

Robot Compatible Environment and Conditions

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Abstract

Service robot technology is progressing at a fast pace. Accurate robot-friendly indoor localization and harmonization of built environment in alignment with digital, physical, and social environment becomes emphasized. This paper proposes the novel approach of Robot Compatible Environment (RCE) within the architectural space. Evolution of service robotics in connection with civil engineering and architecture is discussed, whereas optimum performance is to be achieved based on robots' capabilities and spatial affordances. For ubiquitous and safe human-robot interaction, robots are to be integrated into the living environment. The aim of the research is to highlight solutions for various interconnected challenges within the built environment. Our goal is to reach findings on comparison of robotic and accessibility standards, synthesis of navigation, access to information and social acceptance. Checklists, recommendations, and design process are introduced within the RCE framework, proposing a holistic approach.

Keywords

robot compatible environment, RCE, architecture, home environment, service robots, human-robot interaction

1 Introduction

As mobile robots appear in various areas of our lives, harmonization of the built environment with the digital, physical, and social environment becomes emphasized.

The Robot Compatible Environment (RCE) is a novel approach. It takes into account the capabilities of robots and synchronizes the built environment with physical aspects, social and info-communicational needs. In this properly constructed or altered environment mobile robots can navigate safely and efficiently. Safe, reliable, and social robot collaboration in home environments is the basis for mobile service robots to contribute to the well-being of users.

This paper proposes a model based on the analysis of the physical and social environment with the integration of multiple disciplines: robotics, architecture, intelligent home design and human factors. As a result, the concept was generated and guidelines were introduced, leading to a discussion of creating the RCE framework.

2 Robotics trends and interactions in living environment

Similarly to humans, who exist together with the surrounding space and are responsive to the cues offered by the environment [1]. Robots have to learn from and interact with those cues, be it physical or social, whereas a more compatible environment will create better co-existence. Uncovering elements of a technologically defined space is the first step, and then user defined interaction affordances are to be discussed.

Most robot environment related standards are derived from industrial robotics and although lately standards for mobile robotics started to appear, they lack environmental considerations.

There is careful calibration and challenging work in laboratories, where a small number of unique and custom-made robots are being developed. Focus is set on determining position and orientation via navigation solutions.

Fundamental robot research focuses on path planning in static environments via employment of the probabilistic roadmap methods [2] or various motion planning experiments [3].

The artificial intelligence of a service robot system can be implemented on the robot or distributed between the robot and the external environment. The Intelligent Space (iSpace) is an intelligent environment that provides both information and physical support to humans and robots.

2.1 Robots in everyday life

When robots will enter into the complexity of our everyday life, they will meet unstructured environments [4]. Before they can appear in great numbers, robots should become more than tools, capable of safe navigation and task fulfillment; they need to be socially fit into the domestic environment. Social interaction with people, regardless of age, gender, health, or culture is inevitable, thus environmental customization and attachment will play an important factor.

In case of service robots for elderly, reliability to provide support for the user is essential [5]. Service robots should be unobtrusive, without extra responsibilities on behalf of the user, but act as a trusted and supportive partner or be an emotional companion like the Ethonote or Paro [6–8].

2.2 Basic structures

Robots walking on legs and rolling on wheels demand different requirements. Legged robot locomotion is more complex with several motors that require high performance controllers to generate proper gait and maintain stability. Cost of such robots is extremely high compared to wheeled counterparts. Therefore, wheeled robots will dominate the market in the coming years due to their easier construction and control.

While our current built environment is human compatible and legged robots might move better within this environment they still offer a complicated and costly solution. On the other hand, wheeled robots are less compatible with human environments, but they represent a technologically feasible and economic solution. This research is concerned to bring these two aspects closer and aims to find viable solutions in creating or refurbishing the human environment for robot compatibility (Fig. 1).

3 Research method

International standards and regulations of various countries define spatial requirements for accessibility of the

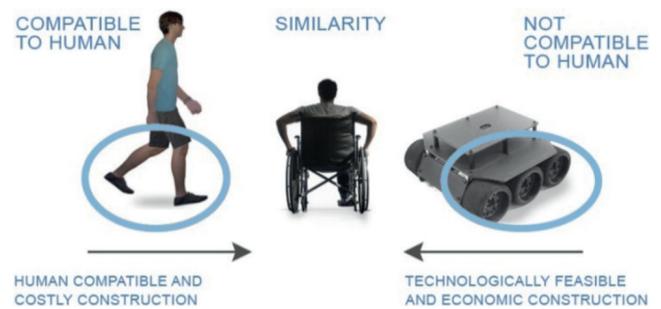


Fig. 1 Human compatible and technologically feasible aspects

built environment (e.g., ADA, BS, ISO) [9]. These accessibility standards and regulations were analyzed and compared to the robotics standards and navigational demands.

