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Towards a Comprehensive Taxonomy for Characterizing Robots

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Abstract. Every day a new robot with advanced characteristics and technical qualities gets developed. The increasingly rapid growth of robots and their characteristics demands a bridge between the application requirements and the robots' specifications. The mapping process requires a supporting conceptual structure that can capture as many robot qualities as possible. Presenting robot characteristics through the proposed conceptual structure would enable designers to optimize robot capabilities against the application requirements and help application developers to select the most appropriate robot. Without a formal structure, forming links between the robot domain and the application domain is impossible. This paper presents a novel theoretical representation that can capture robot features and capabilities and express them as descriptive dimensions that can be used to develop capability profiles. This profile is intended to unify robot descriptions and presentations. The proposed structure is reinforced with several layers, sections, categorizations and levels in order to allow for a detailed explanation of robot characteristics. It is hoped that the proposed structure will influence the design, development and testing of robots for specific applications. At the same time, this structure would help highlight the corresponding outlines in robot application requirements.

Keywords: application profile, robot capabilities, robot features, robot interactions, robot profile, robot requirements

1 Introduction

There are many types of robot. Each robot has its individual features, capabilities, and corresponding application requirements. Defining both which robot should be used for what application and what application is best for which robot is a complicated process. It demands mapping between the application requirements and the robot capabilities. This requires a comprehensive taxonomy of robot descriptions. Most of the existing robot taxonomies and classifications (e.g., domain [16], field [14], size [4], ontology [12]) focus on several characteristics but do not include all of them. These classifications are not enough to bridge the gap between the two domains, nor are they adequate for comparing one robot with another. Also, the continual development of robot characteristics, the frequent updating of application requirements, and the lack of consistency in naming conventions among the relevant fields, all hinder the mapping process. There is, therefore, a need to present robot characteristics in an abstract structure to capture the fixed as well as the dynamic characteristics. These characteristics should include all aspects of robot features, capabilities, interactions and reasons for robot performance presenting them as skills and intelligence. Consequently, the proposed structure requires new dimensions for identifying and describing individual robots, an objective that is a considerable challenge in the continuously expanding field of robotics. Moreover, this structure should support the robot domain with robot capability profiles (as a set of outlined hierarchies for robot characteristics), and, at the same time, it needs to provide the application domain with a corresponding layout for straightforward comparison and analysis of robot requirements.

The Multi-Annual Roadmap (MAR) is a substantial, over 300 pages, well-structured document [16]. It accompanies the Strategic Research Agenda to analyse robot technology and the details of the robot market. The MAR is updated annually to prioritize the technology and the strategic development that will shape, European research development and innovation. The MAR contains a detailed explanation of robot characteristics; however, using the MAR to characterize robots is a complex process. In addition, the MAR does not include all robot characteristics (e.g., emotion, social capabilities, cognitive interactions). In this study, we propose a consistent conceptual structure that captures robot features, capabilities and interactions, adopting the levels used in the MAR where possible, and innovating where necessary. Hence, we propose not to replace the MAR, but to extend it by encompassing the MAR system of ability levels within a straightforward taxonomy that is supported by a layered hierarchy. The proposed model has been presented to roboticists during the development process and refined through their feedback.

2 The proposed conceptual structure

The proposed conceptual structure defines the embedded relations between technical and operational capabilities and features of any particular robot. To accommodate the complexity of these relations in describing a robot, the proposed structure divides robot characteristics into three main layers [9], as presented in Fig. 1. Each layer is further divided into sections and subsections. Some of the sections present robot capabilities and others capture more elements of the robot. Each robot capability may be characterized using the ability levels provided in MAR. The ability levels are presented from no capability to full capability with specific intermediate levels. However, some capabilities are not covered by MAR which highlights areas in need of further attention.

