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A Comparative Study on Context Assessment Approaches in Mobile Robots

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A mobile robot is an autonomous machine that is not fixed to one physical area. It has ability to move around in the environment to give versatile kind of services to user. The environmental knowledge (context assessment) is important for the successful navigation of robot in current environment. This survey aims to define clearly the meanings of context and context-aware system. We contribute a structure for the categorization of context-aware approaches within each viewpoint by studying, analyzing and comparing the existing approaches. The satisfactory characteristics of mobile robots related to context awareness are proposed in this paper. In this paper, contextual awareness approaches are grouped into several categories such as context acquisition, context modeling, service oriented architecture (SOA) and their frameworks, user perception approaches and others. These categories are further subcategorized and compared regarding several general characteristics. Each category is populated with old as well as current literature by discussing merits and demerits of the models. According to current literature there is not such model that fully satisfied all the requirement of context modeling *e.g.*, context representation from heterogeneous sources, context reasoning, context management of distributed systems, dynamic service composition and service discovery *etc.* The open areas for further research are described as well in this paper.

Keywords: autonomous machine, context-aware system, environmental knowledge, context modeling, categorization

1. INTRODUCTION

Humans communicate with each other using different kind of mediums, *e.g.*, language, gestures, *etc.* Context information is one of the most important aspects that contribute to the success of communications. When humans interact with the context-aware systems, system knows nothing about the human environment. One has to feed information (context) in system to make the system aware of context. Context awareness is an inevitable characteristic for an intelligent mobile robot that helps robot to navigate in a diverse environment. The environmental change in context-aware system (*i.e.*, mobile

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robots) may correspond to the change in location, object's position, user, activity *etc.* Context awareness is an inevitable characteristic for an intelligent mobile robot while interacting with humans in order to perform different tasks.

1.1 What is Context?

Several attempts have been made by different researchers to define context and context-aware system. Some authors provide the synonyms of context as situation and environmental condition [1-3]. Some discussed mainly three aspects of context as location, user and object [4, 5]. It is too specific and could not put in all kind of computing applications. One of the famous definitions defined is "context is any kind of information that is used to characterize the situation of an entity" [6]. An entity can be a person, place or object that is considered to be relevant to the interaction between a user and an application. It succeeds to some extent to provide a practical definition. [7] does not discuss some important aspects of context *i.e.*, environmental conditions, time context, other creatures *etc.* There was need to present such definition that describe all the aspects of context information. The context is defined as, the existence of entities within the environment and their interaction with other entities and applications influenced by environmental condition cause to form a situation at different places and time, the possible aspects of a situation are collectively termed as context information of the situation. Context refers to the environmental knowledge which includes different aspects of a situation. Anything that is related to the user is the part of context even those condition from which they influenced like environmental conditions (*i.e.*, weather, temperature, noise level *etc.*) are also the part of context. Context is categorized in following categories:

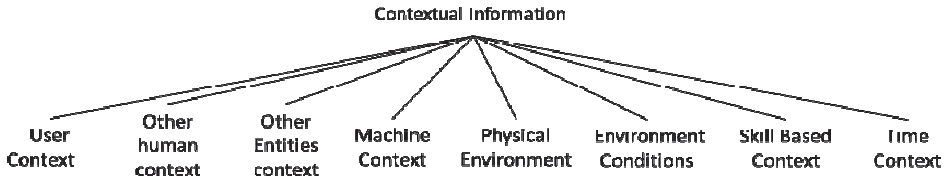

Fig. 1. Categorization of context information.

1.2 User Context

It includes user name, age, language, attitude, emotional state, behavior *etc.* The user of a system can be one or more. A user is not necessarily required to be a human. It can be a person, a system (another robot) or animal.

1.2.1 Human's context

It includes all the others that are not the user of a system. But they can mutually interact with the user and system. A system should know its valid user. In a situation the user (focused person) is a valid user and in another situation the same user may be in the category of human's context and will be the unfocused person for system.

1.2.2 Other entities context

It includes all the other creatures except humans *i.e.*, animals, birds *etc.* A user interacts with other creatures *i.e.*, dog, cats, parrots *etc.*, that lives with humans. A mobile robot interacting with human or animal like dog, cat should know the difference between an animal and a human. Robots can also be used as a care taker of animals.

