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# Toward a framework for robot-inclusive environments

Ning Tan [a,*], Rajesh Elara Mohan [b], Akiko Watanabe [c]

[a] SUTD-MIT International Design Centre, Singapore University of Technology and Design, Singapore
[b] Engineering Product Development, Singapore University of Technology and Design, Singapore
[c] Department of Architecture, Tokyo Denki University, Japan

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ABSTRACT

Robots are capable of navigating and performing tasks in a wide range of environments. Yet, there is no systematic research on the relationship between robot and environments. In this paper, the intention is to place in context the importance of co-consideration of environments and robots for creating an intelligent living environment. As such, we develop a framework linking both robots and environments. The framework consists of (1) the robot-inclusiveness which measures how inclusive the environment for the robot is, (2) a taxonomy which classifies robot-environment interaction into five categories, (3) five design criteria and guidelines which support the design and evaluation of autonomous robotic systems in indoor and outdoor environments.

## 1. Introduction

Nowadays, more and more robots are emerging in a wide range of social environments, including both domestic spaces and public areas. We can classify these environments into two categories. The first category is only the spaces where the robots are doing specific tasks. There is no any interaction between the robot and the environment. One typical case of the first category is conventional industrial robots that have been widely used in a lot of factories and workshops. Unmanned factories are emerging increasingly. In this case, the robots concentrate on doing their jobs, such as welding [1], assembly of automobile bodies [2], product packaging [3], etc. There is no interaction or information exchange between the robot and the environment. In recent years, the application scenes of robots have been shifted from the conventional factory environments to public and domestic environments. Service robots are getting popular in shopping malls. With the growing number of elderly people, assistive living technologies are demanding for present and future life. For industrial workshops and public indoor areas to private domestic space, more and more robots are playing important roles for improving productivity efficiency, providing public service, and offering private assistance.

The second category is that the robots involve in acting on and interact with the environments, which means the robots will make an impact on the environments. In this case, robots are more interactive with the environments and even responsible for building, cleaning, or interacting with the environments. Moreover, the interaction intensity or degree (i.e., the effect on the environment from the robot) varies depending on different tasks. A floor cleaning robot can vacuum the dirt and trashiness is much less invasive to the environment than a construction operation task [4] performed by robots where the robot contributes to carry the materials (e.g., bricks and concrete) and build the construction additively. The industrial manipulators are being used in some new scenarios, such as tile placement [5]. Meanwhile, there have been some work on building maintenance, and cleaning, such as for bridge maintenance [6], external wall maintenance, facade windows cleaning [7,8], tunnel inspection [9], additive fabrication [10], etc.

Robots with different levels of autonomy are facing different environment settings which impose different degrees of difficulties and complexities on the robots. For example, a wheeled robot is efficient in moving in a house or shopping mall with smooth ceramic tiles; however, the same robot may not be able to do the same things in a mess workshop with pipes, cables, components on the floor. A static environment would be much easier than a dynamic environment for the robot therein. For example, in a manless warehouse, the robot can transport the heavy goods from one storage rack to another autonomously; a robot (e.g., Adept PeopleBot [11]) for specimen delivery in hospital would need additional capabilities like recognition of human or moving objects and obstacle avoidance.

Since the environment is so essential for the robot autonomy and performance, in this paper, we propose a novel framework that combines robots and spaces. A complicated environment does not mean to

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* Corresponding author.

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be robot-friendly, because a complicated or overdesigned environment might focus on the aesthetics, but might not take into account of the existence of robots at all.

The rest of this paper is organized as follows. Section 2 reviews the relevant studies and proposes a framework for environment design considering robots. Section 3 discusses the robot-inclusiveness of the environment which is the first component of the framework. Section 4 proposes a taxonomy of relationship between robots and environments. Section 5 presents the design criteria and corresponding key design guidelines of environments. The correlations between the three proposed facets are presented in Section 6. Finally the paper is concluded in Section 7.

## 2. Related work and our contributions

Human-robot interaction has been intensively studied and a lot of related articles have been published since last decades, where a taxonomy and its updated version of human-robot interaction were proposed in [12] and [13]. They claimed that using these classifications to define individual HRI (Human-Robot Interaction) systems will allow for the comparison of different HRI approaches in many different categories. In [14], it is claimed that human-robot interaction differs from human-computer interaction in four dimensions, two of which are related to the factor of environments. However, the corresponding taxonomy for robot-environment relationship is missing.

