CARE

Cooperation of AI Robot Enablers to Create a Vibrant Society

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Demographic changes in our society are putting a heavy burden on care facilities and health-care infrastructure. While the elderly population is steadily increasing, there is an acute shortage of caregiving experts and professionals. This problem is becoming more severe in superaging societies, namely, Japan. Hence, this urges new and practical solutions for welfare facilities to mitigate the burden on caregivers and human supporting partners by introducing robotics assistance through information and communication technology (ICT). In this work, we present a new multirobot cooperation and coordination framework at different intellectual computation levels for care facilities. The framework is developed to bring the health-care 4.0 concept one step closer to reality, under the ongoing project "Moonshot Research & Development," in Japan. First, we present an Internet of Things (IoT) integration system that is designed to include different passive and active assistive robots. Then, we redesign robot systems and develop a semiautonomous platform that can perform tasks based on user/patient interaction in real-world care facility scenarios. Our framework provides human–robot interaction under shared autonomy between the user and assisting robots to improve the efficacy of the users in everyday tasks. Tohoku University's new state-of-the-art Living Lab facility is used to prepare a real-world scenario, where we present our experimental results. We also discuss the open problems in future care and human assistance aspects.

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INTRODUCTION

Care facilities are highly dependent on human assistance and social cooperation. Current demographic conditions in several countries have led to severe challenges due to acute declines in population. Particularly in Japan, the percentage of older adults increases yearly. It is estimated that by 2036, one-third of Japan's total population will be over 65. An aging society puts much financial burden on the nation's resources as its health expenditure increases. On the other hand, the demand for care workers to cater to such a superaged society has increased drastically due to a severe shortage of skilled labor. Accelerating new research areas in assistive support by integrating ICT and robots in care facilities can reduce the burden on nursing care workers and improve the overall efficiency of everyday caregiving. Moreover, mental and physical compatibility is required to help/assist patients and the elderly. Caregivers face immense stress when caring for recipients and, at times, also face abusive behavior from patients. This issue becomes sensitive when a patient has an appropriate level of disability. This was also evident during the COVID-19

Digital Object Identifier 10.1109/MRA.2022.3223256
Date of current version: 8 December 2022

pandemic, where health workers had to work in a highly contagious environment and provide patient care. Robot support systems can improve patient and caregiver satisfaction and abilities by sharing the workload. For example, the same task could be done with a service robot, which would keep both the patient and the caregiver safe. This has motivated different robot technologies to be integrated into care facilities [1], [2], [3].

> “WHILE THE ELDERLY POPULATION IS STEADILY INCREASING, THERE IS AN ACUTE SHORTAGE OF CAREGIVING EXPERTS AND PROFESSIONALS.”

The notion of service robots is not new, and such robots are continuously finding their way into our everyday life. A number of different service robot platforms from the industry were introduced earlier [1], [4]. However, there is a serious gap in integrating different robotic platforms and technologies into the current health-care infrastructure. This open problem exists because robotic systems in care constitute a broader topic mainly pertaining to service robots that are aimed at helping users with daily activities and/or as companion robots that provide emotional and psychological support for the well-being of recipients. A more general trend for using robots in care facilities relates to socially assistive robots (SARs) [5], [6], [7]. These robots cover broader subjects in medicine, care facilities, offices, and other public areas, tending to different applications and services ranging from rehabilitation, entertainment, communication, and health monitoring and tracking to the delivery of goods and hospitality. Various studies have discussed the importance of automation and robotics in care facilities [8]. The earliest noticeable discussion was by Kassler [9], where the potential of robots in assisting and giving services to users was envisioned as the next era for health care.

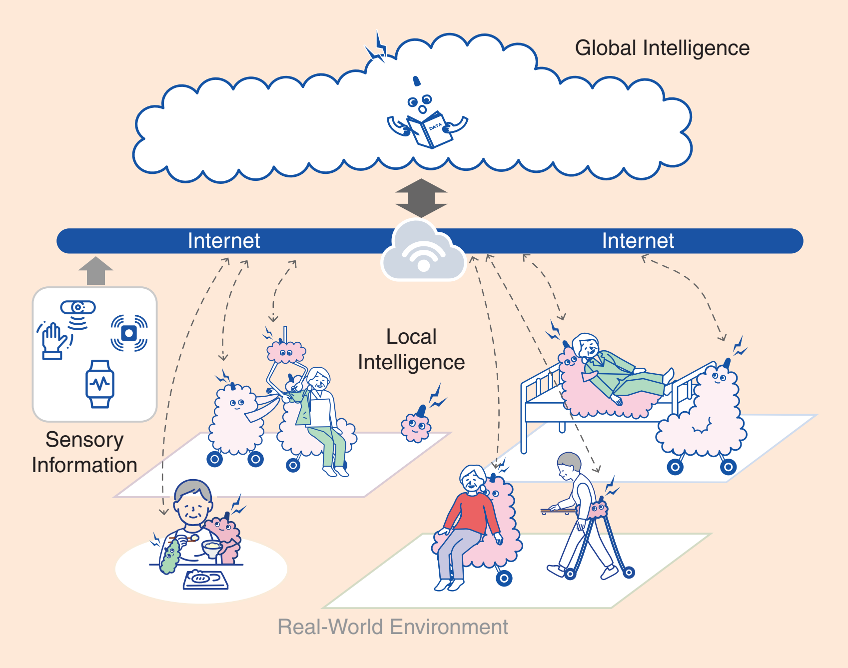

FIGURE 1. The proposed CARE framework for multirobot cooperation in home care.

This resulted in the development of multiple scenarios in which robots provide various services to help patients [1], [3].

Another exciting area where much interest has grown recently is the integration of SARs with assistive ambient living (AAL) [10]. Here, the focus is on providing assistive care to individuals at home. Using social robots and sensor integration, the aim is to monitor, assist, and provide social and cognitive care to individuals from the early onset of disease, especially in cases where only reasonable nursing care is required [11]. Earlier studies of such integration in several European projects have demonstrated the successful use of SARs and sensor integration for long-term monitoring and tracking of users at homes and facilities, providing relevant assistance, and the interaction between elders and robots in different scenarios [12]. The ASTROMOBILE project presented a social robot that interacts with and gives certain services to the elderly [13]. The Robot-Era project [14], [15] studied the acceptance level, technical feasibility, and satisfaction of elderly users by employing three mobile robots in different service areas, such as domestic, condominium, and outdoor environments. CompanionAble [16] and SERROGA [16], on the other hand, studied long-term use of SARs in private homes. Other cases include the Strands project [17], where robots were deployed in a large public environment. Very recent works include the MoveCare project [3], [18] that successfully tested and demonstrated the use of SARs with AAL by using a social mobile robot, Giraff.X, for long-term operation in private houses of elders living alone and targeting individuals who were at risk of falling into frailty.

With similar goals, Japan’s government, through the Japan Science and Technology Agency, initiated a new large-scale funded research and development initiative known as the “Moonshot Research & Development Project,” in 2019 (https://www.jst.go.jp/moonshot/en/). This project aims to create a vibrant and symbiotic society by the year 2050, with multiple artificial intelligence (AI) robots installed in various public facilities (commercial, cultural, tourist, sports, nursing, hospital, and childcare) and maintained as social infrastructure. Within the several goals of the project, Cooperation of AI Robot Enablers (CARE) (https://srd.mech.tohoku.ac.jp/moonshot/en/) is one of the projects with a focus on enhancing the human quality of life by creating new robot technology in the coming decade (see Figure 1). Through the

CARE project, we are developing a mulirobot cooperation system for welfare facilities and researching the design and development of advanced assistive robots for homes and welfare facilities by the year 2030.

This article presents a fundamental concept of multirobot cooperation for welfare facilities within the framework of CARE. The main contributions of this study are

- An IoT integration system is designed to include different passive and active assistive robots.
- The safety and preferences of the user are considered with input from individuals' interests, disabilities, and physical status (self-efficacy).
- A new concept of human–robot interaction is designed with shared autonomy among assisting robots, human-given inputs, human safety, and assistive controllers.
- A realistic Living Lab facility and scenarios are introduced for experimenting with our proposed framework, and they are evaluated for potential application through expert advice.