1.2.3 Machine context

It includes information about an application or machine like how it works, what feature it has, how to use it *etc.* A machine can be a static as well as dynamic machine.

1.2.4 Physical environment

It includes physical infrastructure of environment, geographical information, objects of different shapes and their types *etc.*

1.2.5 Environmental conditions

It includes all the conditions like weather condition, light, audio and temperature *etc.* each condition has its lower and higher intensity level.

1.2.6 Time context

Everything happened at specific time within time duration/time period.

1.2.7 Skilled based context

It includes all the information that enables a robot to perform different tasks efficiently, *e.g.*, if a robot is assigned a task, how to make a cup of tea?

1.3 Context-Aware System

Like context most of the authors discussed context-aware computing as software that adapt its behavior according to only three aspects of context [1, 8]. The aspects corresponds to user, location and nearby people that is too specific [1, 8]. [7] tried to generalize this definition as "A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends upon the user's task". [6] does not mention important features of context-aware system that can be helpful for the designer of an application. We define context-aware system as, a system is context-aware if it has ability to sense context information (the possible conditions regarding the situation may already be stored as locally, distributed or may directly be sensed from environment), also predict future situations and adapt its behavior accordingly by planning and performing the required task. According to the definition a context-aware system must process the following characteristics:

1- Provide services to user without user intervention.
2- Provide an interactive agent interface in order to interact with user and other systems.
3- Capability of discovering services and planning to accomplish a task.
4- Capability to take rational decisions, ability to deal with the uncertain and unplanned tasks.
5- Predict future situations.
6- Capability to execute service automatically if required by user and allow changes if needed.

1.4 State of the Art of Current Research

There are few researchers who surveyed or reviewed the approaches of context awareness in mobile computing. [9] surveyed and categorized the approaches in context-aware applications, context models, sensing mechanism, system infrastructure and also discussed security and privacy issues of context-aware systems. [10] discussed the concepts of context acquisition, context-aware applications, context-aware applications development frameworks, security and privacy issues. [11] discussed specific category of context-aware approaches. Security and accuracy of decision data was also discussed in [12, 13], however, they discussed in the context of machine to machine communication.

According to the best of our knowledge no one categorized the approaches related to the context awareness web services which includes service discovery, service composition, ontology oriented architecture, agent interfaces *etc.* and do not provide the comparison study. These approaches have great importance in service oriented architectures (SOA). Mobile robots provide different kinds of context-aware web services. These approaches help to compose and provide the effective context-aware services. In this review context and context-aware system are redefined. In Section 2, context awareness approaches are categorized in context acquisition, context modeling, context-aware web services, user perception approaches and others. In context acquisition approaches the different ways to acquire and sense context information are discussed. Context modeling approaches are subcategorized in the schema models, spatial models, hybrid models and engineering approaches. Schema models and engineering approaches are further subcategorized. The approaches related to the context-aware web services and context-aware application development frameworks are discussed. In we discuss the user perception approaches. We discuss the approaches other than the approaches discussed in previous Sections. In Section 3, the different categories of approaches are analyzed and compared regarding several general characteristics. In the end, the conclusion is discussed.

2. CATEGORIZATION

The different approaches of context awareness in mobile robots are categorized are shown (Figs. 1-5). Some of the above mentioned categories and subcategories are discussed in existed surveys.

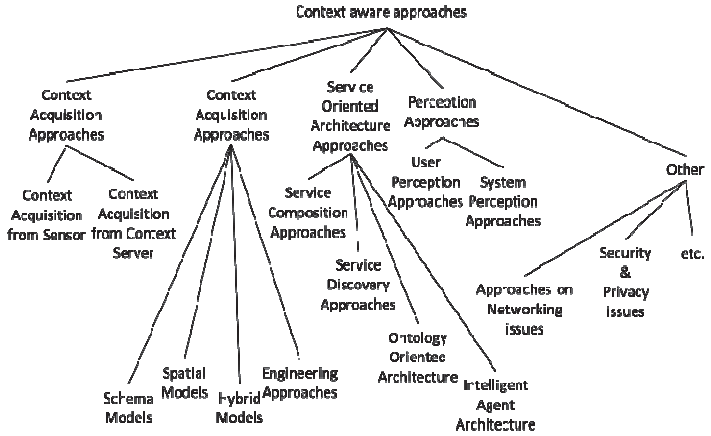

Fig. 2. Categorization of aware approaches.

