takeuchi, S., and Shimoyama, I. (1996) 'What is robot intelligence?', *Proceedings of the 1996 IEEE IECON 22nd International Conference on Industrial Electronics, Control, and Instrumentation*, vol.1, pp.XLI-XLIV.
Morales, Y., Carballo, A., Takeuchi, E., Aburadani, A., and Tsubouchi, T. (2009). Autonomous robot navigation in outdoor cluttered pedestrian walkways. *Journal of Field Robotics*, 26(8), 609-635.
OSHA (1987) *'Guidelines for robotics safety'*, US Department of Labor, Occupational Safety and Health Administration, Office of Science and Technology Assessment.
Pfeifer, R. and Bongard, J. (2007) *'How the body shapes the way we think: A new view of intelligence'*, Cambridge, MIT Press.
Regnier, V. (1993) 'Design principles and research issues in housing for the elderly' in American Association of Retired Persons and Stein Gerontological Institute (eds.) (1993) *Life-Span Design of Residential Environments for an Aging Population*, American Association of Retired Persons, pp. 21-28.
Richards, M.G., Hastings, D.E., Ross, A.M., and Rhodes, D.H. (2007) 'Design principles for survivable system architecture', *2007 1st Annual IEEE Systems Conference*, pp.1-9.
Robinson, J.W., Thompson T., Emmons, P., and Myles, G. (1984) *'Towards an architectural definition of normalization: design principles for housing severely and profoundly retarded adults'*, Center for Urban and Regional Affairs, University of Minnesota.

Royer, E., Lhuillier, M., Dhome, M., and Lavest, J. M. (2007). Monocular vision for mobile robot localization and autonomous navigation. *International Journal of Computer Vision*, 74(3), 237-260.
Singh, V., Skiles, S.M., Krager, J.E., Wood, K.L., Jensen, D., and Sierakowski, R. (2009) 'Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles', *Journal of Mechanical Design*, vol. 131, August, pp. 081010-1-08010-18.
Soroka, A.J.; Renxi Qiu; Noyvirt, A.; Ze Ji, "Challenges for service robots operating in non-industrial environments," 10th IEEE International Conference on Industrial Informatics (INDIN), pp.1152-1157.
Usability First (2012) *'Principles of Accessible and Universal Design'*, http://www.usabilityfirst.com/about-usability/accessibility/principles-of-accessible-and-universal-design/
Valero, F., Mata, V., and Besa, A. (2006). Trajectory planning in workspaces with obstacles taking into account the dynamic robot behaviour. *Mechanism and machine theory*, 41(5), 525-536.
Welke, K., Issac, J., Schiebener, D., Asfour, T., and Dillmann, R. (2010, May). Autonomous acquisition of visual multi-view object representations for object recognition on a humanoid robot. *In Robotics and Automation (ICRA), 2010 IEEE International Conference on* (pp. 2012-2019). IEEE.
Wisspeintner, T., van der Zan, T., Iocchi, L., and Schiffer, S. (2010). Robocup@ home: Results in benchmarking domestic service robots. *RoboCup 2009: Robot Soccer World Cup XIII*, 390-401.