The article is organized as follows. In the "CARE: Cooperation of AI Robot Enablers" section, we introduce the concept of cooperation of AI robot enablers and discuss the details regarding the assistance and automation level in the proposed caregiving system. Next, "The Living Lab" section describes the Living Lab facility at Tohoku University and explains different Living Lab robots as assistive and service robots. The interface between local and global intelligence is explained in the "Web-Based Message Passing Interface for Robots Using Robot Operating System" section. In the "Human Interaction With AI" section, we explain human interaction with AI systems, with a description of sensory systems and our developed human detection, tracking, and condition evaluation system. The "Multirobot Cooperation in Human-Friendly Environment" section describes local intelligence by considering multirobot cooperation with the coexistence of humans. The "Experiments and Discussion" section explains an example scenario demonstration for the proposed concept.

CARE: COOPERATION OF AI ROBOT ENABLERS

This section discusses the main idea of the developed framework under the Moonshot Project. Our focus is on developing multirobot collaboration while considering the human factor for long-term intelligent assistance and support for humans by utilizing new sensor development, sensor fusion, robotic assistance, human–robot cooperation, and data processing. Our aim is to develop an AI robotic care system that caters to the needs of a specific user by providing the most relevant robotic support as the user request for a certain task to be done. By learning individual preferences and processing sensor data over a long period, the AI can then recommend the best output and provide support to the user by deploying and/or collaborating with different robots. In contrast to other relevant projects discussed earlier that have used SARs for long-term support in homes and care facilities, our project has several key features, summarized in Table 1. Our system can provide appropriate support to the user by distributing tasks to multirobot systems, where each robot can do a specific task.

TABLE 1. The comparison of different projects within the CARE framework.

PROJECT	IoT INTEGRATION	MULTIROBOT	WALKER OR WHEELCHAIR SUPPORT	AUTONOMOUS NAVIGATION	SPEECH INTERACTION	INDOOR, OUTDOOR, OR BOTH	CONTINUOUS MONITORING	REMOTE OPERATION	SHARED AUTONOMY	STATIC OR DYNAMIC SAFETY ASSISTANCE
CompanionAble [19]	—	—	—	✓	✓	Indoor	✓	✓	—	—
ASTROMOBILE [13]	✓	—	—	✓	✓	Indoor	✓	✓	—	—
SERROGA [16]	—	—	—	✓	✓	Indoor	✓	✓	—	—
Giraff.X [3]	✓	—	—	✓	✓	Indoor	✓	✓	—	—
EnrichMe [2]	✓	—	—	✓	✓	Indoor	✓	—	—	—
Robot-Era [14], [15]	—	✓	—	✓	✓	Both	✓	✓	—	—
STRANDS [17]	✓	—	—	✓	✓	Indoor	✓	✓	—	—
Smile [1]	—	✓	✓	✓	—	Both	✓	✓	✓	—
CARE (Ours)	✓	✓	✓	✓	✓	Both	✓	✓	✓	✓

Unlike a single robot platform, our proposed system is easier to implement, and task distribution and allotment among the robots can be efficiently handled without hindering the overall task execution. First, we integrate multiple robots with the IoT system and provide support not just in indoor but outdoor environments, as well. Our framework includes service robots, autonomous walkers, and wheelchairs. For specific tasks, the most appropriate robot is selected by the global intelligence AI. Second, our system considers shared autonomy when the user is physically interacting with a robot system (e.g., a bed or walker). Analyzing human input through wearable and external sensor data makes the response smoother for the user when engaging with the robots. Third, our system considers safety a feature during the entire assistance phase. The safety of human motion is quantified in real time, which provides information together with incoming obstacles in the environment for creating a shared autonomy policy for the robot and human interaction.

> “ANALYZING HUMAN INPUT THROUGH WEARABLE AND EXTERNAL SENSOR DATA MAKES THE RESPONSE SMOOTHER FOR THE USER WHEN ENGAGING WITH THE ROBOTS.”

THE CONCEPT OF AI ROBOT ENABLERS

Care facilities are critical institutions that get tremendous attention in automation and robot integration. Additionally, caregivers need to support patients from many different aspects. The goal of the research and development of adaptable AI robots is not to provide excessive support and services to users but to realize human-centered care that encourages users’ independent movement, tasks, and other activities. The interaction between an adaptable AI robot and a user is accumulated as experience. The user’s success (and failure) experiences are shared between the user and the AI robot to improve the sense of self-efficacy; i.e., the user can actively participate (physically) and perform the desired action or task with support from the AI robot.

CARE is a flexible and supportive assistance technology that helps users to accomplish tasks by combining AI robots, assistive devices, sensors, and user interfaces. In this concept, each user will be assisted based on his or her disability and required support level. Also, the SARs will work in harmony with heterogeneous order to achieve different tasks assigned by the users. This happens under a global intelligence that monitors the environment and uses other sensory systems to keep the users’ satisfaction and health at the uttermost level under self-efficacy boundaries.

ASSISTANCE AND AUTOMATION LEVELS IN CAREGIVING

Caregiving happens in different aspects. Based on the Expanded Disability Status Scale (EDSS) [20], a disability can be quantified in different levels, where zero indicates that a person has normal neurological and physical functions and is able perform different tasks easily. However, a person needs assistance for anything over a value of three, either physically or mentally, to continue required activities. In our current research plan, we are considering the EDSS $\text{EDSS} \in [2.0, 6.0]$ range. It is important to note that the ultimate goal of the project of adaptable AI enablers is to achieve level 8, which will be possible with improvement in mechanism and sensory designs as the project progresses. Also, EDSS level 7 is not a consideration for the current work since the restricted immobility of a person might require heavy carriage support that is not practically feasible with currently available robots.

The automation level is dependent on a person’s disability and requested tasks. As shown in Figure 1, if a person with severe disability requests assistance, a wheelchair-type assisting robot will go for the support. However, if the EDSS is around five, and considering user requests/preferences, a walker-type assisting robot will approach the user. Additionally, our service robots work under safety protocols (obstacle avoidance with other moving robots) to bring required items. We think this framework for automation using IoT systems and other robots can be a stepping stone for efficient care. Also, the IoT system plays an important role in connecting different sensors and robots using the Internet communication framework. The communication can transmit and share information among different processes, e.g., robots’ positions, requested tasks, and individual data, between global and local intelligence within the multirobot ecosystem. In the future, by mechanism design and control improvements, new robots with different abilities can be integrated into this ecosystem.

THE LIVING LAB

As part of the Japan Ministry of Health, Labor, and Welfare’s “Project for Establishment of a Platform for Development, Demonstration and Dissemination of Nursing Care Robots” (https://www.kaigo-pf.com/livinglab/), the Living Lab aims to accelerate the flow of the development, demonstration, and dissemination of nursing care robots as an evaluation and effectiveness verification organization for such robots. The Living Lab is a group of facilities that promote the development of nursing care robots based on the needs of nursing care settings by reproducing actual living spaces and developing new technologies and services with user participation. It supports organizations and institutions that wish to evaluate their nursing care robots in development and verify whether they can be used in actual nursing care settings. Based on evaluation and expertise in the field of nursing care, the Japan ministry selected eight Living Labs to participate in this project nationwide. These Living Labs also aim to build a network through this project and support developers by leveraging their respective strengths. The Aobayama Living Lab, at Tohoku University (https://srd.mech.tohoku.ac.jp/living-lab/), was selected as one of the eight Living Labs for undertaking next-generation nursing care robot research and development.

The Living Lab is a care facility and home where different robots, advanced sensors, and guidance systems are integrated to replicate a concept for future welfare facilities, as demonstrated in Figure 2. It simulates a nursing home environment, with toilets, bathrooms, kitchens, living space, and a simulated outdoor environment with stairs and slopes. The layout of the Aobayama Living Lab is presented in Figure 3. In our Living Lab, we have developed a cooperative care support system in which multiple care robots and sensor systems work together to provide support rather than being limited to a single care robot. Different robots with specific abilities with respect to users' required tasks are utilized in our facility.

> “CARE IS A FLEXIBLE AND SUPPORTIVE ASSISTANCE TECHNOLOGY THAT HELPS USERS TO ACCOMPLISH TASKS BY COMBINING AI ROBOTS, ASSISTIVE DEVICES, SENSORS, AND USER INTERFACES.”

