Cloud Networked Robotics

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Abstract

This paper proposes a new field of research called *Cloud Networked Robotics,* which tackles the issues for supporting daily activity, especially for the elderly and the disabled, throughout various locations in a continuously and seamless manner by abstracting robotic devices and providing a means for utilizing them as a *cloud of robots*. With recent advances in robotic development environments and in integrated multi-robot systems, robots are acquiring richer functionalities and robotic systems are becoming much easier to develop. However, such stand-alone robotic services are not enough for continuously and seamlessly supporting daily activity. We examine the requirements in typical daily supporting services through example scenarios that target senior citizens and the disabled. Based on these requirements, we discuss the key research issues in cloud network robotics. As a case study, a field experiment in a shopping mall shows how our proposed prototype infrastructure of cloud networked robotics enables multi-location robotic services for life support.

1. INTRODUCTION

Robotic services are systems, devices, and robots with three functions: sensation, actuation, and control. Providing robotic services to support daily human activities through socially interactive behaviors is an emerging topic in robotics research [1]. For the last decade, many studies have been performed on how to develop robots that can be useful in supporting daily activities and how they can behave in naturally and socially acceptable ways so that people can intuitively accept them as new members of society. As a result, many robots are commercially available. One example product is an intelligent house-cleaning robot called "Roomba" that was first marketed by iRobot in 2002. Guidance robots for museums or airports are another popular market. Although this movement toward a "robotic society" era remains relatively small, it is quickly approaching. With the rapid growth of the Internet and the spread of smartphones, our lifestyles are greatly changing. Such slow but stable change for the forthcoming aged society requires further changes that cannot be fulfilled by technology enhancement in cyberspace. Physical supports in the real world, which can only be acted upon by such new devices as robots, are emergently required. Efforts are concentrating on developing robots that can perform a variety of acts from housecleaning and folding laundry to helping caregivers bathe and feed incapacitated senior citizens. Although the tasks that robots can perform remain limited, their ability to perform single daily tasks is rapidly improving.

With such improvement, the composition of robots is becoming increasingly complex. New sensing and actuation devices are being developed every year. New methods and algorithms for functional elements are being proposed, such as navigation, manipulation, human detection, and speech recognition. Even just a few decades ago, developers clearly understood every detail of which their robots were composed. But faced with such rapid progress in robotic technology, possessing such understanding is becoming much more difficult. To support developers, tools, libraries, and standard frameworks for composing robots are becoming available. They are accelerating the development of individual functional modules and the construction of stand-alone robots by improving their reusability and mutual connectivity.

In addition to such stand-alone service robots, recent research has focused on the approach of *Networked Robots*, which overcomes the limitations of stand-alone robots by having robots, environment sensors, and humans communicate and cooperate through a network [2]. In 2002, a group in Japan first proposed the concept of networked robots. Following this, several definitions have been proposed, such as one by the IEEE Robotics and Automation Society (RAS) technical committee. Networked robots have become one active research field in robotics, and many large projects with field trials have been performed to show how this new concept can enhance the ability of individual robotic services.

Even though these efforts have increased the ability of service robots, they remain insufficient for thoroughly supporting daily activities. In daily life, we rarely keep doing only one thing in a single place. In the morning, we wake up, wash our faces, eat breakfast, and brush our teeth. In the daytime, we may go grocery shopping or browse around a bookstore. We may need medical treatment at a clinic. After returning home, we have to do housework, wash clothes, prepare dinner, and so on. Sometimes we take care of our pets or do gardening. As such, the activities of our daily life consist of sequences of different tasks performed in different contexts. The question is whether stand-alone or networked robots are sufficient for continuously supporting us in such situations. In the far future, when we can produce real human-like robots that can perform everything humans can do, such robots are likely to support us always and everywhere. Unfortunately, the arrival of this far future remains murky.