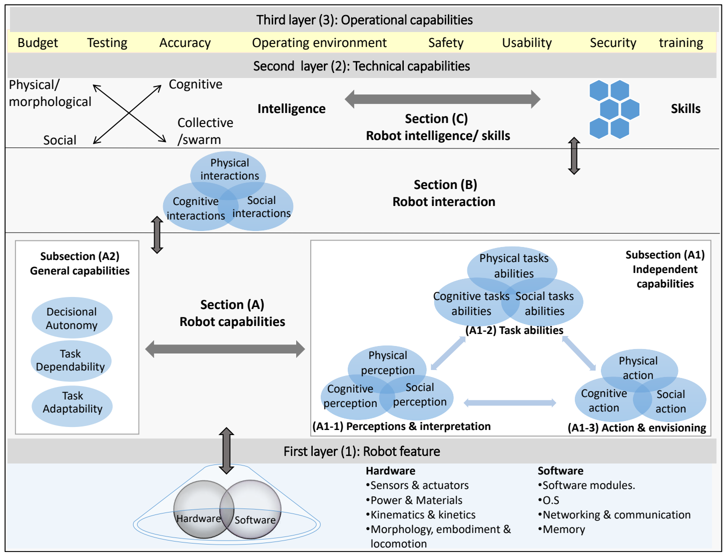

Fig. 1. Conceptual structure for characterizing the operational and technical capabilities of different robots. Layer (1) covers a robot features in term of its hardware and software components. Layer (2) shows the technical capabilities and its sections and subsections. Layer (3) captures all the operational capabilities of the robot.

The First Layer: Robot Features

This layer captures the robot components, including the hardware, the software and their specifications, as presented in Fig. 1, layer (1). The robot components and the specifications are fundamental in determining the robot capabilities and interactions types [1][8]. They are considered as key aspects in robot assessment and improvement. Examples of the hardware concepts are presented in Table 1 and the software concepts are presented in Table 2. This layer also includes other robot specifications that depend on the hardware and software together, such as the robot interface (command line, GUI, speech, pen, etc.) or robot presentation medium (physical robot, simulated robot, hologram robot, etc.)

A robot's hardware and software determine its capabilities and interaction types [1][8]. Therefore, the robot capabilities are presented in the structure in layers above the feature layer (1). However, in MAR [16] there are several types of capabilities that describe the robot hardware or software components, so they are located in the first layer of the the structure. These capabilities are:

– The parameter adaptability, presented in 5 levels.
– The component adaptability, presented in 5 levels.
– The mechatronics configurability, presented in 5 levels.

Table 1. Capturing robot hardware (first layer).

Hardware	**Characteristics**
Sensors	external and internal sensors
Actuators	external actuators and internal actuators
Internal structure	– kinematics: • geometry of the mechanical structure, such as Cartesian, articulated, cylindrical, parallel, spherical/polar, swing arm, etc. • variables of the manipulator's joints and links – kinetics: • force that acts on the kinematic skeleton • joint motors and degree of force of that motor
External structure	– physical measures of the robot, including weight and dimensions, presented in width x, length y, height z – robot power source – colour, shape, body frame, outer body texture and pattern
Embodiment	anthropomorphic, zoomorphic, caricature, functional, screen character, etc.
Locomotion	fixed place, bipedal, wheeled, quadruped, hexapod, octopod, climbing, etc.
Design	design approach and design structure, etc.
Electronics	computational platforms
Mechanics	mechanical system and connection mechanism
Materials	internal and external materials

Table 2. Capturing robot software (first layer).

Software	**Characteristics**
Operating system	presented O.S.(e.g., ROS, or YARP) or firmware
Memory	memory size, sensory memory (instinct data/ imitating data)
Networking and communication	– network connections such as Wi-Fi or cables, I-cloud and connectors – network purposes (e.g., Internet of things(IOT) and Internet of skills (IOS)
System engineering and architecture	programmed modules, managing complex system, system life cycle, systems architecture and design
System design and development	system design, system theories, system integration and system of systems

The Second Layer: Technical Capabilities

Some robots are limited to one capability while others have multiple capabilities. Therefore, listing robot capabilities is an important aspect of robot identification. Technical capabilities are divided into three sections: robot capabilities, interaction capabilities and intelligence. Each section depends on the outcomes from the lower(s) sections located in the layer underneath it, as presented in Fig. 2.

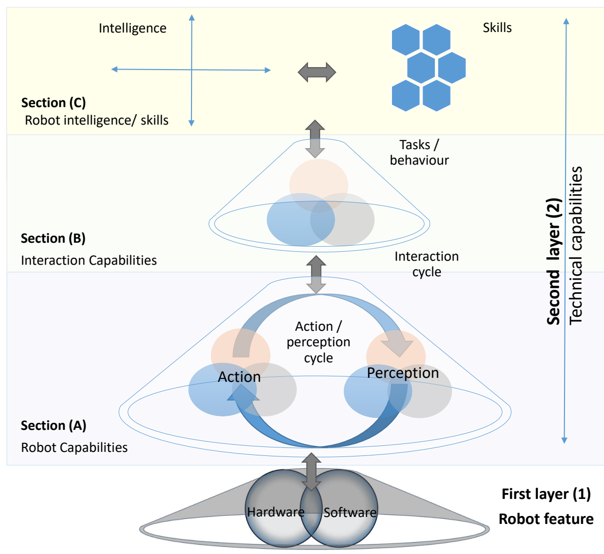

Fig. 2. A hierarchical presentation of the conceptual structure to capture the robot characteristics (robot features layer and technical capability layer). The technical capabilities layer is divided into three sections. Each section of technical capabilities depends on the section underneath it (The first section of the technical capabilities layer depends on the outcomes from the robot features in the lower layer. The interaction capabilities section depends on robot capabilities section. Finally, the robot intelligence/skills section depends on the interaction capabilities section.).