In the constructed facility, we have active and passive supporting robots (see Figure 2). The active supporting robots consist of electric wheelchairs and walker robots. We utilize an automated bed system and a service robot for passive supporting robots. In the group of active supporting robots, the automated wheelchair system is redesigned using a commercially available Whill robot. This robot is equipped with different onboard sensors, e.g., encoders, joystick control, and inertial measurement units (IMUs). The wheelchair was upgraded with additional sensors, such as a ToF (Time of flight) color and depth camera and 2D LIDARs, for sensing and autonomous navigation tasks. The walker robot is an automated walker developed by RTWorks [21]. This robot is also upgraded with external sensors for autonomous navigation within the facility. Also, all robots contain a tablet interface to let users/professionals have direct interaction with ongoing operations in a robot. This includes a direct interface for users to remotely operate the robot during its ongoing execution of tasks and for changing requests.

In the group of passive supporting robots, a multifunction bed with onboard actuators has been modified with hybrid switches for head and height adjustment. Furthermore, these

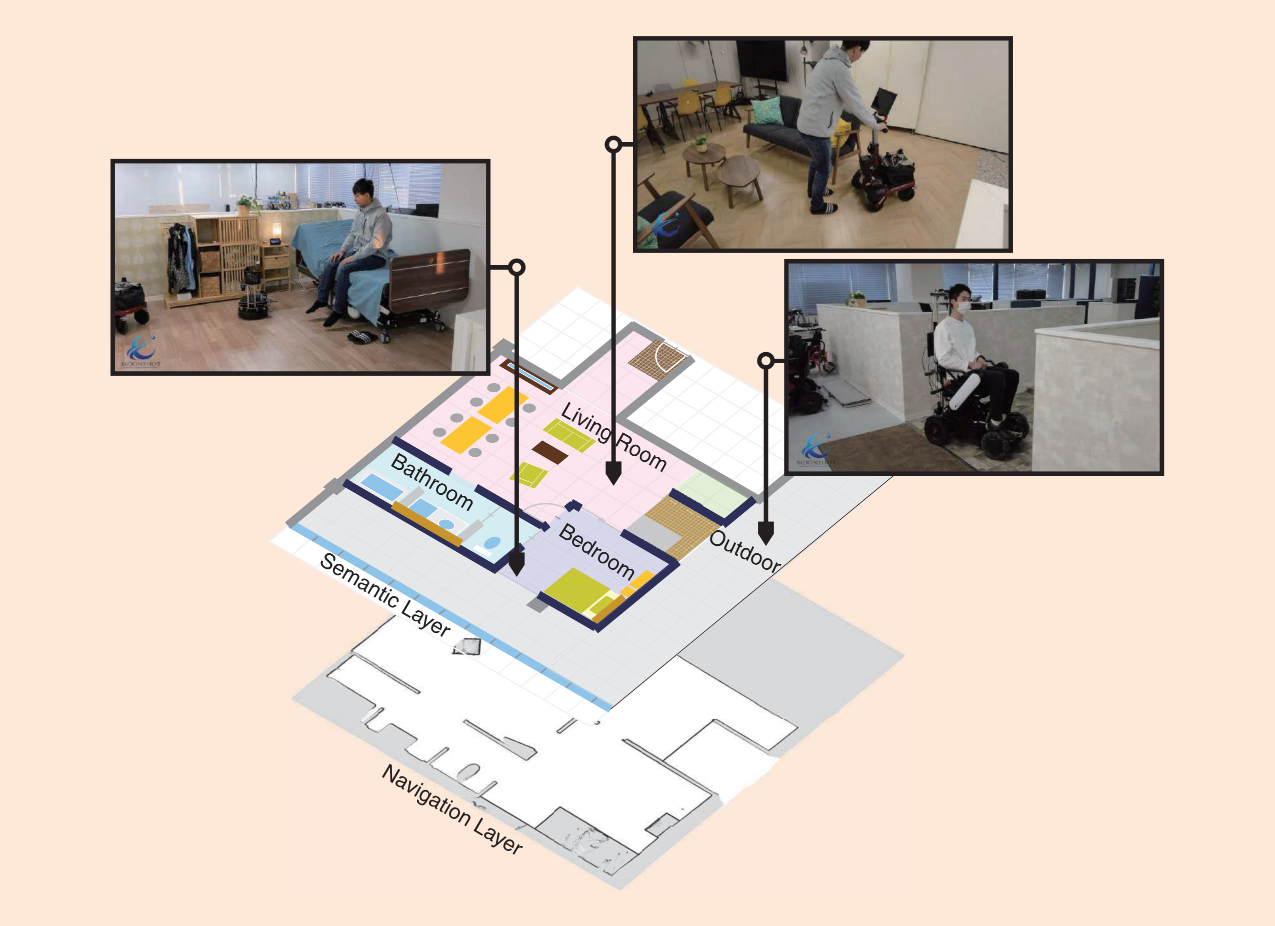

FIGURE 2. The multirobot cooperation framework in Tohoku University's Living Lab.

smart switches are placed in such a way that they can connect directly to the Internet cloud to feed information about bed states and manipulate bed positions in relation to ongoing tasks. Also, a mobile service robot based on the TurtleBot2 robot platform is currently developed for applications such as delivering small objects to users and interacting with them during different tasks.

WEB-BASED MESSAGE PASSING INTERFACE FOR ROBOTS USING ROBOT OPERATING SYSTEM

In the CARE project, we are working on cooperative control of multiple robot groups and sensor groups using a common interface for communication and exchanging information between users and robots operating in the Living Lab. We focus on developing a smart decentralized multirobot architecture in which the most appropriate robot will come to a user based on individual needs and requests.

A communication medium is necessary for different robots to pass messages and share information. In the past, plenty of research has been carried out about the topic of communication and coordination among robots, and different approaches have been proposed [22]. Recently, cloud robotics has been getting a lot of attention [23]. It invokes cloud-based technologies, such as cloud computing and storage, parallel processing, and Internet services, for sharing information among different robots and agents. All these approaches are solutions crafted for a specific application, and it is necessary to adapt and implement them for particular applications.

In our framework, we have considered Robot Operating System (ROS) the middleware for the sake of modularity and also for the smooth integration of different sensor libraries into our robot framework. Using ROS accelerates the development process vastly and enables researchers to implement complex systems quickly. ROS relies on host computer network capabilities to distribute messages in a system. When multiple robots are run in the same network to communicate with one another, all their sensory information travels through the network so that each robot is able to see the other robots' status (i.e., the other robots' topics, where sensor readings are published, messages, and services). This can be very data intensive: when the number of sensors in the system increases, the network traffic becomes larger, and this is duplicated when an additional robot is added. To this end, creating a way for different robots to transmit only the necessary data at the right time is desirable.

To achieve this asynchronous communication among different systems using ROS, we proposed an interface based on the Node.js JavaScript runtime. Node.js is traditionally used to create websites and back-end application programming interface services; in this case, we use it to provide an interface among systems. We based this architecture on the framework proposed by Giller et al. [24] to connect ROS with IFTTT, which is a software platform that connects apps, devices, and services from different developers to trigger one or more automation processes in those apps, devices, and services.

INTERFACE STRUCTURE

The proposed interface's general layout can be seen in Figure 4. The interface was developed as a ROS node that creates a webserver with custom webhooks that the developer can specify via the launch file. The webserver interacts with ROS in a bidirectional way: it can launch ROS services when a webhook is triggered, or it can trigger a webhook in other webservers when a specific type of message is published in topics that the webserver is subscribed to. The relations between the webhooks and the service to be launched (incoming information) as well as the topic name and the webhook to be triggered (outgoing information) are easily configured in the launch file, requiring no further programming. The information among systems is transmitted using the HTTP protocol, and custom fields can be added to the request as JavaScript Object Notation (JSON) payload.