As the requirement of services becomes more complicated, it becomes more difficult to develop a robotic service that supports a wide range of activities because they may occur at different locations and discontinuously based on user demands, but supposedly satisfied in an organized manner. Moreover, each person may have different service demands. For example, since senior citizens often have imperfect walking abilities, when performing navigation for such users, we need to choose an alternative route that avoids stairs or slopes. Robotic services require such considerations that are unnecessary for information systems.

The complexity of robots that can perform multiple types of tasks may exponentially increase. Similar to home appliances, various types of robots with a single ability will become available. Cost is another concern in the industrialization and proliferation of such robots. Robotic devices are still expensive to produce and their complex nature requires high maintenance cost. We need a means to combine and share different types of robots with limited abilities that are available at a certain time and place to perform a sequence of robotic services that are useful to support our activities.

Based on these considerations, in this paper we propose a new field of research named *Cloud Networked Robotics,* which abstracts robotic functionalities and provides a means for utilizing them. In cloud networked robotics, various equipment and devices that can measure the world or interact with people in both the physical and cyber worlds are treated uniformly. Such devices include stand-alone robots, sensors, and smartphones. These "robots" are logically gathered to form a *cloud of robots* by networking to realize an integrated system that provides seamless support in daily activities using the available resources on demand (Fig. 1). In such continuous support, instead of sequences of individual services, new, emerging features are expected not only in the usability aspects but also in system configuration and as novel research topics, such as the optimization of resource assignments and planning based on the statistical pattern classification of global user behaviors.

As common infrastructure, the World Wide Web has fueled the Internet's quick expansion with versatile usages and applications that were not intended at its invention. Similarly, common methods for accessing robotic functionalities and for constructing robotic service applications are required besides enriching stand-alone robot abilities. Such access methods provide application developers means to access different robotic functionalities independent of details in different robots and to treat a set of robots as an abstracted "cloud". Today, engineers who are quite familiar with the internal configuration of robots can only develop robotic applications. As cloud networked robotics progress, programmers without detailed knowledge of robots will be able to freely create robotic applications with new ideas never intended by robot developers. At the same time, this will also increase the lifespan of individual robotic services even under the rapid development of new robotic technologies. Such new services and their usages will, in turn, provide further interesting challenges and research topics for cloud networked robotics.

In Section two, we examine related works that support the development of robotic services. Recent efforts on robotic development environments and integrating various kinds of robots are reviewed to identify the missing elements for realizing daily support robotic services.

In Section three, we define the concept of cloud networked robotics. Requirements in typical daily support services are examined through example scenarios that target senior citizens and the disabled. Based on our examinations, we list the key challenges of cloud networked robotics research.

Based on these considerations, we constructed a prototype system with which to examine our concept. In Section four we introduce a case study project: the Life Support Robot Technology project. We describe our prototype infrastructure system and field tests utilizing this infrastructure. In addition, we describe the current situation of the standardization of common protocols used in this prototype.

The last section concludes this paper and provides discussion on possible future research topics in cloud networked robotics.

2. Related Works

The development process of robotic components has improved in the recent decade because of the standardization of robotic components and the expansion of such robotic middleware as ROS [3] or RT-Middleware [4]. Since such middleware is commonly used, robotic functional modules are now becoming commoditized so that robot developers do not have to implement all the features of their robots; instead they can find and reuse modules suitable for their purposes.

Improvements in network technologies, especially wireless networking, have also changed robot development. The spread of wireless networking and mobile phones allows robots to be connected to networks without cabling problems because they physically move and perform complicated motions. At the same time, robotic applications can now perform collaborative operations among multiple robots connected by networks. For example, the mobile-robotic fulfillment system proposed by Kiva Systems [5] successfully improved the efficiency of logistics by deploying many transportation robots in a warehouse and organizing them based on their location information aggregated by a network. This approach suggests a requirement for common frameworks to aggregate and manage information about robots, such as location information for organizing multi-robot systems.

Networked robot systems [2] extended the concept of multi-robots toward collaboration among different types of robots. Since its concept was proposed in 2002, many studies have been performed around the world. In the concept of networked robots, the various involved devices can be organized as three types of robots: visible, virtual, and unconscious. Visible types are physically embodied agents with a physical actuation facility; virtual types appear on the screens of mobile information devices as agents for communicating with users; unconscious types are mainly deployed in environments for sensing and form ambient intelligence.