1 Robot capabilities, presented in Fig. 2, layer (2), section (A), represent capabilities produced by the robot's hardware (HW) and software (SW) features. Hence, robot technical capabilities are located above the robot features in layer (1).

2 Interaction capabilities, presented in section (B), are produced by robot capabilities, and are therefore located in the section above the robot capability in section (A).

3 Robot intelligence, presented in section (C), depends on skills and behaviour that emerge from robot interactions in section (B). Therefore, robot intelligence is located above the interaction capability section (B).

Thus, the hierarchical model presented in Fig. 1 consists of three layers and sections. Some sections are divided into subsections and some of the subsections are divided further into sub-subsections. Each sub-subsections is divided into categories and each category contains a list of specific descriptive concepts. The concepts are ranked according to the system ability level adopted from the MAR [16]. To designate a specific technical ability for any given robot, at least one of the concept levels for that specific capability should score more than 0. Each of the layers, sections, subsections, sub-subsections, categories, concepts and levels are described in more detail throughout this paper.

Section (A): Robot capabilities

Robot capabilities are divided into two types. The first type is defined as 'independent capabilities' because they do not rely on any other capability, as presented in Fig. 1, layer (2), section (A), subsection (A1). The second type is defined as 'general capabilities' and depend on independent capabilities, as presented in Fig. 1, layer (2), section (A), subsection (A2).

Independent capabilities, subsection (A1): The independent capabilities are not contingent on any other capabilities. They are grouped according to a perception-action cycle [2], as shown in Fig. 1, layer (2), section (A), subsection (A1). The cycle captures the flow of actions that take place within the robot. Therefore, the independent capabilities are grouped into three sub-subsections: (A1-1) Perception and interpretive capabilities. (A1-2) Robot task abilities. (A1-3) Robot actions and envisioning.

(A1-1) Perception and interpretive capabilities. Capabilities in this sub-subsection provide the robot with the act of perceiving. Robot perception is described by the following three concepts:

1. Robot perception categories: There are three categories of perception: 1) Physical perception to capture perception towards objects. 2) Cognitive perception to capture perception towards information. 3) Social perception to capture perception towards people, as presented in Fig. 1, layer (2), section (A), subsection (A1), sub-subsection (A1-1).

2. Robot perception types: according to MAR [16], there are six types of perception each type given a number of levels:
   (a) Perception abilities (9 levels).
   (b) Tracking abilities (7 levels).
   (c) Recognition abilities (13 levels).
   (d) Sensing static surrounding perception abilities (7 levels).

(e) Self-location (8 levels).
(f) Interpretive ability in the robot (10 levels).

3. A robot's modes of perception, also known as the interaction modes, define the data collection methods used by the robot to perform the perceptive capabilities. There are several perception modes such as visual, auditory or physical (such as mechanical, magnetic, chemical, etc.) [14].

(A1-2) Robot task abilities. The robot task abilities, as presented in Fig. 1, layer (2), section (A), subsection (A1), sub-subsection (A1-2), are divided into three main categories. In each category, different correlated concepts are defined and levelled. The three categories of task abilities are: 1) Physical tasks: to describe the mobility and manipulation ability of the robot. 2) Cognitive tasks: to capture the ability of the robot in performing any informatics or data manipulation, such as learning, reasoning and problem-solving. 3) Social tasks: to describe the social ability of the robot, such as emotions, relationships, behaviours, and personality [3][5]. There are no defined social concepts, descriptions or levelling presented in MAR for social tasks. Therefore, identification of social indicators to describe the degree of these social tasks is suggested as a research area. Table 3 illustrates the categorization of task capabilities, sub-types and their levels.

Table 3. Categories of robot task capabilities, sub-types and their levels.

Types, subtypes and levels of robot capabilities	
Physical tasks	– robot motion capabilities, captures the system moving ability through: • unconstrained motion of the robot, presented in 8 levels • constrained motion, presented in 6 levels – robot manipulation capabilities, captures the system manipulation ability through: • grasping capabilities, presented in 9 levels • holding capabilities, presented in 6 levels • handling capabilities, presented in 10 levels
Cognitive tasks	– learning abilities, also known as acquiring knowledge, presented in 16 levels – reasoning abilities, presented in 9 levels
Social tasks	define indicators for different degree of social capabilities.