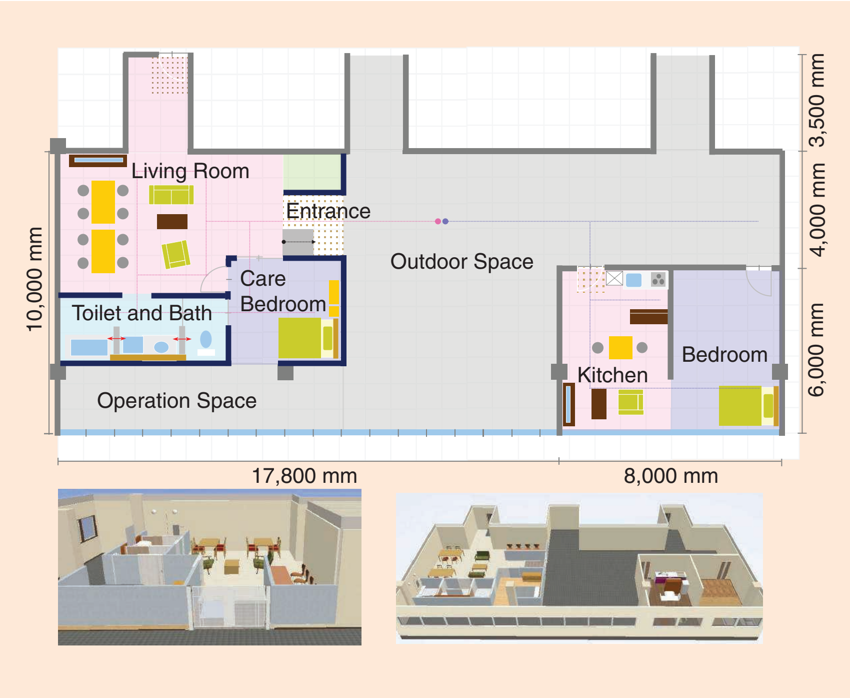

FIGURE 3. The Aobayama Living Lab.

NETWORK REQUIREMENTS AND WEBSERVER ADDRESS

With this architecture, we can have multiple robots running their own ROS core in their local loopback network, which is much lighter and faster than communicating over wireless networks. If the robots were connected to the same network, they would be able to reach one another by using webhooks formed with one another's Internet Protocol addresses. To simplify naming and enable the robots to communicate from any network, we use ngrok, which is a cross-platform application that enables developers to securely expose a local webserver to the Internet with minimal effort. This requires only that a robot has a connection to the Internet. In this way, robots can address one another using webhooks formed with the URL assigned via ngrok.

INTERACTION BETWEEN SYSTEMS AND IoT

As explained before, to trigger a service in a robot, a web request with a JSON payload is used to trigger a webhook, and the robot will process the request-and-call service in its own ROS core. This enables us to trigger these services from another robot and any device that can generate a web request, such as voice assistants (Siri and Alexa), Internet services (IFTTT), and even a web browser. Because the interface enables the robot to trigger remote webhooks (outgoing information), it can also trigger IFTTT webhooks so that the robot can interact with any of the 700+ web services provided via IFTTT.

HUMAN INTERACTION WITH AI

The CARE framework, including the different subsystems, is presented in Figure 5. There are three main systems: global intelligence, local intelligence, and external sensors with human interface systems. The global intelligence is responsible for collecting user commands and processing them to detect and track participants in the environment by using a previous database of individuals. The next step is to determine the available and suitable robots for tasks. Autonomous robots perform tasks based on their structure, sensors, and motors within the local intelligence. Each of the components of the framework is discussed in detail in the following.

REQUEST UNDERSTANDING

Human and robot/guidance system interaction is one of the key points in achieving successful executions based on patient/user requests. However, these interactions have certain bottlenecks since requests from a user might happen multiple times, and the user/patient could change his or her opinion during an ongoing task. Moreover, the safety and ergonomics of the human interface are important; hence, the person can interfere with the execution at any time he or she wants to.

The interactions are divided into direct and indirect parts in this work. These interaction interfaces require different sensors that help the general intelligence of the care system to act responsively and on time. For direct interaction, a physical user input device, such as a tablet/smartphone, and verbal interaction through a commercially available virtual assistant, such as Amazon Alexa voice services and Google voice assistance, is utilized. When physically interacting with smartphone and tablet-based communication, the user can send direct commands to the available robots by using custom shortcut buttons. These shortcuts consist of tasks with varying complexities. For example, there is a complete task request for bringing drinks and for sending a robot back to the base station. Another example is bed assistance, where the user can adjust the bed to his or her desired head angle and height. For voice-based communication, apart from simple task requests, the person can interact with a virtual assistant through normal conversational sentences to ask for service and assistance from various robots.

For indirect interaction, different sensory systems are placed in the environment. These include fixed cameras for person tracking and recognition, a motion capture system for precision tracking and analyzing of body posture, force plate sensors mounted near the bed and sofa for calculating standing/sitting force, and a RGBD camera system mounted over the bed for pose estimation and performing sleep analysis patterns. Please note that we maintain a database of the Living Lab users, whose information (age, gender, face, voice

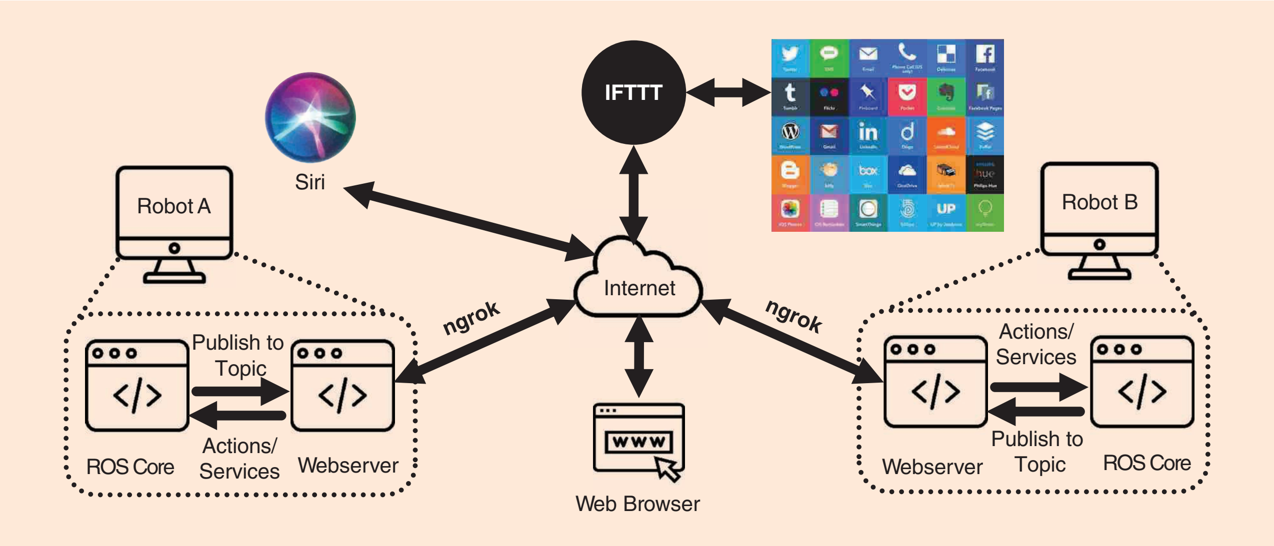

FIGURE 4. The structure of the developed communication interface.