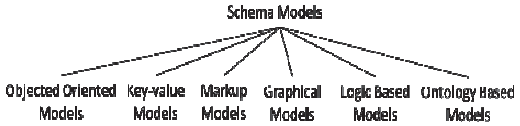

Fig. 3. Sub categories of context models.

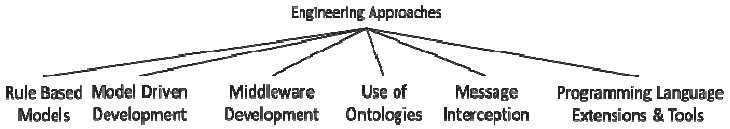

Fig. 4. Sub categories of engineering approaches.

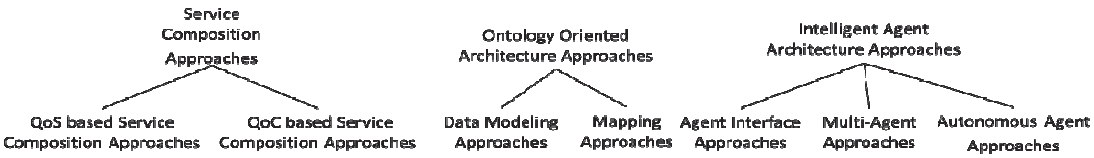

Fig. 5. Sub categories of service oriented architecture.

The above mentioned categories and their subcategories are discussed in detail. The approaches help to compose, discover and present context-aware services. They have great importance in SOA. In the "others" category approaches are discussed that address issues related to context awareness.

2.1 Context Acquisition Approaches

For mobile robot acquisition and representation of context is an important issue in current environment. There are different ways to acquire context in mobile robots, dynamic context is acquired through sensors directly from the environment and also ac-

cessed from the context server (discussed in Section 2.2). The concept of semantic web has got much popularity in mobile robots [14]. Some of the context information needs to enter manually *e.g.* user profile information.

2.1.1 Context acquisition from sensors

There exist many sensors that are used in robotics through which we can acquire context information, namely: location sensors, motion sensors, audio, optical, bio-sensors and specialized sensors discussed in [15]. Schmidt *et al.*, demonstrate the utility of sensors integration in ultra-mobile computing to accumulate context data in their approach. A layered architecture has been presented in this approach for sensor fusion that consists of four layers: sensors, cues, context and scripting [15]. Automated sensing techniques are discussed by [9].

2.1.2 Context server

Most of the mobile applications are distributed. Clients access information from the server. Context server stores the context information about the devices, user personal information and also store sensor data, so multiple clients can access the single piece of information at the same time. A new ad-hoc concept in the field of mobile robotics has been introduced in which mobile robots cooperate with each other to perform a task. In this scenario context information may be stored at one place in the context server [16].

2.1.3 Semantic web technology

Semantic web services and sensors are used in mobile robots for the aim of providing seamlessness of service at anytime, anyplace and in any format. Mobile applications typically access the web services. [14] presented architecture of semantic URS (ubiquitous robotic space) with the conceptual vision of URC (ubiquitous robotic companion). This architecture consists of three components; a Surf agent (SA) that is responsible for automation integration procedure. EKR (Environment knowledge Repository) in which knowledge is described in KB (knowledge bases) that consider devices and sensors data as a part of context. EKR consists of domain KB and device KB. Device Web Service (DWS) is an implementation of devices, including sensors, robots *etc.* In [17], Gaines and Shaw gave concept of context acquisition from World Wide Web (WWW). They presented knowledge based architecture to acquire the knowledge from WWW for modeling and inference purpose, but this is not implemented in the real world yet in robotics field, because it involves a lot of effort to develop the tools and strategies to design this type of architecture. The issues in context acquisition are given below:

1. Environment effects to acquire context information directly due to physical complexity *e.g.*,
   a. Glass resistance (from windows and doors)
   b. Noise pollution (unnecessary audio sound)
   c. Some environmental conditions like meteorological condition effects the context acquisition through sensor about weather condition, *etc.*

2. Context acquisition from heterogeneous sources is difficult task.
3. The same information acquired from different sensor may discord.
4. The target result may change due to context information acquisition from different sensors.
5. Due to low sensors strength, some of computation intensive are difficult to access
6. Context acquisition from context histories is difficult task during service computation.
7. Due to the limited capability of information sharing, context is difficult to access from agents.