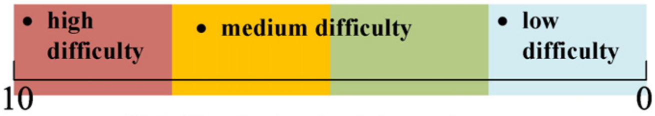
Autonomy is a critical criterion related to human-environment relationship and varies widely across robot platforms. A lot of literature dealing with levels of robot autonomy are focusing on human-robot interaction. The autonomy levels for unmanned systems were developed by taking into account three factors such as task complexity, human interaction, and environmental difficulty [15,16]. The measure of environmental difficulty is decomposed into categories including static environment, dynamic environment, electronic/electromagnetic environment, mobility, mapping and navigation, urban environment, rural environment, and the operational environment.

A framework was proposed for levels of robot autonomy in human-robot [17]. According to the definition of autonomy proposed by Beer et al. [17]:

> “*The extent to which a robot can sense its environment, plan based on that environment, and act upon that environment with the intent of reaching some task-specific goal* (*either given to or created by the robot*) *without external control*”,

we can know that given a specific robot, the robot autonomy decreases when environment difficulty increases [18]. Therefore, we can depict this relationship in Fig. 1. To increase the robot autonomy, on one hand, the robot should be developed to be more powerful that can navigate and work in the environment; on the other hand, we could design a less complex environment where the robot can fit more. This is a trade-off between cost, technology development level, and performance expectation.

(a) Autonomy level of a robot



(b) Difficulty levels of the environments

**Fig. 1.** Comparison of robot autonomy and environment difficulty levels.

Although previous models and frameworks have addressed autonomy in HRI and automation, there is no literature really looking at the relationship between the robot and environment systematically that allows designers and researchers to consider how the design of environment will impact the interaction between the robot and environment.

Here the difficulty in Fig. 1 is not equivalent to complexity. An environment with high complexity sometimes could be difficult to the robot and sometimes could be easy. A complex environment could be well designed to be robot-friendly which might be sophisticated, but also could be unordered that generates complexity.

The applications of robots to building and construction design have been explored since early 1980s when a robot was applied to construction for the first time in Japan [19] and show a big potential in the labor-intensive and highly-dangerous construction industry [20]. In his PhD thesis [21], Krom discussed the potential and opportunities for use of robots in construction processes. Moreover, some generic approaches or frameworks have been developed in this regard. Demsetz [22] described a method of construction task identification compatible with a general approach to automation. The proposed two steps of task identification procedure encouraged the consideration of a wide variety of approaches to automation. Skibniewski has done fundamental and significant works in the area of robotics application to construction. In [23], he introduced a concept of flexible construction systems where the construction work environment was evaluated for the readiness to accept robotics in the job-site configurations. Changes in work organization and construction systems were recommended to bring the work process in line with the requirements imposed by the automated equipment. Evaluation methods for the equipment performance applicable to construction robotics were summarized and scrutinized for their usefulness in this work domain. The impact of robotics implementation in the construction industry was evaluated with the emphasis on surface treatment operations [24]. Skibniewski [25] presented a knowledge-organization framework including the technical and economic decision criteria of site implementation of robots, as well as the presentation of types of data to be supplied for case-by-case decision-making. The concept of an expert system for decision support in the application of robotics to the performance of construction tasks was presented and sources of construction robot technical knowledge were outlined. A model of technological transfer was proposed in [26] for the development of a new taxonomy of work tasks targeted for technology applications. The model incorporated a matrix framework for representing a match between the generic components of work tasks, typical engineering projects, generic components of technology, and specific self-contained technologies. It is recognized that there must be wide-ranging changes in construction before automation can be implemented in practice. However, the innovation rate of construction is too low, and thus it is unclear how the steps necessary for automation could be realized [27].

Robot-environment interaction has been investigated widely. The issue of environment adaption for robots in the context of construction/manufacturing has been discussed as well as the side aspect of how such concepts could be used in the context of service robotics/service environments [28]. In [29], the sensory-motor phase-plots were used to characterize robot-environment interactions. The learning robot-environment interaction with echo state networks is presented in [30]. The interaction problem between robotic rovers and the planetary environment was studied in [31], such as mars imposes unique constraints on mobile robotics. M. Vukobratovic et al. dealt with the direct interaction between a robot and a dynamic environment, including the human-robot physical interaction [32]. It provides comprehensive theoretical and experimental coverage of interaction control problems, starting from the mathematical modeling of robots interacting with complex dynamic environments, and proceeding to various concepts for interaction control design and implementation algorithms. U. Nehmzow [33] discussed the quantitative problem of robot-environment interaction