To be able to create design recommendations for RCE, guidelines and best practices of environments were reviewed, and feedback was received from actors and experts of related disciplines. Based on our proposed framework, the environment must be harmonized and interconnected. In this way the human-robot-environment system can exist, where behaviors and actions are related to environmental factors.

Research started with the analysis and decomposition of human environment, defining its semantics and interrelations. Basic social competencies were uncovered that work in relation to the environment. Relevant issues of risk prevention and robotic accessibility were determined and synthesized in order to formulate genuine guidelines and detailed design recommendations for the robot compatible environment.

Beyond safety considerations and viewing the environment as an obstacle cluttered space, our aim was to draw parallels between robot's characteristics and contextual conditions of the indoor architecture. By uncovering boundaries regarding depth and efficiency we were looking for of how well a robot may serve its purpose, how can it become a free moving companion yet integral part of a building.

4 Results

In this section findings are presented regarding the relevant elements of accessibility and robotics regulations and standards [9, 10].

Results start with decomposition of technologically defined space and user centric factors. Collected dataset elements (physical features, navigational and social issues) spatial affordances and limits were identified, followed by design guidelines [11]. The topic was addressed with basic key questions of Who, What, Where, When, why, how to uncover situation and context.

4.1 Dataset elements

Defined problem areas can be derived to dataset elements via identifying who uses the environment, their needs, and behaviors, as well as stakeholders and their actions through mapping of the design process.

As shown in Table 1, factors of the design process and their basic attributes are introduced in relation to basic questions.

After defining actors and scenarios understanding and building relation specific social behavior with environment related elements, their affordances and associated functions is next.

Dataset elements and their semantics are introduced regarding basic building blocks, objects, accessible routes, and communication of the robot. Functional actions, in relation to existing rituals or new interactions between objects and space, are created by affordances [12]. Affordances of the environment offer potential object usage; thus, their matching relations can provide functional interactions [13].

Moreover, physical, and communicational elements are present with their possibilities and constraints. Multimodal communication through senses can enhance redundancy and provide navigational and social interaction cues when received. The 3 most important senses as follows (1) visual: gaze, eye contact, facial, gestural, or bodily expressions, perception of environments and its objects, (2) auditive: voice or intonation sounds, (3) tactile: touch, surface, vibration, feedback. Robots must be sensitive (through visual, acoustic, position, touch sensors) to human and environmental cues, from understanding basic gestures to interaction events or changes of environment. When creating or enacting rituals within the environment their spatial or timely constraints and their solutions are context based. E.g., the robot has to provide space when needed: when opening a door, giving advance for a slower moving human, or when someone is in a hurry. Also, during communication turning towards the partner and the characteristics of interaction space (distance, sensorial capabilities, and social issues) must be implemented.

Table 1 Factors involved in RCE design process

	WHO	WHAT	WHERE	WHEN	WHY	HOW
RCE VISION	all	list factors strategy	identify spatial opportunities	list events process cycle	define RCE goal	list processes develop plan
CONCEPT FRAMEWORK	all	Semantic model physical model	process flow	process schedule	define plan strategy	process model
ANALYSIS OF ROBOT SKILLS	robotics engineer	physical cognitive within cognitive	capabilities and restrictions within space	control structure	rules	application functions
SPATIAL REQUIREMENTS	architect	spatial data	on location	process structure	spatial rule design	AEC modeling
HRI SYSTEM	user experience designer	Interface logical data	laboratory on location	schedule	interaction rule design	create interactions
SAFETY CONSIDERATIONS	architect designer	risk, hazard evaluation	on location	schedule	compliance	functional check
DESIGN PLAN	architect	plan	database	design schedule	RCE	documentation drawings
CONSTRUCTION	constructor	Building indoor area	on location	design-build schedule	build	build program
EVALUATION	auditor	data checklist	on location	1 year	feedback check	Monitoring inspection
RECONSTRUCT	Architect constructor	rebuild checklist	on location	schedule	finalize	rebuilding
MAINTENANCE	robotics engineer facility manager	RCE	on location	schedule	avoid breakdown	management upgrades
	environment	objects parameters	3D coordinates functional space	continuous	RCE	static/dynamic affordances
RCE	user	assign task feedback	within RCE	task assignment	Interaction	interaction
	robot	navigation interaction	assigned position	runtime	program sequence	interaction with space and user function