2.2 Context Modeling and Engineering Approaches

Context modeling techniques are used to represent the behavioral description of context by describing the relationship between the different pieces of context information in system. An efficient context model must fulfill the following characteristics discussed in Section 3.

2.2.1 Schema models

Schema based modeling focuses on the representation of context information and their relationships. Here we will discuss different types of schema modeling approaches. The Key-value pairs are old models for modeling context information. They are used by describing the list of attributes with their values. An action is trigged when these keys matches the actual context information [1]. FAWIS is another system that uses the key-value pairs to represent and translate the context information present in web based applications [18].

Markup models are the hierarchical structures including markup tags, in which context information is modeled using Extensible Markup language (XML). Comprehensive Structured Context Profiles (CSCP) is used to cover the problem of dynamic context and reduce the complexity of representing context information as compared to the static profiles [19]. In graphic models context information is represented and modeled with the help of unified modeling language (UML). The class diagram is used to represent the context and the relationship between the different pieces of context information. Simons [20] proposed a context modeling profile (CMP) using lightweight UML extension for mobile distributed system. A UML profile is proposed to integrate with the existing UML based software in [21]. The context UML is proposed to develop the context-aware web services in [22].

2.2.2 Spatial data models

Most of the researchers present the spatial models, because space is an important context in mobile robot navigation. In [23], they presented a computational method that uses the spatial knowledge to find the objects, and relations between the objects. In [24], Yuan presented a framework that acquires spatial context from environment representation. In which author not only considers the characteristics of spatial models but also considered to which extent the context information can be considered while providing service to the user [25].

2.2.3 Hybrid models

Some of the hybrid approaches have been presented in order to develop a more flexible structure to fulfill the functional as well as non-functional requirements of a context-aware system. In [26], Henricksen *et al.* presented a hybrid approach that uses ontology and graphical model in order to use the best characteristics of both models *i.e.* to represent the context information.

2.2.4 Engineering approaches

Different approaches regarding the context modeling solution have been presented that help application designers to develop the context-aware systems. These approaches can be used in combination to develop a context-aware application. Here we will discuss all these approaches.

Rule based systems consist of three main parts: fact base, knowledge bases and inference engine [27]. Rule based reasoning technique is employed for the development of context-aware application in [7]. A rule based model has been proposed by using Event-Control-Action (ECA) pattern in [28], this architecture provides solutions for managing and proactively reacting upon the changing of context information. A rule based technique is proposed for mobile context based applications in [27].

2.2.5 Perception approaches

In this section two categories of perception approaches concerning context awareness are discussed. The approaches are namely System and User perception approaches. Nigam and Riek [29] presented a context based approach for the social perception of mobile robots. They discuss the issue of mobile robot perception of sensing the real world context information while navigating in environment. Another approach that discusses the mobile robot visual perception of forest trail presented Giusti *et al.* [30].

2.2.6 User perception approaches

Some approaches of context awareness focus more on user rather than systems. The purpose of these types of approaches is to understand the user intelligibility level, viewpoints and their behavior regarding context-aware system so that system can be designed by tracing the user behavior, understandings *etc.* Lim *et al.* [31] designed a web based infrastructure that contains functional input-output interfaces of an intelligent system, which purpose is to conduct an online study for the novice user. The purpose of this study is to realize that how to ensure the user satisfaction, trust and acceptance of the context-aware system by providing different kind of explanation to the user.

2.3 Others

Many approaches have been presented that cover the issues regarding different topics of context-aware systems. Some approaches discuss the security and privacy issue related to the context-aware systems because some of the users do not like to explore his/

her personal information [32]. Mostly present context-aware systems do not cover the security and privacy issues that cause misuse of context information. Some approaches have been presented that discuss the issues related to the networking. Daniel *et al.* Lazewatsky *et al.* [11] discussed regarding teleportation of robot system in their paper, in which feedback to the human operator is mostly provided through videos. In literature, service interoperability is sub-classified in to three levels, but author of this paper realized to add one more level called "context level" as a part of interoperability sub-classified level.

