Ubiquitous Robot: A New Paradigm for Intelligence

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Abstract. This paper presents a systematic review of the recent development in ubiquitous robotics, with a focus on its implication on intelligence. Ubiquitous robot (Ubibot), the third generation robot, is characterized by its unprecedented power to sense environments and provide sophisticated services autonomously. Based on the architectures of existing Ubibot projects, we describe a general framework containing the perception, intelligence and execution modules as well as the middleware layer used to integrate the three modules to make them collaborate seamlessly. Two representative projects are introduced to exemplify the state-of-the-art progress in Ubibot, along with a brief discussion of various underlying communication techniques. In the perspective of intelligence, we point out that Ubibot opens up new horizons for investigating and applying popular AI techniques such as computer vision and pattern recognition, compared to traditional robots. Furthermore, a list of new challenging research topics is identified that deserve full consideration in the future to make Ubibot more robust, effective and adaptive.

Keywords: Ubiquitous robot · Middleware · Intelligence · Communication

1 Introduction

Ubiquitous robot (Ubibot) refers to the third generation robots following industrial robots (first generation) and personal robots (second generation) [1]. Ubibot is built upon classical robotics and the concept of ubiquitous computing, which was first proposed by researchers in the Robot Intelligence Technology (RIT) Lab., KAIST in 2002 [2]. Naturally, it is expected that robots can perform a variety of tasks in the increasingly complicated environment [3]. However, developing a standalone robot that can provide all desired services can be extremely expensive and time consuming. Instead, it is reasonable to combine robots with limited abilities via the ubiquitous network containing sensors and portable devices to provide a wide range of services promptly at much lower cost [4]. In this ubiquitous space (U-space), people can gain access to required services anytime, anywhere and in various ways.

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Each personal robot is typically a standalone platform with a computer and wired network, providing "one person, one robot, and user-commanded" services [5]. This class of robots is characterized by the spatially localized entity, which prevents them from serving humans better [1]. By contrast, Ubibot removes the necessity of the conventional notion of a single platform by defining three components: intelligence, perception and execution. In practice, these three components are implemented by software robots, sensors and devices, and mobile robots, respectively [6]. This multi-robots platform breaks the spatial limitation of traditional robots and can provide users with seamless context-aware services timely via wireless ubiquitous network whenever the environment changes, providing "one person, many robots, seamless and context-aware" services [5].

Ubibot is closely related to networked robots (the two terms are sometimes used interchangeably by researchers) as the components of Ubibot need to exchange data via the network frequently. With the help of networks, the sensing and operating ranges of robots can be extended, allowing them to communicate with each other over long distances to coordinate their activity [7]. The key difference is that Ubibot is a collection of robot components, instead of fully functional robots. Also, the communication among components is likely to be much more complex and intensive as they need to collaborate extensively to finish a specific task (just imaging the level of collaboration required among eyes, brain and legs for human to walk properly).

Another related concept is cloud robot that employs cloud technologies such as cloud computing, cloud storage and other Internet technologies to enhance the capability of single-robot platforms [8]. Cloud robots can benefit from the powerful computing and storage resources (e.g., knowledge base) in the cloud and share information with other robots and smart agents. By contrast, Ubibot focuses more on the collaboration of various components, although the intelligence module can also invoke cloud technologies when necessary.

In 1985, Brady defined robotics as "the intelligent connection of perception to action" [9]. Traditional robots are often designed for a single scene and tasks are statically preprogrammed during the production process. As a result, they are unable to provide adaptive services as well as operate in uncertain and dynamically changing environments. Featuring context-awareness, self-learning and higher-level intelligence, Ubibot can sense changes in the environment continuously via advanced communication technologies and make proper decisions/actions [10]. In other words, Ubibot is an ensemble of mini-robots with specific functions distributed in the space and, when strategically combined together, they can be regarded as a single powerful virtual robot. More importantly, since Ubibot always exists as a collection of interacting components, there are many challenging issues that require intelligent solutions, including the optimal utilization of hardware/software resources and the reconfiguration of components in the event of partial system failure.

Section 2 presents a general architecture of Ubibot and two representative case studies. Section 3 introduces the underlying communication technologies used in Ubibot while Sect. 4 gives an in-depth analysis of the implication of Ubibot on intelligence. This paper is concluded in Sect. 5 with some discussions and prospects for future Ubibot systems.