These sensory and social aspects help defining relationships in the environment with its artefacts, objects, and related actions between human and robot, thus creation of a semantic database is essential (Fig. 2). In addition to landmark detection or spatial mapping for accurate navigation purposes, context-based meaning making, classification of artefacts and objects (that are more than just obstacles), creating new boundaries are within the goals of RCE. Hierarchy and order are context dependent and based on social and communication factors with several levels. E.g., meaning of sound and noise does not have to be merely noise control. Signals, noise, sounds of the environment, and sounds of objects, instruments or building elements can guide a robot.

Future service robots are not only show elements or industrial workers but will be companions. The condition for this is the development of new robotic species which are unobtrusively integrated into human communities. Their social evolution is enabled by social environment they act within.

4.2 Guidelines

Guidelines are developed based on technical accessibility requirements and risk prevention for robot compatible environment in comparison with social factors. Guidelines are created with a holistic approach, with a possibility to be included into AEC (Architecture Engineering and Construction) through the developing of Building Information Models (BIM) [14].

An extract from our proposed guidelines is introduced in a table like structure, where columns contain compared issues, and rows contain specific details for which robot compatibility criteria have been defined (see Table 2).

TZ:start			
HZ:relaxation			
HS:living room	HA.task assignment: Bring my cup!		HC:need assistance HC:trust
RS:kitchen	RA.start	RF.task assigned	RC:feedback.ok
ES:functional space:food prep.	RA.search.cup	RF.affordance	
		RF.visual:cup	
ES:kitchen counter	RA.measure:distance		O.cup
ES:free path	RA.maneuver	RF.affordance:path	EO.size:shape:pos
ES:on counter	RA.grasp.cup	RF.size:shape:pos	RC:feedback.found
OZ:static:counter	RA.lift.carry		RC:safety
ES:boundary:wall	RA.query:living room	RF.affordance	RC:trust
ES:free path:door	RA.exit kitchen	RF.visual:door	RC:safety
ES:corridor:width	RA.turn to living room	RF.visual:marker	O:marker
EO:dir.to:living room	RA.movement	RF.affordance: turning space	EC:marker RC:safety
ES:functional space:relaxation		RF.visual:position	O:chair
RS:living room			EO:human pose
ES:motion pattern	RA.maneuver		RC:distance:close
	RA.give.cup:human		HC:feedback:thank
ES:free space	RA.maneuver	RF.affordance	RC:distance:afar

Fig. 2 Semantic relationships snippet within RCE (E: environmental affordance, R: robot, H: user, O: object, A: action, S: space, T: time, Z: state, C: social factor, F: sense)

4.3 RCE checklist

The following checklist questions aim to indicate our comprehensive approach, which serves as basis for robot compatible environment design methodology to achieve seamless human-robot interaction in correspondence with the environment it is set in.

Checklist is created based on the requirements that have been found in our results to facilitate creation of the technology defined space with the inclusion of user needs.

General:

- What is the purpose of robot inclusion?
- What physical and communicational connections are preferred?
- What affordances are provided by the RCE environment for human and robot interaction?

Table 2 Extract from guidelines

Accessibility requirement	Risk prevention	Social factor	Robot compatible criteria
Ramp angle and protection	Tripping. Loosing traction.	Safety	Edge protection on each side of the ramp. Avoid tripping hazard.
Stability and slip-resistance	Instability. Navigation problem. Maneuvering inaccuracy.	Trust Safety	Firm surface resists wheel or robot body marks. Slip resistance helps safe maneuvering. Dirt removal stripes provide enhanced cleanness. Additions to CPR system (Construction Products Regulation)
Adequate space	Get stuck. Collide with obstacle. Motion stop.	Safety Intimacy	Robot dimensions define necessary floor space and turning diameter. Safe charging and maintenance.
Effective communication	False task assignment. Inadequate visual information. Navigation problem.	Engagement Participation	Provide communication space for conversation. Elements in camera view. No obtrusion. Sound detection. Crowd behavior detection for interaction or emergency cases.