Networked robotic services stress cooperation among multi-robots, sensor environments, and coordination among services. Although these improvements have accelerated the implementation of interactive service robots, difficulties remain for developing robotic services that support a wide range of human activities. The dustbot project [6] is an example of such a networked robot system. In it, two types of robots cooperate with external sensory systems to provide two services: door-to-door garbage collection on demand, and street cleaning and sweeping. Information observed by the robot’s on-board sensors is also shared among other robots so that they can cooperate with each other to achieve their tasks.

Recently, several notions of cloud computing have been introduced into robotics that are known as cloud-enabled or cloud robotics. The technologies of web services and service-oriented architecture (SOA), which form the technical foundation of cloud computing, have also been applied to robotic technologies in three ways.

One is the utilization of computational resources for enhancing the abilities of robots on cloud servers, as Kuffner introduced with a cloud-enabled robot. The idea uses cloud computing for various calculations required in robot actions, such as behavior planning and perception. Such “remote-brain” robots can enhance the ability of single robots and simultaneously reduce cost and energy.

Knowledge sharing and the exchange of semantic information are other issues where different types of robots collaborate. RoboEarth [7] and CoTeSys [8] address information sharing among different types of robots. In these projects, such information about robot tasks as operation strategies and knowledge about task targets are aggregated and accumulated into web servers so that robots can automatically generate operation commands required for providing services by referring to the shared information.

Another approach utilizes robotic resources as a cloud to solve the issue of continuous support in robotic services. Since robotic services and robotic components are considered services in SOA, they can cooperate with each other if they are organized appropriately. Du et al. [9] introduced the concept of Robot as a Service and the framework of a Robot Cloud Center. Quintas et al. [10] proposed a service robotic system in which a group of robots and a smart-room share acquired knowledge over an SOA.

The above projects rely on both de facto and de jure standards in the fields of networks, web service, knowledge representation for utilizing the technologies in SOA, and cloud computing. To realize cloud networked robotics, common protocols for robotic services must also be standardized for integration.

3. Challenges in Cloud Networked Robotics

What are the key challenges in realizing continuous robotic support throughout daily activities? To clarify the remaining issues, we examined such typical daily activities of the elderly and disabled as going shopping, going to the hospital, and making friends to form a community. From this examination, we identified the following common features to these activities:

- Different types of supports are required within each activity.
- Activities typically involve moving around among different locations.
- Ways of support may differ among people based on their abilities.
- Activity patterns often follow the way they were performed in the past.

For example, when going shopping, the following supports by robots might be helpful, especially for senior citizens:

- Reminders of what to buy.
- Deciding at which shop to buy certain goods.
- Navigating to the shop with a route best suited for the person.
- Navigating inside the shop to find areas of interest.
- Carrying bags.

These results show that merely combining stand-alone robots or multi-robot systems is not sufficient for continuously supporting daily activities. What is required here is a completely integrated system that consistently manages various types of robots suitable for each part of an activity in many locations of different natures. Using networked robots is the closest for this requirement. However, it is not sufficient in terms of the flexibility for treating variations in robotic functionalities beyond the three types of robots in its concept. Cloud computing is another candidate but it is also insufficient; as in cloud computing, all the resources are basically uniform from the point of computing. What is required here is a new mechanism to provide various robots with different physical functionalities as an abstracted resource as *a cloud of robots*.

At the same time, such knowledge as user preferences and activity history will be shared among the different services provided by each robot. For preference sharing, the single sign on (SSO) system commonly used in web services today offers similar functionality. For robotic services, however, the situation is much more complicated since we need to consider users' physical abilities in various aspects for providing robotic services.

Based on these considerations, we list four key technological issues and as a case study, describe example implementation in the next section.

Multi-Robot Management

For cooperation among varieties of robots, we must classify robot abilities and properly manage the available robot elements. A platform is required to classify their abilities and allocate appropriate robots based on requests from the services and the execution environment. The creation of such common specifications and environments forces the development of separate functional modules, which improves their reusability and mutual connectivity.

