Design and Development of Robotic Systems Based on IoT Platforms for a Hyper-Connected Society

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Abstract. Due to the rapid advancement of robotics and AI technologies, the demand for various services is increasing. While new technologies for robots have been proposed, the actual commercialization of robots remains slow. The reason is that robotic services have not yet been fully integrated into everyday life. Therefore, it is time to discuss how to design and propose robot systems that can meet real users' needs. Our research is focused on designing and developing a robot system for human support. The robot system has been proposed as a central system where a robot partner interacts with humans using smart devices. It is being developed in conjunction with smart home systems to enhance the connectivity of smart devices as a service. Additionally, mobility systems that consider user movement and drone systems to support more proactive services are also being developed in collaboration. This paper provides a comprehensive explanation of our research, with a focus on designing and implementing a robot system suitable for IoT platforms in the hyper-connected era.

Keywords: Modular Robotic System · IoT Technology · Human-Centric System · Hyper-Connected Society

1 Introduction

Recently, with the full-scale digital transformation (DX) [1], robots are being utilized in places like industrial factories and restaurants. As these robots advance, countries with high aging populations are accelerating robot development to cope with the challenges of low birth rates and aging societies [2]. In particular, as the number of elderly people living alone increases, various types of robots are being proposed to provide services that ensure their quality of life [3–5].

Recent advancements in services involve not only the robots themselves but also integrating internet of things (IoT) to connect various home appliances, known as smart home devices [6]. Now, rather than focusing on developing individual robots, it is more important to examine and develop what kind of services can be provided to users. As a result, many studies are underway to implement the internet of robotics things (IoRT) using robots in real living spaces [7, 8]. This connectivity allows robots to interact not only with humans but also with their surroundings, enabling the provision of more diverse services [9]. Specifically, with the integration of human sensing technology and IoT, it is believed that robots will not only be capable of providing basic services but also tailor their services according to human conditions [10]. These technologies are also considered to be applicable as a user support system in a hyper-connected society enabled by 5G [11]. Therefore, we began developing an IoT-based robot partner using smart devices [12].

As shown in Fig. 1, a robot partner using smart devices has been proposed as a central system for interacting with people [13]. To ensure the connection with such robot systems, a system using the ESP32 microcontroller has been developed [14]. To enhance the connectivity of smart devices as a service, it is being developed in conjunction with smart home systems [15]. Additionally, mobility systems that consider user mobility [16] and drone systems for supporting more proactive services are also being developed in coordination [17]. This paper comprehensively explains these studies and focuses on designing and implementing a robotic system suitable for the IoT platform in the hyperconnected era.

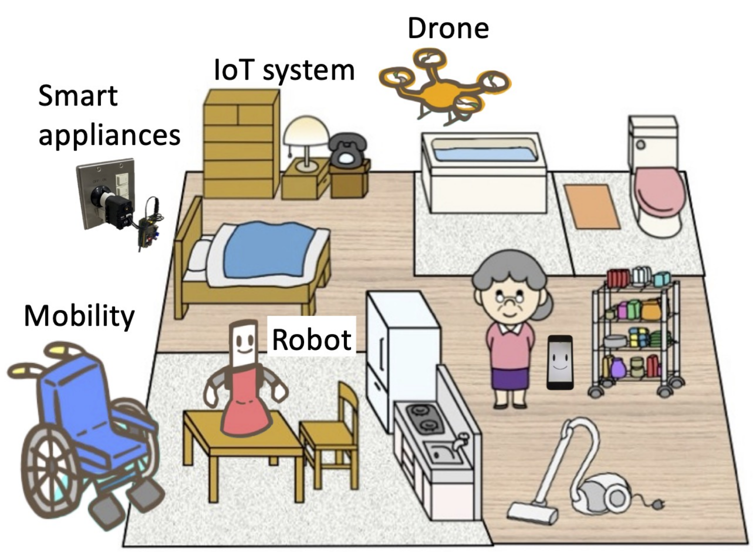


Fig. 1. Overall structure of the research system.