(A1-3) Actions and envisioning capabilities. This is the third subsection of robot capabilities, as presented in Fig. 1, layer (2), section (A), subsection (A1), sub-subsection (A1-3). A robot would not be able to perform an action unless it is listed as one of its available capabilities. The ability of a robot to act purposefully and to assess the impact of its action are separate abilities. These concepts are described in the following section:

- A robot's ability to act purposefully is categorized into: 1) Physical purposeful action, towards objects. 2) Cognitive purposeful action, towards information. 3) Social purposeful action, towards social members. The robot action abilities are presented by MAR in 10 levels.
- A robot envisioning abilities identify the impact of the action on the environment. They are categorized as: physical envisioning, cognitive envisioning and social envisioning capabilities, presented by MAR in 9 levels.

General capabilities, subsection (A2): The general capabilities are part of the robot capability section (A), within the technical capability layer (2), as presented in Fig. 1, layer (2), section (A), subsection (A2). These general capabilities depend on other capabilities. They capture capabilities to perform the perception/action cycles [2]. To describe some of these general capabilities of the robot, the following concepts are defined:

1. Decisional autonomy (12 levels).
2. Task adaptability: system ability to carry on tasks between multiple agents (5 levels).
3. System dependability: ability to perform tasks without errors (8 levels).

Section (B): Interaction capabilities

A robot interactions rely on it's existing capabilities, such as perception, task abilities and actions. The sequence of performing these capabilities as robot actions towards an environment is termed the interaction cycle, or the robot-world feedback loop [17]. The interaction cycles create tasks and/or behaviours. These tasks and/or behaviours generate a specific skill, which demonstrates a distinct intelligence, such as social, physical/morphological, cognitive or collective intelligence, presented in the next section.

The accumulated interaction cycles performed by a robot define its interaction towards object, information and/or social members and determines the interaction category. This section is divided into three categories, as presented in Fig. 1, layer (2), section (B): 1) Physical interaction captures the robot's connection with its environment. 2) Social interaction captures a robot connecting with other social members. 3) Cognitive interaction captures a robot connecting to any information system. Robot interaction categories, types and levels are listed in Table 5. All other robot interaction classifications are also listed in this section (B), such as paradigms, roles, social models of interactions, interaction length/period, social robot interaction types, interaction media, interaction mode and interaction architecture.

Section (C): Intelligence/skills

The third section of the technical capabilities layer encompasses a robot's intelligence/skills, as presented in Fig. 1, layer (2), section (C). It outlines the

Table 4. Interaction categories, types and levels.

Interaction categories	Types with levels
Physical	object interaction level, presented in 8 levels
Cognitive	– robot-to-robot interaction: level of interaction between robots in carrying out tasks, presented in 8 levels – system-to-system interaction: degree of information exchange, not presented in MAR where it is a proposed research area
Social	– human-robot interaction: capture users interactions, presented in 9 levels – human-robot interaction feedback: user perception of robot state, presented in 9 levels – human interaction levels of extent: social interaction in information integrating, presented in 8 levels – interaction cognitive social complexity level, presented in 5 levels – human interaction modality level: present different modalities of human interaction, presented in 6 levels – social interaction learning level, presented in 4 levels – Human-cognitive robot interaction, presented in 8 levels

purpose of a robot's performance and describes the external perception of its actions [13]. It also clarifies what sort of intelligence the designer aims to present in the robot by expressing the ultimate cause of the robot's actions/behaviour captured through specific skills. Therefore, the intelligence is defined by specific skills, behaviours and interactions [5][6]. There are several types of intelligence that might be acquired by the robot [5][7][11]. Each intelligence is represented by specific skills, where most of the intelligent skills are adopted from 'Gardener's theory of multiple intelligence' [11]:

– Physical-morphological intelligence, such as bodily-kinaesthetic skills or visual-spatial skills.
– Cognitive intelligence, such as learning skills or logical-mathematical skills.
– Social intelligence, such as emotional behaviour skills or musical skills.
– Collective intelligence, which captures emerging skills in combining either heterogeneous or homogeneous robots, such as collaboration or cooperative skills.

