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Testbeds for ubiquitous robotics: A survey

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HIGHLIGHTS

- Surveys ubiquitous robotics systems comprising multirobot systems and sensor networks.
- Proposes a taxonomy based on heterogeneity and interoperability among technologies.
- Features analyzed include heterogeneity, generality, flexibility, and usability.
- Identifies trends and gaps, proposing guidelines for researchers and developers.

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ABSTRACT

The growing interest in ubiquitous robotics has originated in the last years the development of a high variety of testbeds. This paper presents a survey on existing ubiquitous robotics testbeds comprising networked mobile robots and networks of distributed sensors, cameras and smartphones, among others. The survey provides an insight into the testbed design, internal behavior and use, identifying trends and existing gaps and proposing guidelines for testbed developers. The level of interoperability among different ubiquitous robotics technologies is used as the main conducting criterion of the survey. Other features analyzed include testbed architectures, target experiments and usability tools.

1. Introduction

In recent years robotic technologies have been integrated with a variety of technological fields in the context of ubiquitous systems. The spread of technologies such as personal mobile computing, camera networks, wearable computing, RFID and Wireless Sensor Networks (WSNs) indicates that we are already living in a ubiquitous world in which all devices are fully networked. The term *ubiquitous computing* was coined by Mark Weiser [1]. His vision foresees everyday objects having some form of computation capacity and, in most cases, sensing and communication facilities. The name *Networked Robots* was created in May 2004 within the IEEE Robotics and Automation Technical Committee, as a consequence of the preliminary work on Internet-based tele-operated robots [2]. The name *ubiquitous robotics* refers to the juxtaposition of networked robots and ubiquitous computing, using robots as devices within a ubiquitous computing system.

The interest in ubiquitous robotics has originated a growing demand for tools for testing and validating algorithms and methods. Although in some domains evaluation and validation with data sets or simulations is widely used, the complexity of ubiquitous robotics makes it necessary to have feedback from real experimentation, which provides a degree of realism that cannot be obtained with simulations.

Recently, the development of testbeds for cooperating mobile robots and sensor networks has increasingly intensified in number and variety. Currently, there exist testbeds that integrate a variable number of robots, which can be homogeneous or heterogeneous [3–26]. There exist testbeds that integrate sensor networks based on WSNs [27–52], cameras [53–59], tablets and smartphones [60–64]. There are testbeds that partially integrate some of these technologies [65–81] and there are some testbeds that fully integrate elements from all these technologies [82–87]. Some of these testbeds are designed to hold general experiments whereas others target specific functionalities or applications. One clear trend is the increase in the level of integration between robotic systems and sensor networks.

This paper presents a survey on existing testbeds for ubiquitous robotics. The starting point of the review is a classification of testbeds, focusing on the level of integration between different ubiquitous technologies: testbeds are classified as non-integrated, partially integrated and highly integrated. Other features such as heterogeneity, flexibility, modularity and usability are also analyzed. The paper has two main objectives. First, it presents the current state of the art focusing on identifying trends, commonalities, gaps and desirable features. Second, it aims to help researchers

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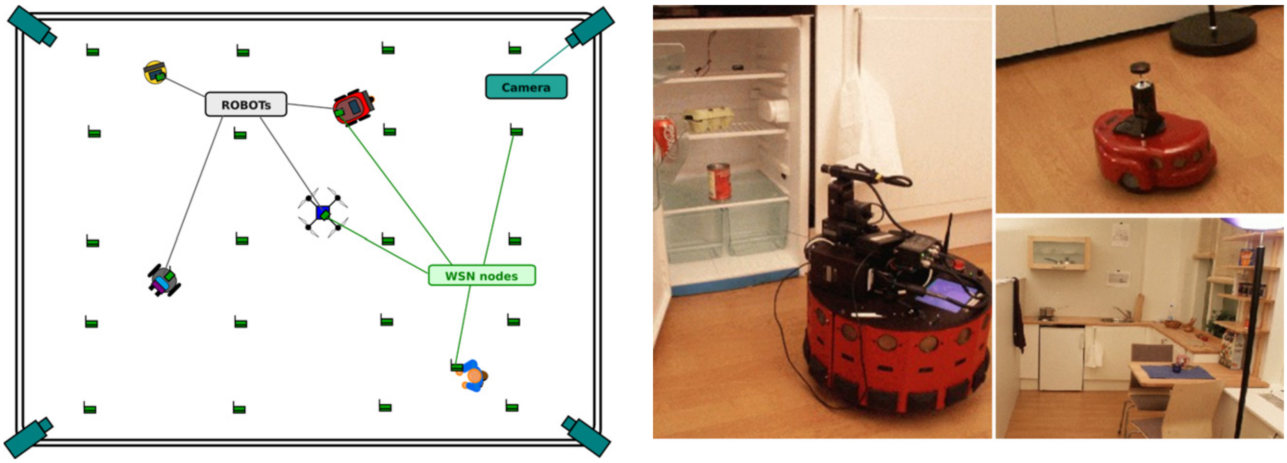

Fig. 1. (Left) Setting of the *CONET Integrated Testbed* [85] integrating mobile robots, a camera network and a WSN with static and mobile nodes carried by robots and/or people. (Right) Pictures from the PEIS testbed [84].
Source: (courtesy University of Örebro).

in the selection of the most suitable testbed for their particular method.