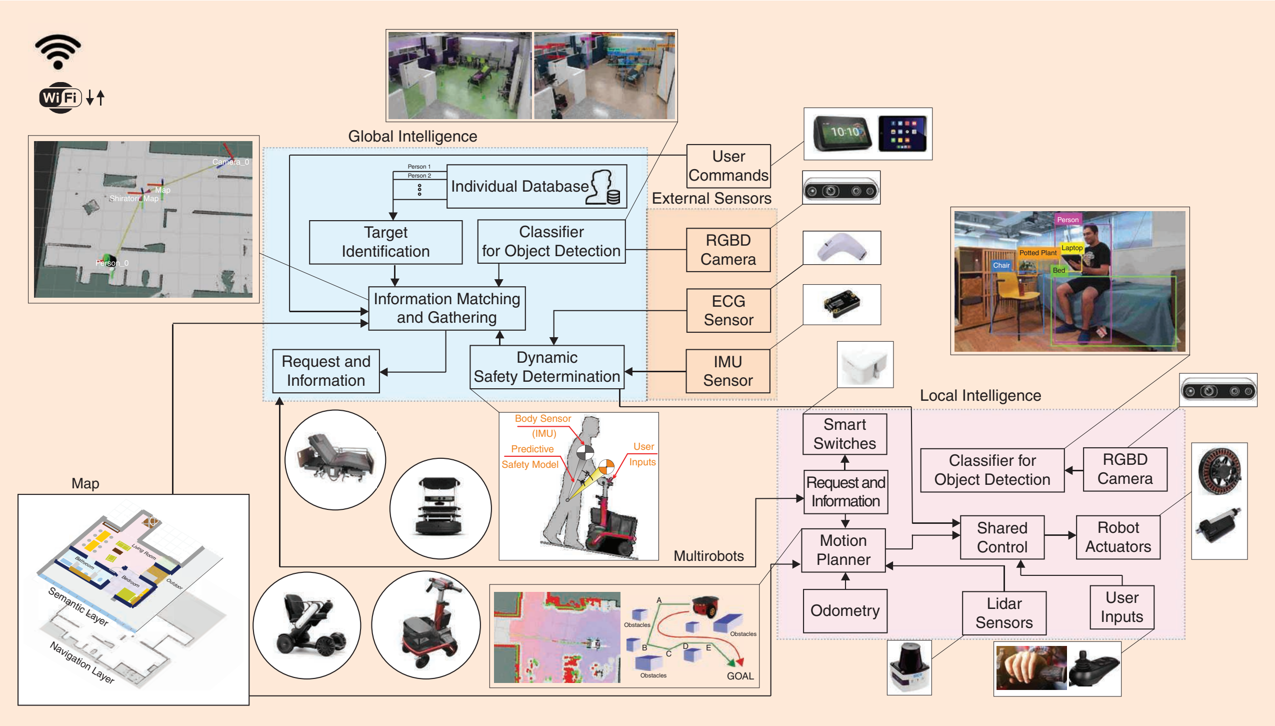

FIGURE 5. The CARE autonomous multirobot cooperation.

patterns, assistance level, and other critical data) is fed to the global intelligence for identifying user commands. Apart from these sensors, the user also wears IMUs, activity recognition devices, and heart rate sensors, as demonstrated in Figures 5 and 6. For instance, the person's heart rate and electrocardiogram data are continuously monitored with a commercially available Hitoe sensor. All these sensors are interconnected through the Internet to designate global intelligence to collect, evaluate, and distribute the required information among robots. Another purpose of the indirect interaction is that without requesting much information from the user/patient, our proposed general intelligence can utilize information from the user and environment to evaluate the ongoing tasks, the robot's condition, and the situation.

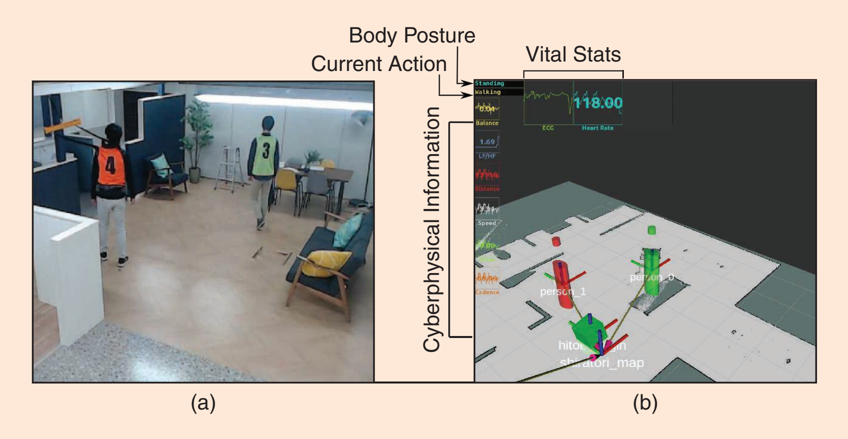

FIGURE 6. A user's health and physical information is gathered with different sensors. The (a) external view and (b) person tracking and status.

INDIVIDUAL TRACKING AND SAFETY

Human self-efficacy is a key factor in care facilities. Self-efficacy can be described as when a person believes in his or her ability to complete a task. There have been different studies that evaluate self-efficacy with respect to the acceptance of robots in health care [25] and robots in care [26]. For instance, Swift-Spong et al. presented that participants, under an autonomous robot's guidance and assistance, improve their overall ability to perform tasks. We have tried to consider the user's self-efficacy from different aspects. Based on the interaction between humans and robots, we have utilized different means of communication, e.g., tablets and verbal commands, which have already been explained. Also, a person tracking and recognition system is developed using an RGBD camera system. This visual system can robustly track and recognize people within the camera's field of view. Then, the recorded person's physical characteristics and preferred choices (for interaction purposes) are called in the global intelligence layer.

The global intelligence directs and informs the relevant robot that matches a person's ongoing disabilities by considering the task requests from the user. The tracked position of the person is transformed into a map that the robot utilizes for autonomous navigation. The classification and categorization of the environment information for global intelligence happen by utilizing the

You Only Look Once (YOLO) v3 [27] object detector. Also, there is a real-time safety model that we have developed. This safety model uses wireless IMU data from a wearable sensor attached to the person's chest to understand the safety dynamics of the person during motion. The model uses a spring damper-based safety model with a dimension-reduced safety data set of the individual [28]. We integrated the safety model with our shared autonomy for certain robots, e.g., walker and wheelchair, to understand whether the person is interacting safely in the environment (see Figure 5).

MULTIROBOT COOPERATION IN HUMAN-FRIENDLY ENVIRONMENT

For robots to operate and navigate freely inside the Living Lab environment and respond to a user's request, we developed several new algorithms for their autonomous operation. The three main robots (wheelchair, walker, and service) in the Living Lab environment are all equipped with sensors capable of performing point-to-point navigation within the fixed environment. They are equipped with range lidars for mapping and localization and performing tasks, such as dynamic obstacle avoidance and responding to the user's calls [29], [30]. At the same time, each robot also has an external camera system for recognizing objects in space and performing high-level planning and object detection. The robots can also be tracked continuously by using a motion capture system installed in the facility to get precise localization. As explained in the previous section, each robot works in a decentralized architecture and can communicate with other robot platforms by sharing crucial information among the robots through message passing. Each of the robots has its own computing unit for processing onboard sensor data, while all the processes requiring heavy computation, such as object labeling, are handled using an external high-end PC, where all the sensor information can be processed smoothly.

The general framework for the autonomous operation of the multirobot system is given in Figure 2. It uses a multilayered scheme, with one layer utilizing 2D and 3D maps for navigation and a high-level semantic layer for scene understanding [31]. Places and objects are tagged with semantic information at the high level, while low-level planning and metric goal-based navigation are done at the lower level. Additional high-level layers can be added in the framework, based on application and use case scenarios, e.g., tagging objects with radio-frequency identification information to help users suffering from weak memory and dementia to help find lost objects. This provides us with rich information about the continuously updated environment for a robust exchange of key messages among several robot systems using the proposed dedicated webserver. In the following sections, we explain important autonomous tasks that the multirobot system can perform.

NAVIGATION AND PLANNING

For robots to autonomously navigate among different target positions in an environment, mapping and localization are important. The process is termed *simultaneous localization and mapping* (*SLAM*), where a robot has to actively map the environment and estimate its position in the built map based on the sensor information [32]. We utilized open source ROS packages to first map the Living Lab area as a 2D grid map and then used the map to perform active localization. This grid map is shared across all the robots working in the environment for navigation. Each robot also runs its own navigation stack (move_base and local_planner) that allows the robot to keep track of dynamic objects in the Living Lab over a period of time. This information is crucial to keep the map data up to date and relevant to the layout and obstacles in the Living Lab. Therefore, we utilize a map update process, where if an obstacle is observed over a set duration of time, its position is merged with the map, and the new information is then shared across different robot platforms [33]. Furthermore, as shown in Figure 7, we test our algorithms in a simulated test environment, a digital twin that can verify the cooperative operation of multiple robots/sensors. For planning, key positions in the map, such as the bed, toilet, living room, base stations, and so on, are stored as topological nodes for navigation [34]. Before performing experiments with human subjects, each robot is thoroughly tuned and tested with its planners to avoid collisions with the subjects. A recovery behavior planner is also considered for the robots to get out of hard situations (surrounded by people) and robot-stuck scenarios (sensor failure).