The Third Layer: Operational Capabilities

The operational capabilities covers the following concepts with regard to a robot: cost, duration, safety, security, testing, training, acceptance, usability, re-usability, reliability, versatility, robustness and the operational environment capabilities of a robot (e.g., ground, aerial, or underwater [14][16]), as presented in Fig. 1, layer (3).

3 Illustration of the conceptual structure

To demonstrate the ability of the conceptual structure to capture robot characteristics in a profile, robot examples are provided throughout the model.

3.1 A Social Robot: Zeno Social robots are engaged in diverse social scenarios. The social aspect of the robot could be situated in any of the social categories throughout the conceptual structure. The following example illustrates the profile of Zeno, a social robot, is located within the conceptual structure. In the first layer, Zeno would be situated as having both hardware and software. In the second layer, if Zeno is programmed with social perception and social recognition abilities to identify people, it would be situated in the social perception category. If Zeno is programmed to name the identified person and greet him, it would be situated in the social task abilities category. If Zeno is programmed to act purposefully with social intent, then it would be situated in the social action category. The interaction categories are defined by Zeno's social interaction cycles. If Zeno is programmed to perform a greeting, for example, waving and shaking hands, then it would have two skills to support both the physical/morphological and the social intelligence. If Zeno is programmed to say hello, presenting some verbal/linguistic skills, it would support social intelligence. In the third layer, the operational capabilities within Zeno would need to be defined, such as cost, duration of performance, safety issues, tests and training, as well as the acceptance and usability rate and operational environment capabilities.

3.2 A Simulated Robot: BabyX An important aspect should be clarified when applying this conceptual structure to simulated robots. The physical aspect of the simulated robot is presented as part of the hardware section in the first layer of the robot features. The following section presents how a profile of BabyX, an interactive simulation, would be situated in the conceptual structure. In the first layer, BabyX would be situated as having both hardware and software. In the second layer and the third layer, the same method is applied as in the social robots.

3.3 Swarm Robotics Applying the conceptual structure to present the swarm robots performance requires presenting the individual swarms capability in a single profile (by using the same concepts applied for the social robot) and the whole swarm system in a separate profile.

3.4 Self-reconfigurable robots Using the conceptual structure in presenting the capabilities of the configurable robot requires presenting each module capability in an individual profile and any combined modules performance in another capability profile.

4 Advantages of the conceptual structure

The conceptual structure is aimed at providing to describe robot characteristics in a clear manner. It outlines robot specifications in layers, categories and levels to present a comprehensive robot profile. The structure can be used in various ways. The most desired benefit of the robot profile is the link between robot capabilities and application requirements. The growth of robot capabilities in laboratories and the corresponding increase in requirements needs an extensive bridging model. Therefore, embedding this conceptual structure within a robot-application mapping framework would improve robot deployment and application selection. The conceptual structure outlines the linking process between requirements and robot characteristics. For any robot application it will define the most appropriate robot. It will also indicate what changes are needed within the robot in order to fulfil a specific application requirement. Moreover, the conceptual structure will enable mapping any given robot to it's most suitable application, where it can clarify the most advanced features of the robot that are essential for a particular application. Some robotic fields are more developed than others. Demonstrating these robots in profiles using the conceptual structure highlights their advanced characteristics, which will help laboratories develop new approaches by mixing available robot characteristics. Therefore, presenting robot profiles helps to develop robots by using available capabilities in the same field or from different fields [15]. On the other hand, using this conceptual structure to present robot profiles will clarify the effectiveness and limitations of each robot, allowing better business decisions.

Furthermore, applying the conceptual structure and presenting robots in layers, categories and levels classifies them. It filters robots along of the conceptual dimensions and matches them to others. This will lead to a taxonomy and classification for various robot types, even from different fields. From a broader perspective, the layers of the conceptual structure are broad and flexible enough to capture current robot characteristics and any future features that might be developed. Additionally, providing a flexible structure to include diverse interests from both industry and academia, helps in understanding divergent interests and approaches. Thus, the conceptual structure can be considered as a point of reference to resolve different views from different disciplines into one harmonized pattern. Finally, the conceptual structure presents a new method for outlining robot descriptions, specifications, evaluations, and validations[10].

5 Conclusions

Bridging the gap between robot application (benefits, purpose and requirements) and technology (features and capabilities) is an important but challenging issue. The aim of this paper is to describe a novel theoretical model to capture robot features and their capabilities in the robotic domain and match them according to the requirements of particular applications. The conceptual structure provides a detailed profile for any given robot. It also aims to the robotic field and its literature by providing a schematic model of classification to improve robot development and deployment. Importantly, the conceptual structure adopts the levels used in MAR where possible, and innovates to expand MAR where necessary.

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