2 Ubiquitous Robot Systems

2.1 General Architecture

As an emerging field of robotics, the notion of Ubibot was created by Jong-Hwan Kim et al. [11]. Afterwards, Bong Keun Kim et al. developed the ubiquitous function services [12] and provided a simulation framework for Ubibot and sensors using RT-Middleware [13] to better solve the ubiquitous localization and mapping problems. Saffiotti et al. presented the vision of an Ecology of Physically Embedded Intelligent System (PEIS-Ecology) and developed a technique for autonomous self-configuration and reconfiguration as well as a robotics middleware structure to cope with highly heterogeneous systems [14]. Yong-Guk Ha et al. investigated the problem that the robot system needs to be interoperable with sensors and devices in its dynamic service environments automatically [15]. Furthermore, Yukihiro Nakamura et al. introduced a framework for the network robot platform (NWR-PF) and a service allocation method for heterogeneous distributed robots [4].

Despite of the diversity of Ubibot in applications and functionalities, Fig. 1 gives the common architecture of Ubibot systems. According to this architecture, Ubibot is divided into three modules: intelligence, perception, and execution modules. The intelligence module refers to software applications with self-learning ability that can interact with human and environment. Due to the essence of software, they can also move anywhere in the ubiquitous network. The perception module contains hardware facilities such as sensors, cameras and other smart devices embedded in the environment. When combined with processors, they can gather and process video, voice, and position data

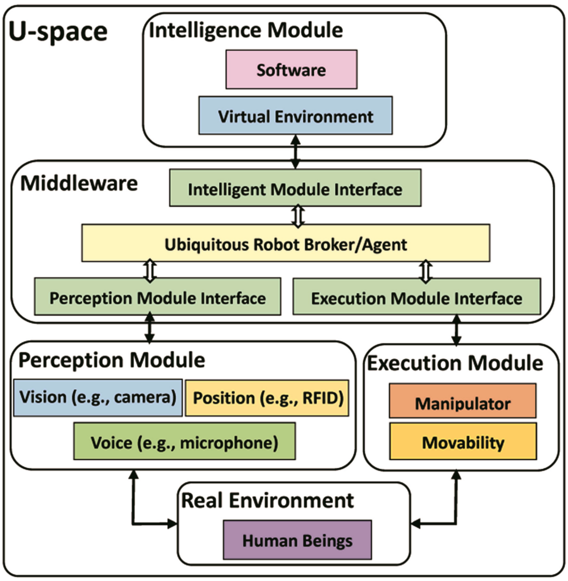

Fig. 1. The general architecture of ubiquitous robot systems

from the environment and provide valuable information to other robot components. The execution module resembles the hands and feet of traditional robots, which can move physically and provide various services. Furthermore, the mobile components can also be regarded as a complementary data acquisition platform, gathering additional information about the U-space by exploring the physical environment. Meanwhile, Fig. 1 contains a component named middleware. This is an independent system or service program for source sharing and communication within and among robot components via a variety of network interfaces and protocols. The middleware structure usually contains three interfaces to link corresponding modules and one broker to enable the system to make an offer of service irrespective of the operating structure, position and type of interface [1].

2.2 URC (Ubiquitous Robotics Companion) Project

The URC project is a conceptual vision of ubiquitous service robots proposed by KAIST in 2003 to provide users with required services, anytime and anywhere in ubiquitous computing environments [16]. To realize URC with robot systems automatically interoperable with sensors and devices, this project designed and implemented a Semantic-based Ubiquitous Robotic Space (SemanticURS), which enables automated integration of networked robots into ubiquitous computing environment, exploiting Semantic Web Services and AI-based planning technologies. According to robots' functions and roles in the U-space, Ubibot was divided into three categories: Software Robot (Sobot), Embedded Robot (Embot), and Mobile Robot (Mobot), corresponding to the three modules in Fig. 1. These three classes of components were implemented separately and connected via network and middleware.