2 Robotic Service Systems for Social Implementations

In this chapter, we explain the development of the robot system. In today's connected world, we can conveniently gather information anywhere. Throughout society, there is a movement toward transitioning to a hyper-connected society [18]. Robotic systems for user support have become increasingly prominent as they offer innovative solutions to enhance the quality of life for individuals, particularly the elderly and those with disabilities.

Our robotic system employs a modularized architecture for robot partners using smart devices to achieve flexible updates based on the reusability of hardware and software modules. Modules from robotic systems are being developed for application not only in robots, but also in mobility devices, drones, and other IoT systems, as shown in Fig. 2.

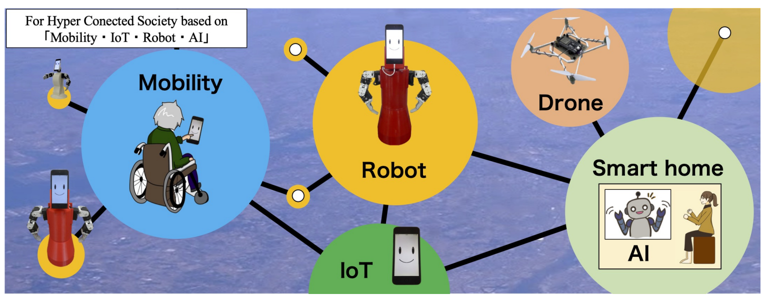


Fig. 2. Development of a robotic system for a hyper-connected society.

2.1 Socially Embedded Robot Partner System Using IoT Technology

Previously, we conducted empirical experiments in nursing homes to develop robot partners for social implementation [10, 19]. Through the analysis of these experiments, we concluded that for service robots, we should focus on developing a customized robot system that meets the needs of each individual, rather than a robot with a specific design. Therefore, we focused on developing a robot system using smart devices that can be easily customized for each user [13].

This robot consists of an ESP32 microcontroller that can communicate wirelessly with smart devices and is designed to expand its movements and functions using a 3D printer as shown in Fig. 3. The ESP32 is a microcontroller with built-in wireless communication capabilities, widely used for implementing IoT systems [14].

In addition, software and hardware were developed to create a robot system tailored to the user's requirements [20–22]. By integrating a smartphone into the monitor section, the robot's facial expressions are displayed. Additionally, we considered several ear attachment designs, including those of a cat, rabbit, and panda [23]. The overall design of the robot can be determined by the chosen ear attachments (Fig. 4). These systems need to be further developed from an engineering perspective to enhance their visually appealing aspects following “individual preferences” and “diversity”.

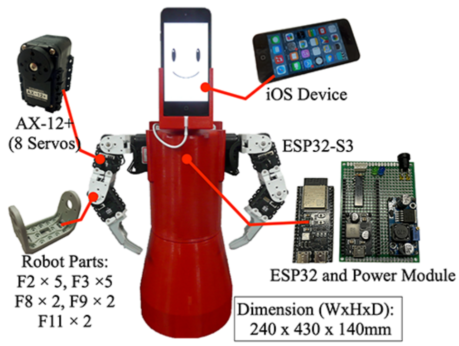


Fig. 3. A robot partner developed utilizing smart device technology.

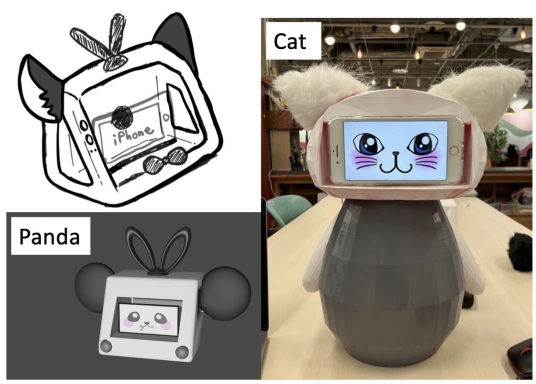


Fig. 4. A robot partner system designed for modular expansion through the exchange of components [23].