The survey is structured as follows. Section 2 presents a brief overview of the main components of existing ubiquitous robotics testbeds in order to introduce their classification according to the level of interoperability among heterogeneous technologies. Non-integrated multirobot and sensor network testbeds are analyzed in Sections 3 and 4, respectively. Partially integrated testbeds are described in Section 5. Highly integrated testbeds are reviewed in Section 6. Found tendencies and suggestions to testbed developers are discussed in Section 7. Finally, Section 8 concludes the review.

2. Classification of existing ubiquitous robotics testbeds

This section is divided into three parts. The first one briefly analyzes the main components used in existing testbeds. The second, classifies testbeds using the level of interoperability among technologies. The third, classifies testbeds under other criteria of interest.

2.1. Main components

Ubiquitous robotics integrates a wide variety of heterogeneous technologies including networked mobile robots, WSN and RFID networks, camera networks and networks of personal mobile computing devices. These technologies have been divided in two groups: ubiquitous systems with and without physical actuation capabilities. The first one falls in the domain of robots. These devices can move, carry sensors or other ubiquitous systems and can interact with the environment. The second includes technologies based on nodes with sensing, computational and communication capabilities that organize autonomously into networks. It groups WSN and RFID networks, camera networks and personal mobile computing networks. These devices can sense the environment, can interact with humans and can perform actions such as turning lights on, but they cannot perform physical actions and are static unless mounted on robots or carried by humans. Through the paper we refer globally to them as sensor networks (SNs).

In ubiquitous robotics testbeds multirobot (MR) systems can be comprised of ground, aerial or marine robots. Ground robots typically use small or medium sized platforms and include sensors such as cameras, RGB-D sensors, laser range finders, ultrasound sensors, bumpers, GPS receivers and Inertial Navigation Systems. Aerial robots, although limited in payload and, thus, in onboard sensing and processing, can move in 3D. Vertical take-off and landing quad-rotors are the most commonly used, although blimps, fixed-wing platforms and helicopters are also found in outdoor testbeds. Underwater or surface vehicles are rarely found in ubiquitous robotics testbeds.

Wireless Sensor Network nodes can be integrated with many sensors including from Surface Mounted Devices to GPS receivers and small cameras. Their radio circuitry can measure the strength of incoming messages (RSSI). Their communication protocol can range from proprietary to standard solutions such as IEEE 802.15.4. Camera networks are frequent in ubiquitous robotics testbeds. For scalability and bandwidth efficiency most adopt schemes with decentralized image processing. Also, the popularization and improvement of performance of smartphones and PDAs has boosted their use in testbeds motivated by the possibilities of exploiting large amounts of measurements from a huge number of users.

Sensors integrated in the above platforms have a high degree of heterogeneity. While low cost, low size and low energy constrain the features of sensors integrated in SN platforms, robots can carry and provide mobility to sensors with higher performance. The same applies to their communication networks. WSNs were designed for low-rate and low-range communications whereas Wi-Fi networks, typically used by multirobot systems, can provide up to 36 Mbps (experimental bound) at greater distances.

Testbeds need an architecture to integrate these heterogeneous components. A high percentage of the testbed flexibility, extensibility and scalability depends on its architecture. If the testbed is designed to solely serve one experiment or functionality, its architecture tends to be monolithic. In contrast, the architecture of general purpose testbeds with open public access tends to be modular and use standard interfaces and Open Source software. Some testbeds include usability tools such as simulators and tools for experiment programming, logging and monitoring.

The purpose of a testbed as an experimental tool is twofold. In some cases they provide a controlled environment to allow algorithm testing and debugging with simulation-like conditions. In other cases they are used to fill the gap between research and market, enabling testing in conditions close to the final application. The former are usually placed in indoor laboratories. The latter are typically deployed in settings, which can range from office buildings to an entire city. Fig. 1 shows pictures of the settings in two ubiquitous robotic testbeds.

2.2. Classification according the level of interoperability among technologies

The integration between heterogeneous technologies is critical for ubiquitous robotics. It is the main criterion in our classification,