For the middleware, researchers proposed a multi-layered architecture of ubiquitous robot system for integrated services [17]. It consists of five layers: software agent layer, Sobot management layer, context provider/task schedule layer, device management layer and physical layer. In this architecture, Embots and Mobots in physical layer directly operate within the ubiquitous environment while Sobots in software agent layer are transferred into various Mobots services. The proposed middleware was implemented and simulated with virtual sensors in the virtual environment.

2.3 NRS (Network Robot System) Project

The NRS project is a five-year research plan on Ubibot proposed by MIAC (Ministry of Internal Affairs and Communications, Japan) in 2004, which aimed at establishing fundamental Ubibot technologies that can greatly improve the ability of recognition and communication, compared with the single-robot platform. The goal of this project was to establish a multi-robots service platform in commercial district. A structured platform of environmental information was built for detecting people's locations and actions by installing cameras, laser range finders and RFID tags in the urban pedestrian street, Osaka. With this platform, robots can acquire information about people's locations and actions, in order to provide them with route guidance and targeted information about surrounding stores.

Similarly, researchers divided Ubibot into virtual-type robots, inconspicuous-type robots, and visible-type robots, corresponding to the three modules in Fig. 1. To integrate heterogeneous distributed robots, a network robot platform (NWR-PF) was introduced with three layers: connection units, area management gateway, and robot-user interaction database [4]. Firstly, the connection units use device-dependent protocols to obtain data from robots and then generate the status of users and robots in the 4Ws (When, Who, Where, What) format. After receiving the information from connection units, the area management gateway determines the most suitable combination of scenario and robots and controls service execution. The robot-user interaction database stores the information of the users, robots and services submitted from the connection units. Meanwhile, another simulation framework for Ubibot using RT-Middleware was also developed [13]. In this scheme, sensors and robots are implemented as RT components and combined by RT-Middleware. Since RT components have common interface module, they can be reused to lower the cost of development.

3 Ubiquitous Communication

In this section, various communication techniques are briefly introduced, which can be adopted in Ubibot to enable collaboration and interaction among different Ubibots (mainly wired communications), as shown in Fig. 2(a) or different modules within the same Ubibot (mainly wireless communications), as shown in Fig. 2(b).

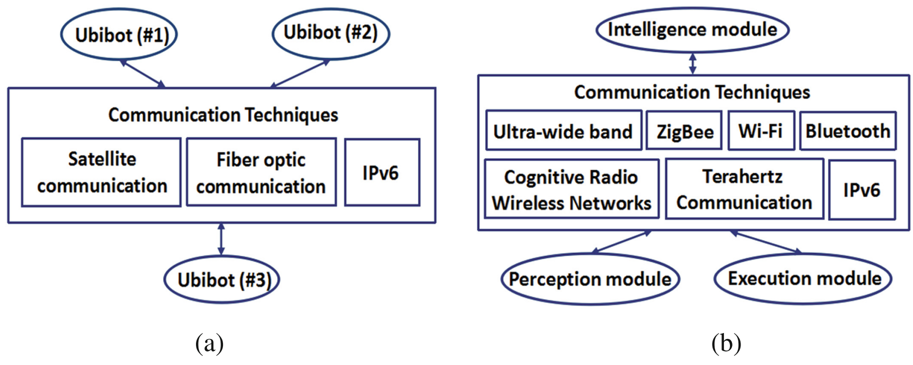

Fig. 2. Ubiquitous communication: (a) among Ubibots; (b) within Ubibot

Fiber optic communication plays an important role in telecommunication infrastructure for broadband networks. It can provide enormous and unsurpassed transmission bandwidth with negligible latency, and is widely used for long distance and high data rate transmission in telecommunication networks [18]. Satellite communication is also an alternative, which can be used to connect sparsely distributed Ubibots.

Short-range wireless communications are dominated by four protocols: Bluetooth, ultra-wide band (UWB), ZigBee, and Wi-Fi, corresponding to IEEE 802.15.11, 802.15.3, 802.15.4, and 802.11a/b/g standards, respectively [19]. Bluetooth is used for wireless personal area network (WPAN) and can be used in perception module for transmitting data to intelligence module. UWB, on the one hand, can be used for indoor short-range high-speed wireless communication [20]. ZigBee is a low data rate WPAN within 10 to 100 m. It features low power-consumption, multi-hop, and reliable mesh networking, making it appealing to battery powered devices. Wi-Fi can be used in the general situation to transmit data among various modules.