2.2 Robotic Control Module Utilizing ESP32

We are developing a robot system using Espressif Systems’ ESP32 microcontroller to connect with smart devices and implement an IoT system as shown in Fig. 5. This research involves developing a low-power microcontroller equipped with Wi-Fi and Bluetooth wireless communication functions. This microcontroller is intended for use not only in robot control but also in IoT applications for indoor systems, such as controlling analog home appliances.

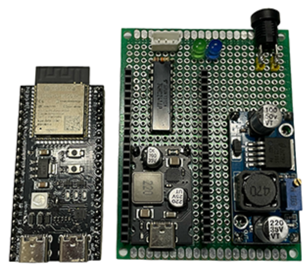
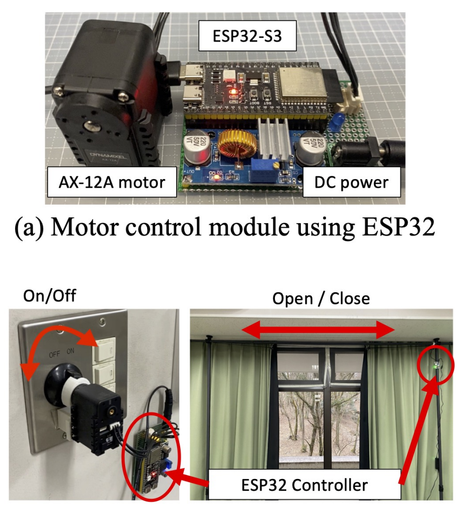


Fig. 5. Microcontroller System for Controlling Motors.

In Fig. 6, this control unit consists of an ESP32-S3 microcontroller and AX-12A servo motor to control home appliances.



(a) Motor control module using ESP32

(b) Home appliance control system

Fig. 6. Control of home appliances using ESP32 microcontroller.

3 User Analysis and Service Provision Utilizing Mixed Reality Technology

As the demand for remote user support systems leveraging digital technology increases, user-customized systems employing digital twin technology are under development [24]. Furthermore, digital twin technology is also being employed for jet engine maintenance [25]. A digital twin is a model that accurately replicates a physical object or system in a digital virtual world. By utilizing this model, we can explore methods to enhance remote work efficiency. To develop such a system, we are utilizing Microsoft's HoloLens 2 in the development of our robotic system as shown in Fig. 7. This device has the specifications shown in Table 1 and can measure gaze and hand gestures. By using this measurement system, the implementation of tailored services is feasible.

(a) Front view (b) Top view

Fig. 7. Head-mounted display for a mixed reality environment: Microsoft HoloLens 2.

Table 1. Specifications of Microsoft HoloLens 2

Itens	Specification
Dimensions	247.90 x 163.07 x 378.97mm
Weight	566g
Display	See-through holographic lenses
Head tracking	4 visible light camera
Eye tracking	2 IR cameras
Depth	1-MP time-of-flight (ToF) depth
IMU	Accelerometer, gyroscope, magnetometer
Camera	8-MP stills, 1080p30 video

Fig. 8 shows the experimental setup for building a digital twin system. By incorporating digital twin technology into this system, it becomes possible to monitor the condition of a building from outside and control smart home appliances as shown in Fig. 9. Additionally, as shown in Fig. 10, linking a virtual robot with a real robot enables seamless services that transcend distance and location.

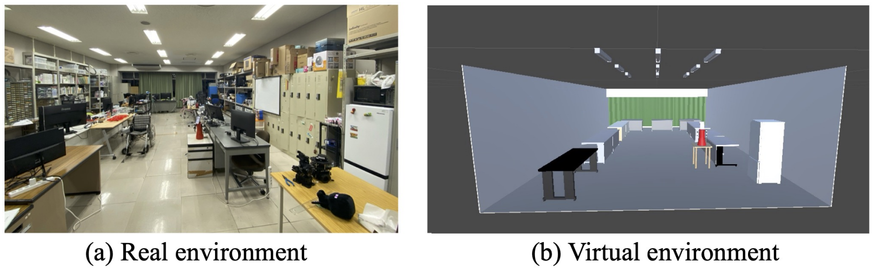


Fig. 8. Development of an experimental environment for applying digital twin technology.