OBSTACLE AVOIDANCE AND SHARED AUTONOMY

During planning, the robot can autonomously navigate toward the human while following and keeping social behavior so as

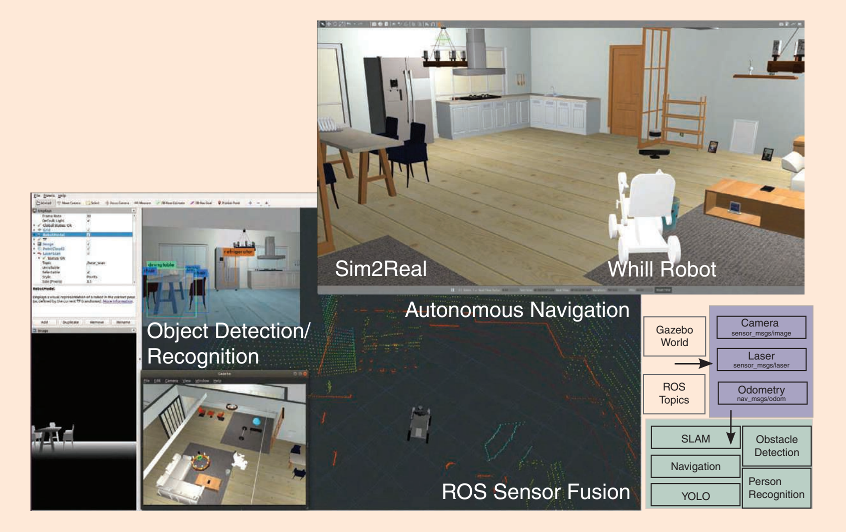

FIGURE 7. The Living Lab simulator (digital twin).

not to get too close to the user, as depicted in Figure 8. Based on the sensor information from the onboard lidars, the robot can keep a safe distance from static and dynamic obstacles while planning. When the subject gets too close to the robot, the planner pauses the current plan and stops moving. By calculating the cost values of the obstacles on the map, the robot then replans a new obstacle-free path or waits for the subject to move before continuing with the planned task.

Motion assists, or shared control, are one of the ways to fill the gap between direct user control and the robot's safe intended trajectory. From a self-efficacy point of view, having shared autonomy helps the person have more control over his or her decisions during the robot's motion. This fact is very important in active supporting robots i.e., wheelchairs and walkers. For example, in the case of a wheelchair user, the joystick input by the user might not be the safe route for the robot to take, and the robot might need to follow certain points.

Also, recent researchers tried to combine sensor information to develop shared control strategies in a mobile robot, e.g., a wheelchair system [35]. In our framework, we utilized our designed assistive control that creates a safe and smooth control strategy that relies on user inputs [36], [37]. Also, we propose a new policy of shared autonomy for the human–robot interaction (provided in Figures 5 and 8) that outputs the control velocities $\mathbf{u}(t)$ to the robot actuators, as follows:

$$\mathbf{u}(t) = \frac{1}{\sum_{i=1}^{m} n_i} \sum_{i=1}^{m} n_i \mathbf{u}_i \tag{1}$$

where $n_i \in [0-1]$, $\mathbf{u}_i$, and m are the trust ratio, raw control input vector from different systems (the planner, human joystick input, and so on), and maximum number of the averaged trust ratio, respectively. For example, in our shared autonomy policy, we have considered human input, the planner, and the assistive controller [37] for $m = 3$. Additionally, the trust ratio n_i for each input is changed continuously by information about the deviation error from the safety model [28] and existing obstacles in the path of the human with a robot in service, as in Figure 8.

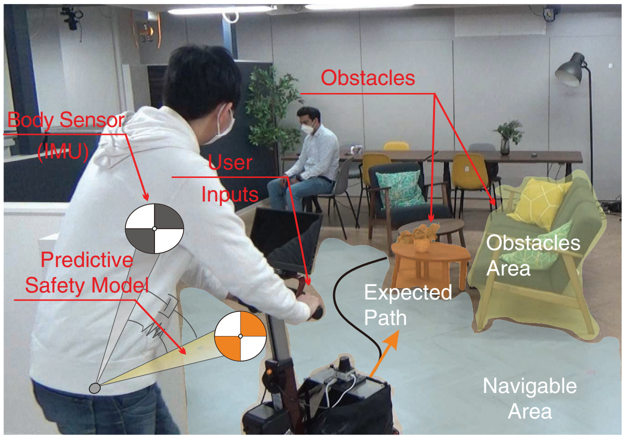

FIGURE 8. The human-friendly environment navigation with shared autonomy and a predictive safety model.

EXPERIMENTS AND DISCUSSION

The CARE concept was exhaustively tested as a home care robot system under different use case scenarios. We briefly explain the process here and show some example scenarios with our integrated multirobot ecosystem. In the end, we checked the quantitative and qualitative performance by doing an extensive questionnaire evaluation with around 80 participants from the engineering, health, and social science fields. The whole experiment concentrated on a scenario where a user in home care carries out daily activities and how our CARE system supports the user in achieving his or her daily tasks. As a first effort, a series of scenarios were constructed to demonstrate our system from the perspective of "getting ready in the morning." The flow of the experiment scenarios is as follows. Readers are strongly recommended to watch the supplementary video available at https://doi.org/10.1109/MRA.2022.3223256 to understand the context of the experiments and our description of them.

EXPERIMENTAL SCENARIOS

GETTING READY

In this scenario, as represented in Figure 9, a user wakes and greets the computer (the global intelligence with voice recognition). Our system keeps track of the person from an overhead camera, greets the person by using a voice assistant, and turns on the lights. Next, the global intelligence adjusts the bed to ease getting up. After that, the person requests a drink via voice assistance. The request is immediately processed, and the user is given a positive response through the AI speaker (the computer). The response asks the user to wait, and meanwhile, a suitable robot is selected to execute the task by using our multirobot communication approach. The global intelligence can process where the request came from by analyzing voice data from the microphone and the user's position from external sensors. The target user is identified from the database, and the selected service robot undocks from its base station and navigates autonomously utilizing the framework explained in the "Multirobot Cooperation in Human-Friendly Environment" section. Notice that the response is immediate, and there are no delays in executing the task.

Important locations of objects in the environment, such as the bed, are previously stored, and the goal is set based on where the person is sitting on the bed. Next, the service robot navigates through the environment, carrying the drink, and the local intelligence for the automated bed, with information from the global intelligence, adjusts the height to ease the patient in picking up the drink from the robot. The mobile robot is responsive to obstacles, including the patient (the local planner), to keep the appropriate distance from the user. Finally, the global intelligence analyzes the task completion by using the external cameras on the scene and confirms that the action was successfully executed (the robot reached the desired configuration). If no other request is in the queue, it commands the robot to return to the base station.

GO TO LIVING ROOM

In the following scenario, the person sends requests using voice assistance about his or her desire to go to the living room. The global intelligence processes the person's statistics (level of walking discomfort and history of similar requests) and suggests that a walker robot will be suitable to use this time. Then, the global intelligence sends the request to the robot walker to complete the task. Based on the person's sitting position on the bed, an appropriate location where the walker robot should be sent is given as a goal. At the same time, the global intelligence adjusts the automated bed height such that the person can comfortably get off the bed with maximum ease. It conveys to the user that the bed height is adjusted and that the robot is on its way. The walker robot stops at the desired location and activates its brakes to avoid wheel slippage. Using camera information, the monitoring system in the global intelligence can predict that the standing task is completed by utilizing the information from the force sensor plates installed under the bed.

Moreover, the global intelligence uses the force and IMU sensors [28] and a safety model on the walker handrail grip to confirm that the user is in the correct position and releases the brake. Then, the robot goes to shared control mode to assist and support the user to the intended place. In the next step, once the user has released his or her grip, the robot senses that the user has completed the task, and the computer sends the robot back to its base station (as shown in Figure 10, time stamp *t* = 2:53).

To demonstrate how our system can work along with a human caretaker, another experiment is conducted as a continuation of the scenario. This scene introduces a human caretaker with control of the robots' operation. This experiment aims to demonstrate how the system can take commands from different users and distinguish between the care receiver and caregiver. The global intelligence keeps a database of different users and, based on where a request is coming from (AI-based voice synthesis, microphone localization, and image recognition), completes the request through the most appropriate selection. The snapshot *t* = 3:44 in Figure 10 demonstrates some sensory system information from the scene. Here, there is an environment classifier; we utilize the YOLO v3 deep learning network [27] to distinguish objects in the scene, and the classifier gives the semantic information of the objects and people. The system tracks the two people in the scene and can pinpoint the request source.