There are also many next-generation communication techniques that can be applied in Ubibot, such as cognitive radio wireless networks [21], terahertz communication technology [22, 23], and quantum communication [24]. Different from today's wireless networks regulated by the spectrum assignment policy, cognitive radio wireless networks can exploit existing wireless spectrum opportunistically. So, it can provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques [21]. Terahertz radio (0.1–10 THz) is characterized by high data transfer rate, good directivity and high transmittance [23]. Terahertz communication is envisioned as a key technology to satisfy the increasing demand for high speed wireless communication as it can alleviate the spectrum scarcity and capacity limitations of current wireless systems. It enables new applications in classical networking domains as well as in novel nanoscale communication paradigms [25]. Quantum communication combines classical communication and quantum mechanics and includes quantum teleportation, quantum superdense coding and quantum cryptography, ensuring highly secure communications.

4 Ubiquitous Intelligence

4.1 New Opportunities

Ubibot features unprecedented flexibility, versatility and robustness compared to traditional robots. For example, a standalone robot often has very restricted field of vision, limited by the single camera mounted on it. Its mobility is also limited, making it difficult to provide services in a wide area promptly. What is even worse is that a single component (e.g., camera) failure can result in the total loss of functionality of the robot. By contrast, Ubibot contains multiple sensing devices of different types, which are distributed in the U-space, providing a full range of sensing capabilities (Fig. 3). Also, multiple mobile components can be scheduled to provide services with minimum latency. Furthermore, due to the existence of components of similar functionality, Ubibot is intrinsically fault-tolerant. As a result, Ubibot has much better capability in sensing and interacting with the environment as well as providing a variety of services. Through reconfiguration, Ubibot can also handle component failures without significantly compromising its functionality. This feature is particularly important for military applications and aerospace industry where robots often need to work in severe and hostile environments.

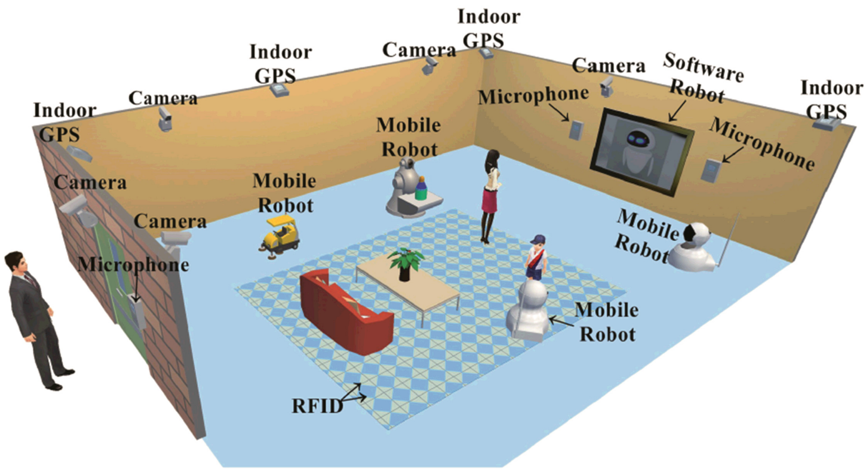

Fig. 3. An example of the Ubibot system. It shows the three key modules: perception (cameras, microphone, indoor GPS, RFID), intelligence (software robot) and execution (mobile robots).

Ubibot also provides potentially much wider opportunities for machine intelligence. For example, computer vision is one of the key techniques in robotics. It is essential for a robot to accurately recognize the surrounding environment to avoid obstacles on its path or grab an object. To provide more personalized services, it is desirable that the robot can identify different users using face recognition techniques. With the help of multiple cameras, Ubibot can acquire richer image/video information, which can dramatically increase the accuracy of recognition. For example, given multiple images of the same object from different angles, a super-resolution image can be constructed with more details [26]. Meanwhile, high-quality 3D reconstruction also becomes feasible, which can greatly help robots understand the shape of objects. With the RFID tags located on the floor, Ubibot can precisely identify the location of human, even in a totally dark situation. In the housekeeping scenario, Ubibot can easily find a misplaced item or provide crucial fall detection service for elderly people. By contrast, due to the limitation of sensing, traditional robots may not be able to be aware of the emergency and raise the alarm in a timely manner.