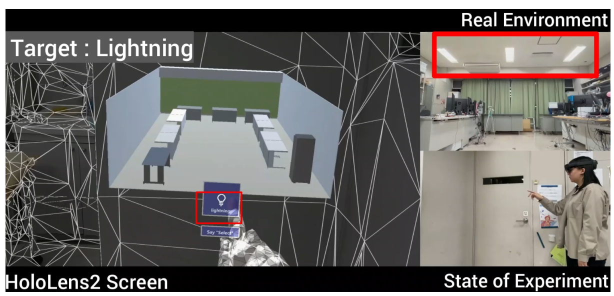


Fig. 9. Development of a smart home appliance control system.

4 Mobility System with Functional Expandability

In the case of user support robots, their assistance is typically restricted to indoor environments. However, an individual's typical movement radius often extends beyond their residential surroundings. Therefore, we have been developing a robot partner system that integrates with mobility solutions to offer seamless services across diverse environments.

4.1 Robotic Personal Mobility Systems

Recently, personal mobility has been attracting attention, and various research and developments are underway. Personal mobility refers to small mobile robots used as personal mobility devices. Until now, electric wheelchairs have primarily

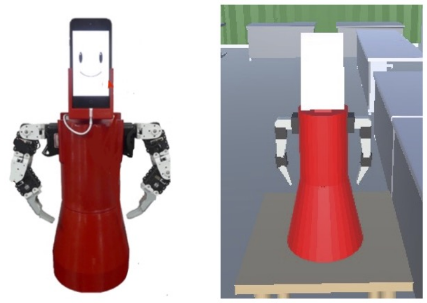


Fig. 10. A robot partner that bridges virtual and reality.

been used to support the independence of physically challenged people. However, recently, electric wheelchairs have also been utilized as transportation tools to reach various destinations, leading to an increased demand for their use in activities such as shopping and sightseeing [26]. We developed a personal mobility system that can be operated by both healthy individuals and those with physical challenges as shown in Fig. 11.

In this study, we built a control system for an electric wheelchair that considers riding comfort. The speed can be controlled by pedaling, similar to stepping on the accelerator pedal of a car [27]. Since this method is considered easy to use without much practice, we proposed an electric wheelchair system that allows speed control through pedaling. We also developed a heart rate measurement system to monitor the user's condition [28]. In this way, it is possible to develop a safer mobility system by combining a short-distance mobility system with a robot support system.

4.2 Modular Structured Drone System

Currently, due to the development of 3D printing technology and IoT technology, technologies related to drones are making rapid progress. It is predicted that the range of services utilizing drones will expand by increasing compatibility between different services through the integration of drone-related technologies with other IoT systems [29].

Therefore, we developed a drone system that considers integration with other robot systems by modularizing it using an ESP32 microcontroller to enable simple network communication, as shown in Fig. 12. The basic specifications are shown in Table 2.

Based on the acquisition of expertise in manufacturing these drones, we will not only define their use as communication modules but also review how to utilize drones by assembling them with desired functions through the combination of drone modules as shown in Fig. 13. This drone is assembled using the power of magnets, including the communication connector. After combining, control