Although these improvements accelerate the implementation of service robots, developers who want to focus on service logics currently face the difficulty of understanding the structure of different abstraction layers of modules. Therefore, the abstraction level of the robotic functions must be carefully designed for service applications and appropriately managed by the platform.

Multi-Area Management

To provide services over a wide area, coordination must be improved among multi-areas. To link several physical points, the platform requires a mechanism to share the spatial information of each area such as map information. It is important to share not only static spatial information like map information but also such dynamic location information as the locations of robots, users, obstructions, and target objects that change their relative and absolute location based on circumstances. For efficient multi-area coordination, this spatial and location information will be managed by a multi-layered management structure in which a local area layer manages the location information of each area and a global layer manages the relationship among local areas.

User Attribute Management

Since robotic services often provide support for physical tasks in user daily activities, robot systems must be properly equipped with functionalities based on the user situations. To support the activities of the elderly and disabled, for example, it is especially important to understand user abilities: walking ability and senses of sight and hearing. The platform will provide a mechanism for commonly managing such user attributes so that all services can choose proper robot systems by referring to the user information.

Service Coordination Management

To execute a number of services across multiple areas, the state of each area must be monitored to determine the start of the services so that the service can be executed in appropriate situations. The platform requires a mechanism for managing the state of the service execution environment. Furthermore, not only a mechanism to execute each service independently but also one to share information between each service is required for the platform.

4. Case Study

This section explores a case study from the Life Support Robot Technology project of Japan. As described in the first section, supporting the daily activities of people provides challenging research topics for cloud networked robotics.

Life Support Robot Technologies

The Life Support Robot Technology project started in 2009 in Japan and remains undergoing. It aims at the development of life support robots with high safety, reliability, and adaptability to enable robots to coexist with people in human living environments. It integrates robots with ubiquitous network technology into the social infrastructure.

In the project, six robotic services for the elderly and disabled are focused on for demonstration experiments: remote listening support service, community formation service, healthcare service, shopping support service, customer attracting service, and touring support service. This section introduces the touring service in a shopping mall (Fig. 2) [11, 12] as an example of a networked robotic service that is provided across multiple areas.

Common infrastructure system

In the project, the common functionalities described in the previous section are implemented as a common infrastructure system called the Ubiquitous Network Robot Platform (UNR-PF) [13]. Its structure is depicted in the dotted part of Fig. 3. First, service applications and robots in each environment are connected to UNR-PF and register with it. The applications and robots discover each other on the UNR-PF and start interacting among themselves.

UNR-PF itself is composed of two platform layers: a local platform (LPF) and a global platform (GPF). LPF is a platform for the robotic system in a single area; GPF is a platform for the robotic system that ranges over multiple areas covered by a number of LPFs. These platforms serve as a middle-layer between the service application and the robotic component layers. The platform is equipped with five database functions and three management functions to provide common services to the service applications and robots.

The database functions consist of robot, map, user, and operator registries, and service cues. The management functions consist of state, resource, and message managers.

The robot registry in LPF contains information about the robots available in a single area, such as robot IDs, shapes, mobility capability, and transporting capacity. The platform refers to this database to assign robots in a LPF suitable for service applications.

The map registry in LPF provides map information of the service execution environment, including the floor properties and information about movable and no-go zones. The map registry in GPF provides positional relations among single areas covered by LPFs to improve service linkage between areas.

The user registry in GPF globally manages information about service users to provide appropriate services and robots to users. This database contains the attributes of each user, such as user ID, call name, degree of walking ability, and sight and hearing abilities.

The operator registry in GPF globally manages information about the operators of robots and/or services. The database contains the available skills of all operators with their operator IDs. Therefore, service applications can hire operator assistance, if required, by the resource manager described below.