There are several detailed, essential criteria that need to be met, as described below with a brief checklist of their influencing factors.

Accessibility:

- Is there sufficient space for robot turning and maneuvering?
- Is there sufficient space for the robot and the user to move together?
- Is the entrance accessible for the robot?
- Are door thresholds easy to roll over them to access rooms, bathroom, kitchen, etc.?
- Are there sufficient ramps?
- Are floors even enough or carpets permit easy maneuvering?
- Are communication elements available?
- Are docking stations easy to reach?
- Is docking station area kept free from obstacles?
- Are there safe evacuation paths for the robot to get out of the way? (e.g., Sprinkler system must not damage the robot in case of fire or another emergency situation)
- Is there a failsafe energy supply for the robot in case of emergency?
- Does the purpose of the robot-usage demand a special space/storage for a spare robot in order to keep the service uptime 24/7?

Interactive objects:

- Are interactive objects easy to access?
- Are interactive objects within reach of robot or robot arm?
- Are interactive objects semantically clear for actions to be taken?

Communication:

- Are location markers clear and visible with robot's camera?
- Are wireless beacons, tags detectable by robot's sensors?
- Is access to visible location markers, wireless beacons, tags maintained and revised the after alteration to building layout, decoration?
- Is there sufficient direct or indirect illumination?

Creation of customization framework is a future goal to ease management of environment in a flexible way via an authoring tool, in respect of user needs and robot capabilities within the environment. Ensuring robot compatibility with the built environment is necessary for future co-inhabitation.

5 Discussion

The greatest advantage of the robot compatible environment is robot integration into the surrounding space. RCE framework was created to get advantages for human-robot-environment interactions, augmented with semantic connections, therefore.

The Robot Compatible Environment is a holistic design framework that views and integrates the parameters and interconnections of objects within an architectural space as a unity for effective physical and social human-robot interaction. The framework is suitable for deployment throughout the design-build process with capability to be included to the related data models.

RCE framework requires the following conditions: transfer of navigation directives to the robot, creation of safe navigation, maneuvering and social interaction within the environment, as well as adequate maintenance space. In case environment is well structured it becomes robot compatible, in other words robot-friendly (Fig. 3).

RCE brings new inputs on safer operation and general acceptance. On one hand in compliance with accessibility and navigation, the two primary requirements are the access of areas both in horizontal and vertical directions for the robot manipulator arm to reach to. In the field of industrial robotics has a history of several decades for this dedicated research [15]. In case of service robots this is supplemented by navigational space, which resides on robot dimensions, weight, torque, and sensorial capabilities.

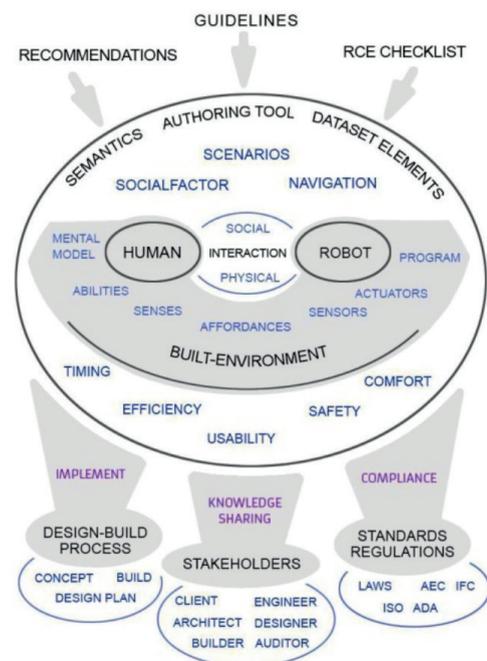


Fig. 3 Detailed robot compatible environment framework

On the other hand, correspondences in a dynamic and seemingly unstructured environment can be made possible with interaction schemes defined by ontologies via semantic interchangeable database. Where information is stored about associations between elements and possible interactions and organized into functional patterns connected to artefacts and objects within the human environment.

In the ecosystem of RCE system levels can be described as microenvironment (immediate, close to body interactions and relationships with objects) and macro environment (social dimensions, meaning-making, influencing other elements). Within these, there are areas that overlap and interaction between elements can be achieved according to context. Thus, not only walls and doors divide a spatial area, as in case of a room, but inside a room or beyond a room there are various areas occupied by definite functional characteristics, e.g., routes, place for relaxation, place for work or play.