For example, the caretaker wishes to send medicine to the care receiver. In the scene, he or she calls the robot to his or her location. The person's position is extracted by information matching and gathering from where the request originated. The global intelligence picks an appropriate robot for the task and sends the robot to the caller's location. Next, the caretaker puts the medicine on the service robot and asks the global intelligence to send it to another person. The global intelligence accepts the request, processes the voice command for key information (e.g., the person's name), and utilizes the camera network and stored database to recognize the person and his or her position on the map. It then sends the same robot to the other person and waits for the task to be completed. The process happens instantaneously, and there is no delay in the communication and message exchange with our proposed system.

GOING OUTSIDE

This scenario demonstrates how the CARE system can be flexibly extended to cases outside the boundaries of a home,

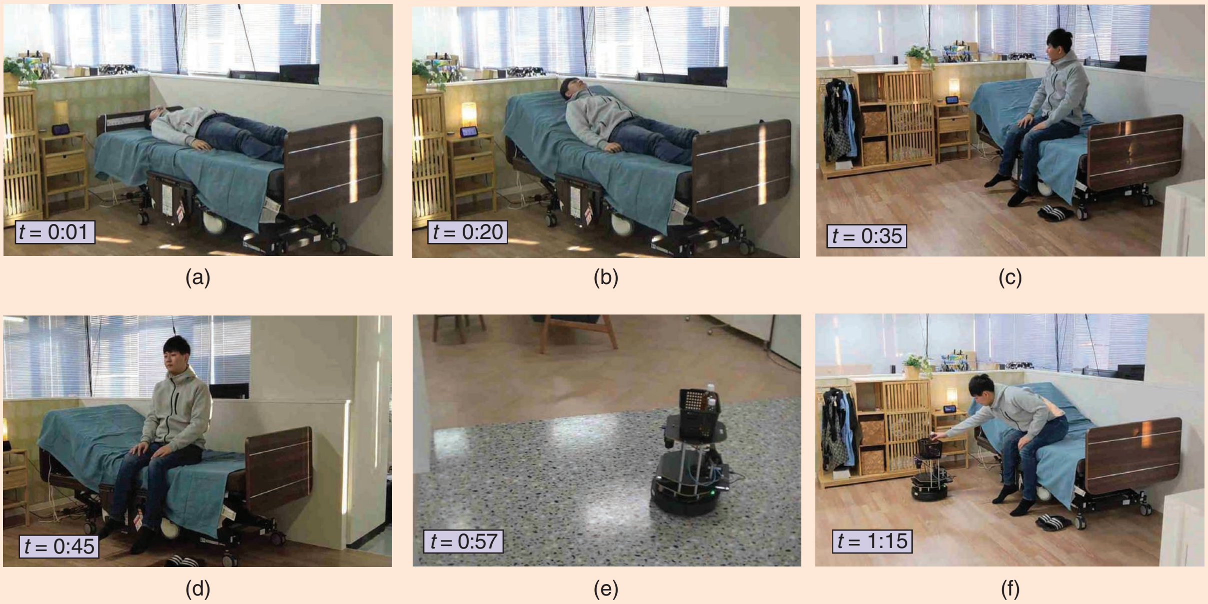

FIGURE 9. The bedroom scene. (a) User wakes up. (b) The automated robot bed adjusts itself. (c) The user requests a drink from global intelligence (computer) using voice assistance. (d) The bed height is adjusted for the user. (e) The service navigates autonomously in the facility to execute the task. (f) User picks up the drink from the robot.

giving users freedom to use robots outside and increasing their self-efficacy in everyday tasks. In our experiments, we consider different case scenarios where a user requests a robot to take him or her outside the house (e.g., for shopping). In this scenario, the user desires to go outside and asks the computer (the global intelligence) for help. Then, the computer processes the request based on the individual's characteristics, preference, health status, and previous history and suggests that the person use a wheelchair and prepares to bring the supporting wheelchair to the entrance of the Living Lab. Our system can also make other recommendations, such as a walker robot based on user health conditions that are continuously updated. For example, suppose the computation based on captured sensory data shows that the user has not walked a lot in a while. In that case, the global intelligence will recommend that the participant use a walker robot.

In Figure 11, at $t = 4{:}38$, the wheelchair is called to the entrance from the outside. The wheelchair navigates the entrance by using its onboard sensors. The wheelchair robot has a ToF camera that uses the classifier for more information about the environment. After the user sits in the wheelchair, the robot takes the person safely to the front of the elevator. Next, the elevator is called for the user via automated switches that can be triggered as the person arrives near the elevator. Finally, with existing shared control for the user, the user starts to move the robot to the desired place in the elevator. In this way, our system can design behaviors of the AI robot that can assist the user in areas beyond the boundaries of home such that the user can feel confident in her or her abilities if he or she works with the AI robot.

EXPERT EVALUATION

To understand the potential of our framework and compare the concept from different perspectives of experts in the field, we developed a new nine-point evaluation. The method was inspired by the NASA Task Load Index questionnaire, with the aim to have a qualitative and quantitative performance evaluation based on third-eye analysis by different experts in the field. We considered respondents in engineering, health professionals, and social scientists as well as the public (others), with around 80 participants, in total, with an approximately equal distribution. Over 58.8% of our participants were aged over 35, and 26.3% were over the age of 45, which has high potential to consider the following framework a technology incubator, incremental research, or a consumer. The questionnaire was designed with an inverse questioning form to avoid biases by the participants, both favorable and unfavorable. The questionnaire was taken for a period of one week. Please refer to the supplementary information for details of questions.

After preparing the data in a spiderweb nine-point scoring format, we can see the results in Figure 12. It is important to note that in our nine-point data evaluation, we have considered our framework from three main factors: engineering (intelligence, usefulness, and convenience), health (frustration and physical and mental demands), and social (anxiety, sociability, and trust) factors. Each expert was asked all the questions, with values between one and 10, where value 5 presents a neutral opinion with respect to the question, and the lower the value, the more favorable the score is. We can see from Figure 12(a) that the academics and professionals from the engineering field showed great interest in the potential of the

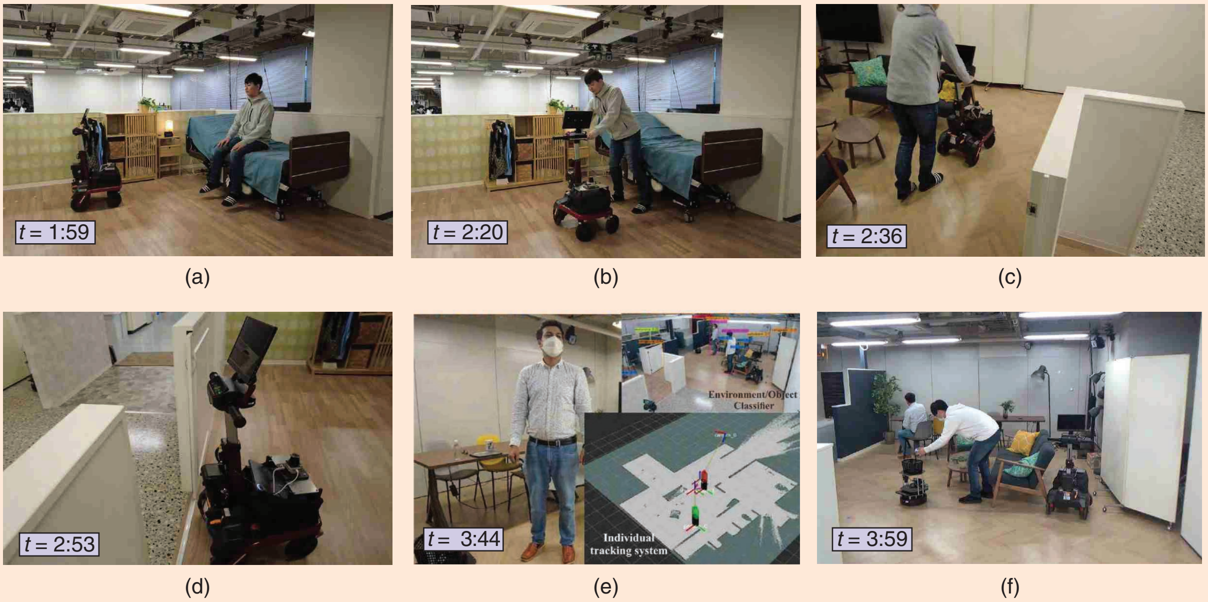

FIGURE 10. The living room scene. (a) The walker robot approaches the user. (b) User leaves from the bed (automatic height adjustment) to use the walker robot. (c) The robot walker assists the user with shared autonomy. (d) The robot walker returns to base after the task. (e) The caretaker commands the global intelligence (computer) for delivering an item to the user. (f) The appropriate service robot executes the requested task and delivers the object to the user using position tracking.

proposed framework from an engineering point of view [engineering (1) mean: $m = 3.607$; standard deviation: $\delta = 1.93$], e.g., performance and usefulness. However, they found the system open to be improved in trust, sociability [social (3): $m = 4.117$; $\delta = 1.91$], and frustration [health (2), with values around four].