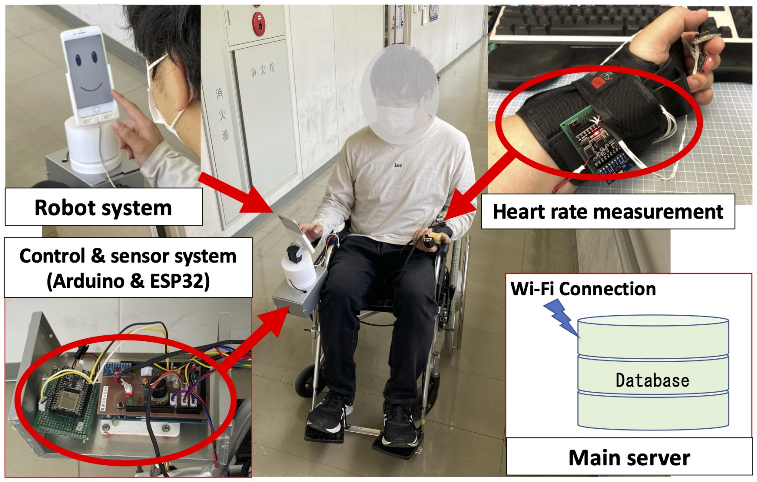


Fig. 11. Development of Mobility Systems for Integration with Robot Systems [28].

Table 2. Specifications of Drone System

Dimensions	200 x 200 x 200 mm
Weight	84.2 g
Microcontroller	ESP32-DevKitC-V4
Sensor	MPU-6050
Motor	Coreless motor 0720
Propeller	3inch × 4.4inch
Battery	3.7V 650mA 25C

values for the drone's attitude are shared through I2C communication (Fig. 14). With the development of such modular robots, it is anticipated that context-appropriate service provision will become possible.

5 Conclusions and Future Works

In this study, we introduced the design and development of a robot system using an IoT platform for a hyper-connected society. Through long-term research on robots, we are developing a system to prepare for the hyper-connected society of the future by defining robot designs and building systems through robot connections. To build a service system where these systems are organically combined and users can live safely and conveniently, we will continue research on systems that measure and analyze people's bodies and emotional states to provide proactive service support from robot systems, rather than just services on user's orders.

In particular, human emotional states are crucial in interactions between people. I believe that customized services can be provided by robots identifying

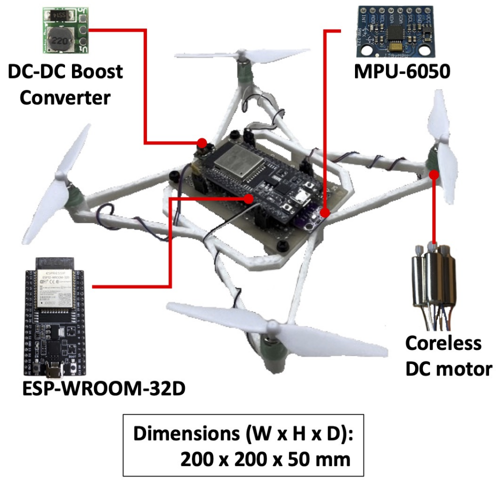


Fig. 12. A drone system considering integration with a robot partner system [17].

Fig. 13. A drone system for standalone use.

these states. Therefore, by measuring and analyzing non-verbal elements such as the user's gaze and gestures, we aim to develop a system where the robot's service can be adjusted according to the user's mood.

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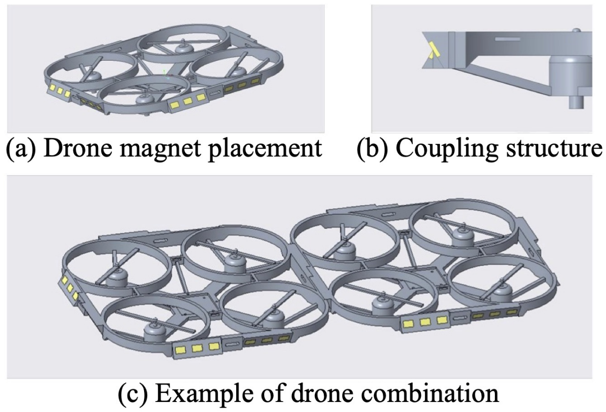
(a) Drone magnet placement (b) Coupling structure

(c) Example of drone combination

Fig. 14. A drone that can be combined using magnets.

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