Compatibility is more than creating accessibility or a contextual map of objects for easy navigation. Current trends for built environments include energy efficiency and increase of comfort level, and robots may prevail in these directions. In connection with home automation systems, robots will be connected with other smart devices and enhance the quality of tangible and intangible indoor environment.

6 RCE design recommendations

Further results regarding personal care robots in home environment were collected in relation to TC 184 standards. Some important, but missing risk elements have been discovered that might be taken into consideration beyond industrial settings, in the shared living environment.

6.1 Communication, signs, and collisions

Adequate communication must be established regarding the human-robot interface, via matching human factors (anthropometrics, safety, efficiency, and comfort) and usability requirements. It should also be supported the communication between the robot and its environments e.g., visual on markers, lighting, or acoustics; enabling the robot to learn and adapt to changes.

The industry derived solutions are characterized by frequent use of warning signs, which can protect from legal incidents but don't resolve the problem. Moreover, a robot with high amount of warning signs does not meet the idea of gaining trust nor social acceptance. On the contrary

particular attention should be paid to co-operative tasks, increased confidence in actions and creating closeness by allowing spatial proximity.

Risks need to be evaluated in regard to collisions e.g., robot-object, robot-human, losing balance, or damage e.g., grasping, crushing injuries, mechanical, electrical, thermal, noise, vibration and other types of hazards.

6.2 Navigation, maneuvering

Robot navigation requires the ability to pursue a path within an environment, reaching various rooms through doors or corridors, while going around obtrusive objects or furniture. It is necessary to map and access spatial information e.g., visibility of marker or solving horizontal and vertical gaps. To achieve these navigational tasks, knowledge of robot's basic dimensional parameters is needed: width, length, height, situation of manipulator arms, turning radius, weight, possible speed, and motor torque. It may well be, that a dimension-changing robot is needed in certain situations.

By arrival to a certain spatial object or during turning, where manipulator arm sweeping movement is calculated as well; a rotational robot occupied space is calculated, depending on turning center point. This minimum space is a space, where robot (or robot and human together) can turn around without the need for reversing movement.

Turning diameter is the diameter of the smallest cylindrical envelope in which the robot can drive in a circle through 360°. Maneuvering might require turn in reverse direction in a narrow space, similarly to turning diameter, steering type defines reverse movement possibilities. Reversing width and robot center point movement is different regarding turning types and steering possibilities (see Fig. 4).

When maneuvering in angled corridors the robot can slide along the wall (front part generates a linear pattern, center point shows a stretched bend during movement).

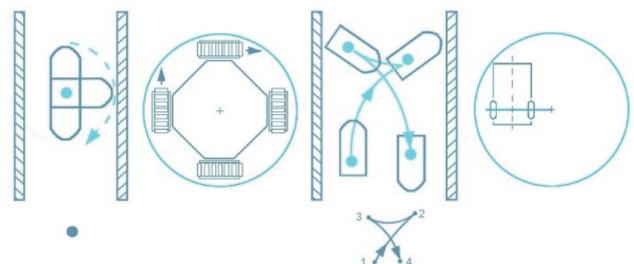


Fig. 4 Reversing movement of holonomic (left) and direct or limited differential drive robot (right)

When navigating in between objects or in case of T or cross shaped corridor intersection, the robot can swing more forward before changing direction (front generates an S-shaped curve, center point shows a mild bend). At doorways more maneuvering clearance is needed, too.

In connection with robot turning characteristics the question arises, whether it is more efficient, if room corners are eliminated and redesigned to a curve.

6.3 Ramps

A Ramp design requires extra space before and after the ramp, it shall be designed to leave enough turning space for the robot to roll onto and off the ramp safely. For ramp steepness angle a minimum of 1:12 ratio is recommended, and its design should include gradual slant at lower and upper ramp endings, considering robot characteristics (dimensions, weight, wheel size, engine torque, drive), with proper edge protection.

When mobile robots can move in 3 DoF by rolling on holonomic drive, not only the robot's head but the whole body can have different orientation from the actual moving direction. A good example for holonomic drive is the ethological model based EthetaBot [6, 7], where moving and orientation is more natural.