The service queues in both LPF and GPF manage the invocation of services. This database contains the ID of each registered service and information about conditions when invoked by the platform. When a service application registers itself to the platform, its ID and initiation conditions are stored in the service queue in the GPF. Then the GPF's state manager distributes the information to the service queues of appropriate LPFs based on the state notification from LPFs.

Message exchanges between service applications and robotic components are handled by message managers through a common interface. When the GPF manager receives a message from a service application, which is typically a request for a command execution, it refers to the registered profiles of the robotic components and delivers it to the suitable ones. When the LPF manager receives a message from its robotic components, i.e., state notifications, it looks up the subscribers of the notification and forwards them the appropriate state manager and/or service applications.

The state managers in LPF and GPF subscribe to the message manager for state notifications registered in the service queue. When the manager receives a state notification, it determines if the state complies with the start conditions in the service queue. If it does, the manager sends a message to the service application to start the service. The resource manager in LPF manages the assignment of such resources as robots and operators. After receiving a command execution message from a service application, it refers to the robot, user, and operator registries to reserve a suitable robot and an operator who can operate the service and the robot depending on the situation.

Field testing

We evaluated the effectiveness of our infrastructure prototype through field experiments on six service cases. This section again focuses on a shopping mall on a touring service that was provided through three areas: the user's home, the shopping mall, and the operator center. Fig. 4 shows its structure and interaction.

Suppose a user interacts with a virtual-type robot on her/his mobile device at home. First, the virtual-type robot connects to the LPF of the user's home (1), and the LPF relays the reservation information to GPF (2).

The touring support service application, which has already been connected to the GPF, receives the reservation notification (3). The service application registers a new service ID for the request and the start conditions of its service, i.e., the user's arrival at the shopping mall, to the service queue on the GPF (4). The GPF finds the shopping mall's LPF from its map registry and registers the service to the LPF (5).

When the user approaches the shopping mall, the virtual-type robot on the user's mobile device connects to the shopping mall's LPF and notifies it of the user arrival (6). The shopping mall's LPF determines that the state meets the start condition of the touring support service and notifies the service application of the invocation request (7, 8).

The service application then requests the resource manager to reserve the robot in the shopping mall (9, 10) and an operator (12, 13, 14). The resource manager refers to the user registry and selects a suitable robot (11). For touring support service, it selects a wheelchair robot if the user has difficulty walking.

After allocating the resources, the service is executed based on the service flow defined in the service application (15, 16, 17), which refers to the LPF's map registry and instructs the robot to move around the shopping mall.

The above scenario was executed in field experiments to demonstrate UNR-PF's effectiveness for the coordination of networked robotic services distributed in multi-areas. Four types of visible-type robots including a wheelchair robot have been operated in shopping malls. Three types of LRFs (laser range finder) have been used for constructing ambient intelligence. A remote operator could operate four robots in the environment at once.

Since the cases only covered part of the networked robotic services, further issues will arise in CNR research as such a platform becomes more widely used. Future research issues are addressed in the last section.

Standardization

The project also advances standardization activities for the key elements of its platform technologies. To share information among the robots and the service applications and achieve interoperability among different robots, we must standardize the specifications of the data structures and interfaces. We have been standardizing the following four key elements of the prototype system: map information, location information, common interfaces, and platform architecture (Fig. 5).

Map information is standardized in the Open Geospatial Consortium (OGC), a consortium for standards associated with geographical information. We have already requested extension to the *CityGML* specifications for allowing maps to contain robot-specific information [14]. This will be reflected in our next revision, version 1.1 in 2012.

To exchange location/pose information among various networked robot elements and robotic services, a standard specification for describing and exchanging location and pose information for robots has been issued as the

Robotic Localization Service (RLS) specification [15].

The standardization of common interfaces between service applications and robotic functional components is treated in OMG as the *Robotic Interaction Service (RoIS) Framework* specification, which was approved in June 2010 and is expected to be issued in early 2013.

The common platform architecture was discussed in the International Telecommunication Union Telecommunication Standardization Sector (ITU-T), study group 16 (SG16). The recommendation, *F.USN-NRP*, was accepted as a standardization work item in 2011 and is expected to be released in 2013.