3. RESULTS AND DISCUSSION

This section concludes our review on context assessment approaches in the field of mobile robots. We have categorized the approaches of context awareness within each viewpoint and detailed description in the previous Sections. Different categories of approaches were analyzed and compared regarding several general characteristics. The requirements that should be considered while representing the context information in the system are discussed as under

1. A context model should have capability to represent context information, their relationship and dependencies so that they can give their collective behavior for an application.
2. A context model should have capability to acquire context information from variety of source.
3. The context information should be stored using a method that it can be easily discoverable.
4. Representation of context information such that decisions can be rationalized to validate and verify a change of context information in an application.
5. Adaption is a key requirement to model context information.
6. A good context model should handle a problematic situation by giving alternative solutions.
7. Standard representation of context information
8. Historical states may be required to be saved for use which is complex due to high update rate
9. It is possible that application designer may face difficulty to represent information due to model complexity *i.e.*, Ontology models are complex due to the lack of efficient tool support.

A good context model should have capability to deal with the uncertain conditions that are not predictable. In Table 1, we compare different context models. "×"sign represents that context models do not fulfill the requirements of context modeling at all. The "✓" sign shows that requirements are satisfied at very low level. The "✓✓" depicts that context model partially fulfill the requirements of context modeling. The "✓✓✓" point outs that requirements are fully satisfied by context models.

Key-value and markup models have several limitations *i.e.*; these models do not have capability to capture context information from heterogeneous sources. Key-value

and markup models require exact matching algorithms to discover services. Key-vale and markup models do not facilitate to adapt according to the change in environment. Key-value and markup models do not allow to reusability of services. However, it is easy to manage due to simple data structure [28, 33, 34]. Logic based models are basically employed to infer new facts from existing one by inductive and deductive reasoning on context information. Context is represented as fact, rules and expressions in logic based approaches. Logic based models can give alternative solution to some extent in case of imperfect context information, they use probabilistic and fuzzy logic to deal with the uncertain condition [35-38]. Object oriented models facilitate the use of reusability and encapsulation and it covers the issues related to the dynamic context. Object oriented models uses different language extensions *i.e.* ORM *etc.*, for the efficient representation of context information that provide the easy retrieval and precision of information[39]. Graphical models fulfill most of the requirements in a better way instead it does not deal with the uncertain conditions. Especially graphical models facilitate to deal with the timeline (histories) and heterogeneity requirements of context modeling. In order to deal with the imperfect context information graphical models have capability to give alternative solutions [40, 41].

Ontology based models got the much more points than the others, because ontology based model represent context in an expressive way with meaning full semantic information by showing the relationships and dependencies between the different pieces of context information. Ontology based models share common vocabulary among the heterogeneous sources. Ontology based models allow mapping and reasoning on context information. No doubt ontology based models provide the efficient representation of context information but its practical use as compared to the other models is less, because the lack of efficient engineering tool support. However, some of the approaches are presented to give the alternative solution in case of service failure. The complexity level of ontology based approaches is high, there is need to develop the more sophisticated tools for the developers. Spatial models fulfill most of the requirements in better way (see Table 1).

Table 1. Service oriented architecture (SOA).

Modeling approaches	Requirements of context modeling									
	Efficient context depiction	Hetero-geneity	Disco-verable	Reus-ability	Reason-ing	Adap-tion	Hito-ries	Imper-fect con-text	Complex-ity level	Uncer-tain con-ditions
Key-value models	✓	×	✓	×	×	×	×	×	×	×
Markup models	✓	×	✓	×	✓	×	✓	×	×	×
Object oriented models	✓	×	✓	✓✓✓	✓✓	✓✓	✓	✓	✓	×
Graphical models	✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓	✓✓✓	✓✓	✓✓	×
Logic based models	✓	×	✓	✓	✓✓✓	✓	×	✓	✓	✓✓
Ontology based models	✓✓✓	✓✓	✓✓✓	✓✓	✓✓	✓✓✓	×	✓	✓✓✓	✓
Spatial models	✓✓	✓✓	×	✓✓	×	✓✓✓	✓✓	✓	✓✓	✓

3.1 Service Oriented Architecture (SOA) Approaches

We discuss different types of approaches that have more importance in service oriented architecture (SOA) in section 2. Here we will discuss some inevitable characteristics that must be satisfied by SOA related to context awareness, given in Table 2. The Table 2 also presents the evaluation of the existing approaches with respect to the presented inevitable characteristics.