6.4 Detailing and views

There are info-communication requirements, and standardized detailing (door details, furniture details, floor patterns, etc.) could prove more effective in case of new buildings, than extra, added elements.

To achieve adequate communication, visual on such elements is essential. Thus, leaving free viewing area, access to natural sunlight, or appropriate spectrum light source is necessary especially if the robot uses marker-based visual orientation.

7 RCE design process

Designing the robot compatible environment is achieved in accordance with standards for robotics, accessibility, and social considerations, integrating various disciplines. It can be realized firstly by investigating robot parameters (physical dimensions, movement, manipulator, and sensory capabilities), followed by the analysis of the environment and its affordances in relation to designated robot tasks.

Once robot navigation and maneuvering space is formed, environment should be properly evaluated via compatibility checklist in parallel with the guidelines.

The RCE approach outlines the RCE design-build process, where architects take part in design and construction and skills, roles and responsibilities are integrated into each step of the process. Building process and its stakeholders (client, architect, constructor teams) and their tasks are to be defined for assessment of building needs, and creation of building program that is aligned with robot compatibility (Fig. 5).

RCE guideline should be implemented from the concept phase and followed throughout all stages of the architectural design-build process. Through this it could be included to the related building data models such as Building Information Model (BIM) to support decision making in an AEC (Architecture, Engineering, and Construction) project [14].

As part of knowledge sharing, robotics education of students and young professionals of diverse disciplines from architecture, civil engineering, mechanical engineering industrial design, cognitive scientists and user experience designers should be integrated in the curriculum.

Naturally, a deeper knowledge on the subtle details of environmental interactions (physical, communicational, social) is inevitable, thus further environmental compatibility research and setting up a wide spectrum of guidelines is needed. This knowledge could be applied in the architectural design process, when designing compatible environment for future service robots. This would lead to more insights on human-robot interactions and a faster appearance and acceptance of robots in our everyday lives.

8 Conclusions

Real-time and seamless communication with and within the environment is a future direction of human and robot cohabiting indoor space. Users require service tasks from robot; thus, robot has to be able to fulfill these reliably and safely. Inclusion of robots requires dynamic adaptability, hence creating and enhancing robot compatible space will enable robots and smart devices to be integrated into the environment defined by balanced compliance to user and technological needs. Semantic database of RCE with its artefacts, objects, assigned actions and their relationships is to be extended to mitigate hazards, reduce risks, to enable communication and social inclusion.

This research contributes to raising awareness to the topic, introduces early findings and defines future directions in indoor robotics, emphasizing the need for standards and guidelines aimed at service robots. An urgent

need of today is to create the robot compatible environment via application of robot design, accessibility standards and social factors. RCE contributes to effective human-robot cooperation in home environment re-interpreting safe and reliable robot navigation, communication, and social affordances of the built-environment. By introducing RCE framework, this research provides design guidelines, checklists, and design-build approach for the home environment, which can greatly contribute to future use and integration of mobile robots.

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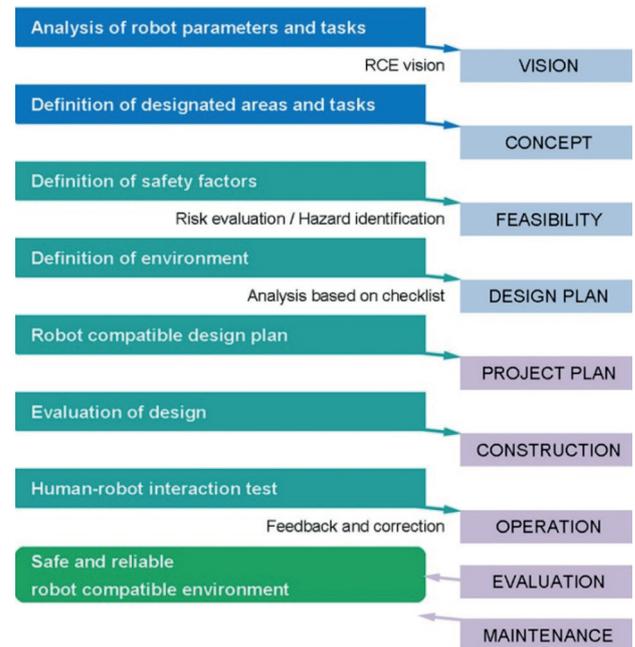


Fig. 5 Robot compatible environment design process

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