5. Conclusion and Future Works

This article proposed the concept of *Cloud Networked Robotics*, which targets continuous support of daily activities that cannot be satisfied by stand-alone robotic services or by networked robotic services. Key research challenges were described through an examination of typical daily activities. As an example, an ongoing research project was described, including a prototype infrastructure implementation and field testing in a real world environment using this prototype. We also introduced the current status of standardization on some core elements of the prototype.

Although the case study realized robotic services to support some daily activities, the application domain was so limited that only few service coordination patterns were covered. To achieve truly useful robotic services, further examination is required. As such, we are planning to make our system publicly available so that researchers and application providers can utilize it for further testing.

The challenges in cloud networked robotics are not fully described in this paper. Many other aspects must be studied, including scalability and dependability. Robotic services supporting daily activity will become a critical element in our lives, and termination by accidents must be prevented. The resource allocation problem will also become more complicated concerning system complexity; it should practically handle cases of resource starvation.

Moreover, cloud networked robot systems will likely encounter security and ethical issues. Sharing user related information such as user attributes and service history will benefit from providing rich supporting services. But at the same time, privacy concerns will arise. Unlike the Internet, which is limited to cyberspace, robotic services are related to both the real physical world and cyberspace, and leakage or misuse of private information may lead to many serious problems. Besides technological challenges, such security considerations with legal and ethical issues will be considered in the future.

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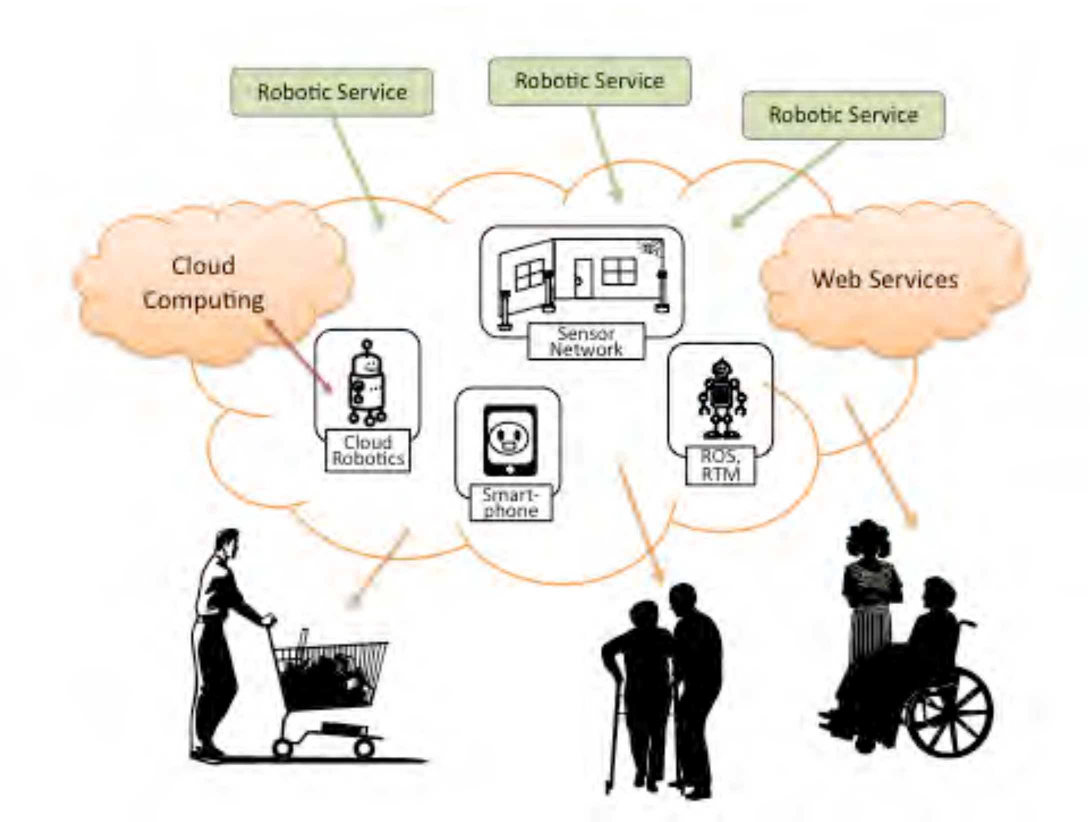

Fig. 1 In Cloud Networked Robotics, a platform layer located between service applications and robotic components isolates and coordinates them to realize multi-area, multi-robot networked robotic services.