Service composition approaches must satisfy the following requirements

1. Consideration of quality indicator to acquire accurate and reliable results
2. If any change occurs while composing, it must be entertained.
3. Information being retrieved must be accurate and relevant
4. Authorized user awareness while retrieving and fetching context information.
5. Ontology oriented architecture must satisfy the following characteristics;

5.1 Semantical integration of different pieces of context information

5.1.1 In response to user query selection of a suitable service
5.1.2 Easy retrieval of required information and to enable reasoning
5.1.3 A reasoning mechanism should have capability to think in logical way to take decisions.

5.2 Context information representation is discussed below

5.2.1 Agent should be intelligent enough that could take decision itself according to the condition.
5.2.2 Easy to use agents interface so that user can easily understand and operate the system.
5.2.3 Agent should monitor the current state of situation all the time.
5.2.4 Agent should have capability to help the disable and week people as a true friend.
5.2.5 Agent should have capability to interact with each other in order to work in group/network.

Table 2. Requirements satisfaction table for SOA architecture approaches.

Architecture/ Frameworks	Requirements					
Service composition architecture	Qos-parameters	Adaption	Precision & recall	Semantic integration	Frequency to take context in consideration	Security issues
	Low	Partially	Partially	Partially	Low	Low
Ontology oriented architecture	Semantic integration					Context representation
	Service discovery				Mapping / Reasoning	Good
	Semantics difference	Syntactically difference	Unavailability of service	Time to discover services		
	Good	Good	Low	Partial	Good / Partial	
Intelligent agent architecture	Decision maker	Attractive interface	Monitoring system	Helper for week and needy people		Co-operative with other agents
	Good	Partial	Good	Good		Partial

3.2 Requirements of Context-Aware Mobile Robots

There are some inevitable characteristics that must be satisfied by context-aware mobile robots. The characteristics are discussed as follows

1. Capable of acquiring context information from heterogeneous sources
2. Change system behavior with the change in environment.
3. Ability to take rational decisions regarding the current situation on context information.
4. Storage of context information from heterogeneous to provide context integrity and storage.
5. Context consistency to minimize the error level.
6. Semantic interoperability requirement of context-aware distributed system.
7. Automatic execution of services without intervention of user.
8. Management of automatic task, *i.e.*, self-charging of mobile robots.
9. Service discovery in respond to user request.
10. Context integration mechanism for the efficient context retrieval and precision.
11. Connectivity to acquire context information from the semantic web or context server.

4. CONCLUSION

In this comparative study different definitions of Context are discussed and a new definition of context is also proposed. Different types of context information that may be required by a mobile robot are discussed, *e.g.*, user context, human context, other entities context, machine context *etc.* The paper also proposes a new definition of CAS. The state of the art concerning context assessment approaches is reviewed and the categorization is provided depending on the various aspects in the domain of context acquisition. The issues concerning context acquisition are also discussed as they are important for the outcome result of the approach. The approaches for modeling the context information are also discussed in detail by categorizing them in different categories. The approaches focusing on the architecture of Service that acquires the information is also discussed under SOA. Similarly, class of approaches that consider the perception techniques to acquire the context are categorized and discussed. Furthermore, the approaches are evaluated in the tabular form based on the common features. Following topics in context awareness need further research in mobile robotics.

1. Approaches for context acquisition from heterogeneous sources.
2. Dynamic service composition is an important field of research
3. Semantic integration of services for context-aware services
4. Tools and strategies for the ontological representation of context information
5. Security and privacy issue in context-aware system
6. Context reasoning on uncertain and unpredictable situations need further research

Moreover, context awareness can be designed and applied as a standalone software module. That can be embedded with the operating system of a mobile robot. The charac-

teristic as a standalone module makes it more flexible. It helps to provide software support and required update in the module so that the robot behavior can match its surrounding. A more adaptive and context aware intelligent robot can be more acceptable as compared to a robot without this capability.

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