4.2 New Challenges

As a brand new class of robots, Ubibot itself creates a series of unique technical challenges that needs to be properly addressed to make Ubibot work efficiently and reliably. A list of possible research topics is as follows:

- *Optimal Planning Problem*. For example, in Ubibot, video cameras may be fixed on the ceiling in an indoor setting but can be also mounted on a UAV (Unmanned Aerial Vehicle) or an AGV (Automatic Guided Vehicle) for extended surveillance range. Due to the limited onboard power supply and tight restriction on the data acquisition latency, Ubibot needs to optimize the route and schedule of UAVs or

AGVs to fulfill the above objectives. This problem is related to TSP with Neighborhoods (TSPN) [27] with the additional factor that multiple agents can collaborate to finish the data collection. Similarly, given multiple users to be serviced/tasks to be fulfilled, there is also a need of intelligent algorithms for scheduling one or more mobile components.

- *Load Balancing Problem.* Since Ubibot can continuously receive information from the environment, the amount of streaming data to be processed is significantly greater than in traditional robots. In the presence of multiple intelligence components, there is a requirement for properly balancing the workload on each component so that all data can be processed with minimum delay. Furthermore, certain tasks may be passed onto external computing facilities in the cloud for better processing capability. There are several factors that need to be taken into account to ensure efficiency, such as current workload level, task type, security requirement, timeliness, communication overhead, data parallelism vs. task parallelism, priority and granularity.
- *Reconfiguration Problem.* One of the most distinctive features of Ubibot is its capability of reconfiguration to cover component failures or extend system capacity. Components should be self-aware and self-organizing, requiring little if any human intervention. For example, newly added components should automatically be configured and added into Ubibot, following the "plug-and-play" paradigm. When one or more components become inoperative, other components should adjust their technical parameters (e.g., surveillance range) to maintain coverage and capability. Note that in military applications, some components may be deliberately designed as disposable devices, such as the warhead for intercepting missiles or satellites. With the reconfiguration feature, most other components (e.g., sensing and intelligence) in Ubibot can be reused, reducing system cost dramatically.
- *Self-Adaptive Component Problem.* Once deployed in the ocean, on the land or in the orbital space, Ubibot should require minimum service from human. In face of the unforeseen environment changes, components in Ubibot should be self-adaptive to some extent and update their functionality to better suit the new operational environment or compensate for faults. This attractive feature can be achieved using the idea of evolvable hardware [28], which applies EAs (Evolutionary Algorithms) to evolve a population of candidate circuits and implements the solution in FPGA. This is particularly appealing when there is no sufficient prior knowledge on circuit design and the specification only states the desired behavior of the component.
- *Ubiquitous Modeling Problem.* It is essential for a robot to build a systematic model of its working environment. In general, the U-space can be seen as a sophisticated data acquisition and processing platform and Ubibot can build comprehensive models using the diverse data acquired from various sensors. For example, Ubibot can monitor and record the movement of human users and conduct trajectory mining to better understand their behavior patterns, in order to provide more personalized services. Meanwhile, Ubibot can analyze the historical data regarding the occurrence of key tasks and the amount of processing time required, to obtain insightful guidance for maximizing the utilization of resources. A key issue is that the data is produced by various devices and is likely to be stored separately. Consequently, distributed modeling/mining techniques are required to create a unified view of the data.

5 Conclusion

As the third generation robot, ubiquitous robot has been developed following the paradigm shift of robotics and ubiquitous computing, which can provide services anytime and anywhere. Based on various existing Ubibot projects, we present a general architecture of Ubibot consisting of three modules: intelligence, perception, and execution, which correspond to software robots, sensors and devices, and mobile robots, respectively. A middleware layer is used to integrate the three modules to make them collaborate seamlessly. Meanwhile, two representative Ubibot projects (URC and NRS) are introduced to demonstrate their principles. Furthermore, typical communication techniques are discussed to highlight their unique characteristics. We point out that, Ubibot brings more opportunities for current AI techniques and significantly extends their applicability in robotics. More importantly, Ubibot comes with new technical challenges that deserve in-depth investigation and competent techniques are to be developed to ensure its efficiency, flexibility and robustness.

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