Fig. 2 Scene from touring support service in shopping mall. Wheelchair robot navigates and interacts with people based on commands and environmental sensor information sent from the infrastructure system.

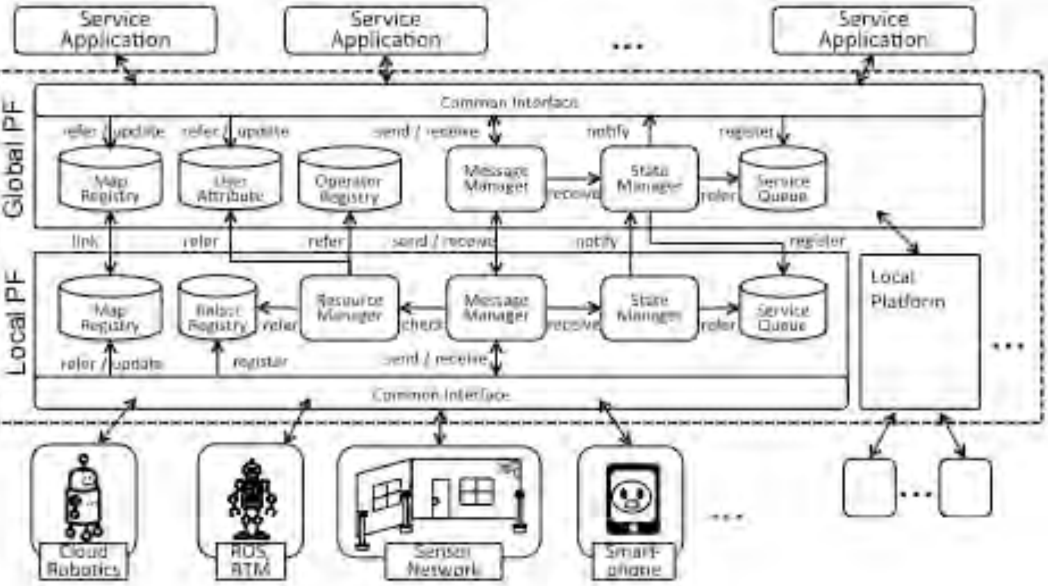

Fig. 3 Overview of ubiquitous network robot platform system. Platform provides common interface to service applications and robotic components and isolates each other.

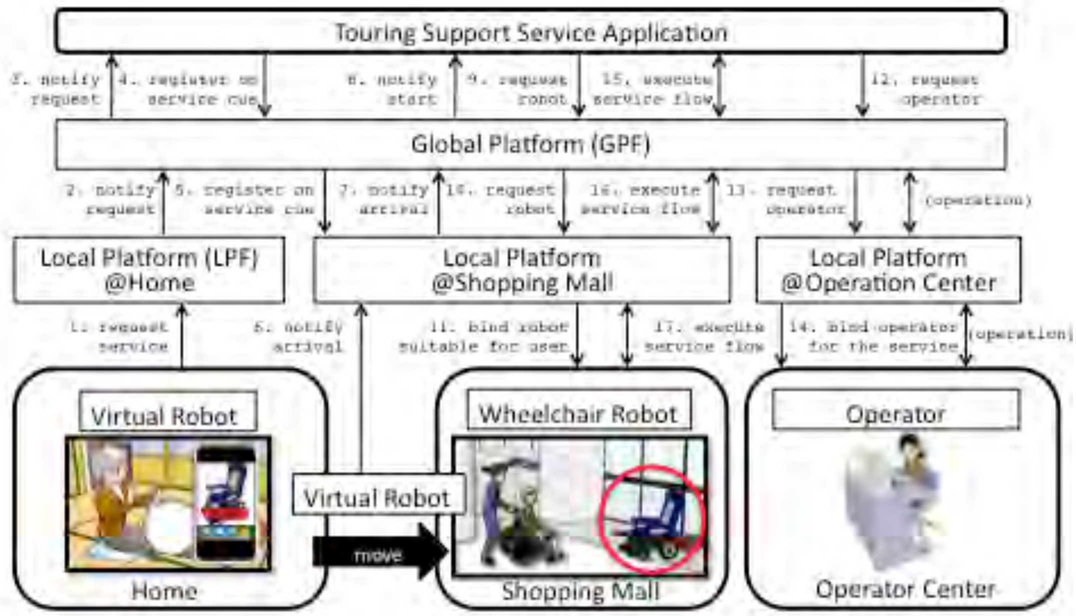

Fig. 4 Command sequence of touring support service. User can make reservations by a virtual-type robot at home. The service will prepare a wheelchair robot for disabled users on arrival based on user attributes.

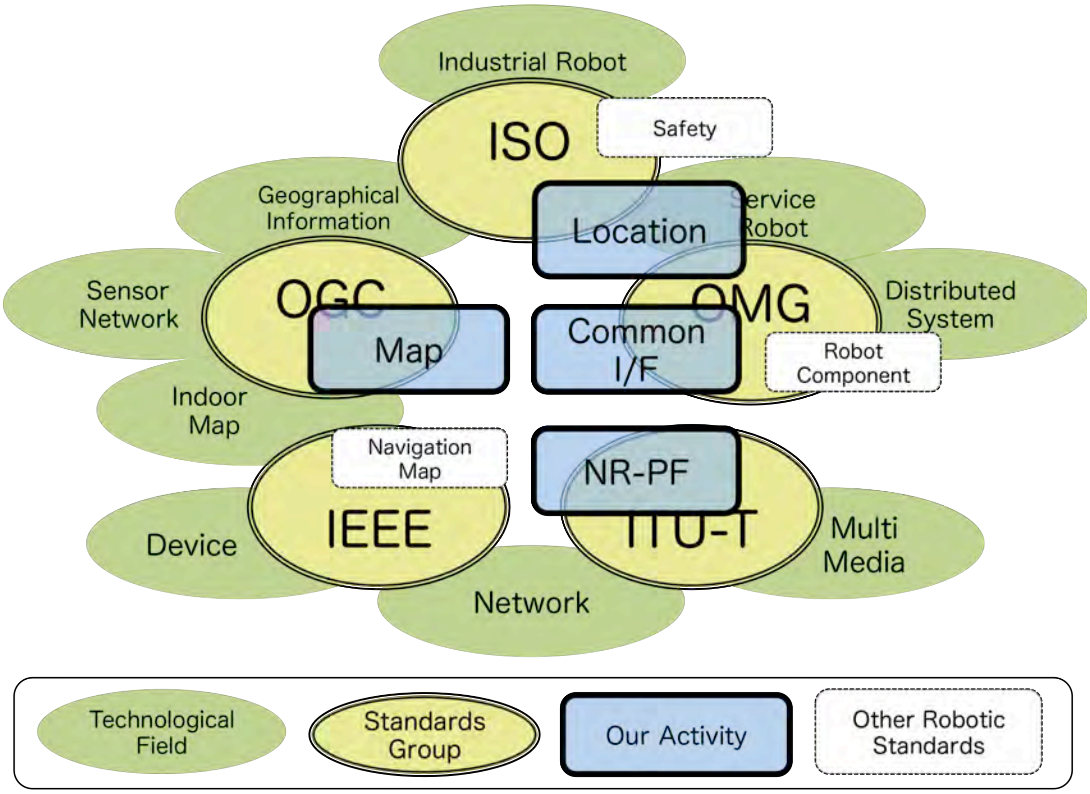

Fig. 5 Four key elements of platform technologies and corresponding standards groups