More interestingly, the second group that agreed with the potential of the CARE framework was the health sector. It showed high interest in the practicality of the robots in the framework, with a slight increase of value by 0.3 scores [engineering (1): $m = 3.92$; $\delta = 1.796$]. However, it found the trust and sociability [social (3): $m = 4.608$; $\delta = 1.53$] hard to score and not as highly positive. This clearly shows potential for improvement, for example, by working on human–robot interaction and human psychology to make users feel more relaxed and keep them in the loop of what is happening. This group also commented on giving more freedom in human–robot interaction, where the robot and global intelligence respect users directly/indirectly. It pointed out that some patients might require slower and smoother interaction with a robot, due to disabilities, e.g., dysarthria and intractable diseases, and even slower motor function due to age issues. This will require the global intelligence to build a case-specific user assist that will be one of our future aims.

From the social scientists' point of view, they had an overall neutral assessment of the robots' capabilities [health (2): $m = 4.911$, with $\delta = 1.84$; social (3): $m = 4.843$, with $\delta = 1.483$] but showed interest in the engineering application of the framework [engineering (1): $m = 4.41$; $\delta = 2.106$]. However, they had similar concerns regarding the framework's sociability, frustration, and physical demand. To generalize the overview, we check the scores by including all the experts in the field, which results in Figure 12(b). The participants gave scores around four for health [$m = 4.425$; $\delta = 1.873$] and engineering [$m = 3.98$; $\delta = 1.92$] factors, but they still found space for improvement regarding social factors, such as anxiety, sociability, and trust [$m = 4.693$]. This issue was aligned with other sectors that find it challenging to understand human–robot interaction, with certain levels of anxiety.

CONCLUSIONS AND FUTURE WORK

The use of assistive robots to support elders and caregivers is an inspiring and inevitable goal in robotics research and development. However, this requires a fundamental concept that future research could build on. This article proposed a framework for future welfare facilities through the new concept of the Living Lab. First, we explained the Moonshot Project and CARE initiative. Then, we presented the framework's main ideas by explaining the assistive and service robots and sensory system within it. We described our framework as an adaptable AI that supports users by sensing physical conditions, expressions, surroundings, and daily conditions and providing the most appropriate support through several robot systems. The global intelligence utilizes an innovative multirobot IoT interface, and sensory feeds try to correspond to user requests by selecting the best options. The aim is to develop an assistive multirobot cooperative system that promotes user self-efficacy, e.g., safety, individual characteristics, health conditions, and preferences.

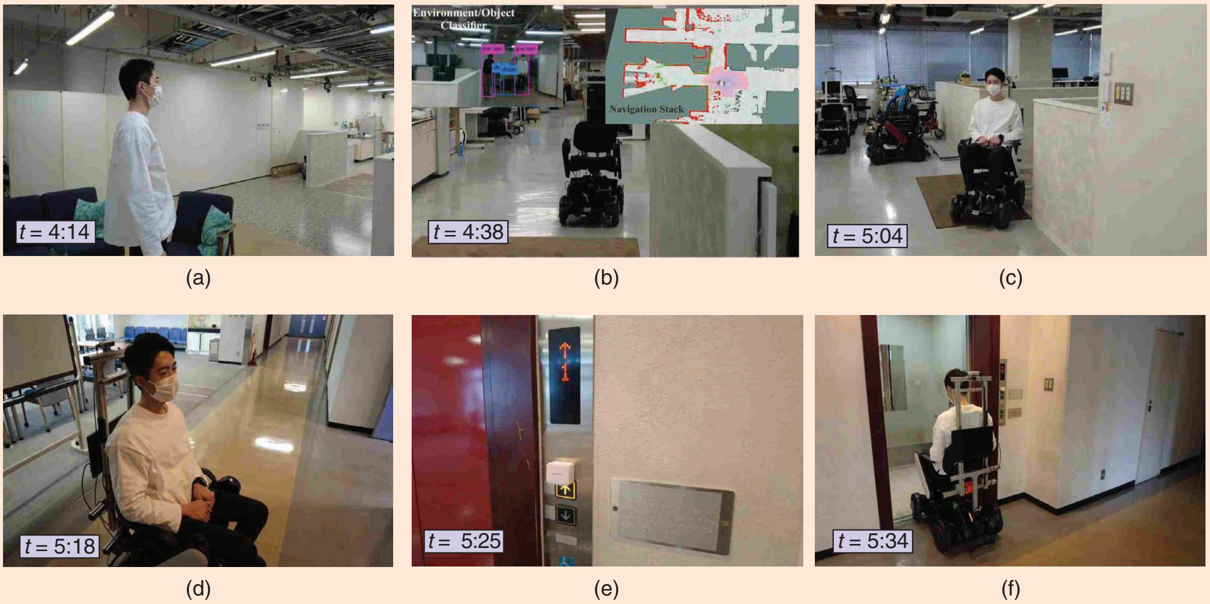

FIGURE 11. The outdoor scene. (a) The user desires to go out and requests the global intelligence via voice command. (b) Based on the user's data and health preferences, a wheelchair robot is selected and it approaches the user autonomously. (c) The wheelchair navigates to outside facility. (d) The user calls for the elevator. (e) Smart switches are actuated and the elevator button is called. (f) The patient takes control of the robot with shared autonomy to move the wheelchair robot.

This framework was explained through different levels of computation, from the robots' navigation to the chosen strategy in the communication interface. The system can also aid in helping people avoid forgetting and mistaking their medicines and provide feedback among family members, friends, and caregiving staff about the same. We also presented a new webserver system for multirobot communication and the sharing of messages among different agents in real time. Such systems in the home care scenario can provide appropriate support to users by distributing tasks to multirobot systems, where each robot can do a specific task. Unlike a single robot system, our proposed system is less complex, and task distribution and allotment among the robots can be efficiently handled without hindering the overall task at hand. The robots work with humans under a shared autonomy policy that considers a person's safety and the obstacles in an area as well as our proposed sensory information from a facility along with wearable sensors. We did an extensive questionnaire evaluation with a new nine-point scale. From the evaluation results, experts in the field of health and engineering expressed keen interest in the potential of the robot; however, they highlighted open challenges regarding anxiety, trust, and sociability factors. Also, certain experts found the system frustrating, which could directly correlate with sociability. Social scientists also had a certain level of interest but indicated their concerns regarding social interactions and physical demands.

Although the concept was successfully presented through several demonstrations in real-world cases, many problems should be addressed in the home care robot scenarios. These problems can be grouped into different levels of engineering, social science, and AI aspects. From the engineering aspect, the safety, real-time risk assessment, and development of advanced actuating mechanisms in assisting people with severe disabilities is challenging. Furthermore, there is a significant amount of research on developing different assistive mechanisms to help patients from different aspects, such as motion assistance, toilet support, and more challenging tasks, including transfer support. Also, there are studies on understanding the ethical and psychological issues regarding robot and human interaction in social science. For example, how will a robot understand a person's needs, and to what extent can it provide physical and emotional support? Can machines understand human stress and experience with robots? What if an elderly person cannot get used to the way robots interact with him or her? How can we make a quantification for evaluating ethical issues at the low level?

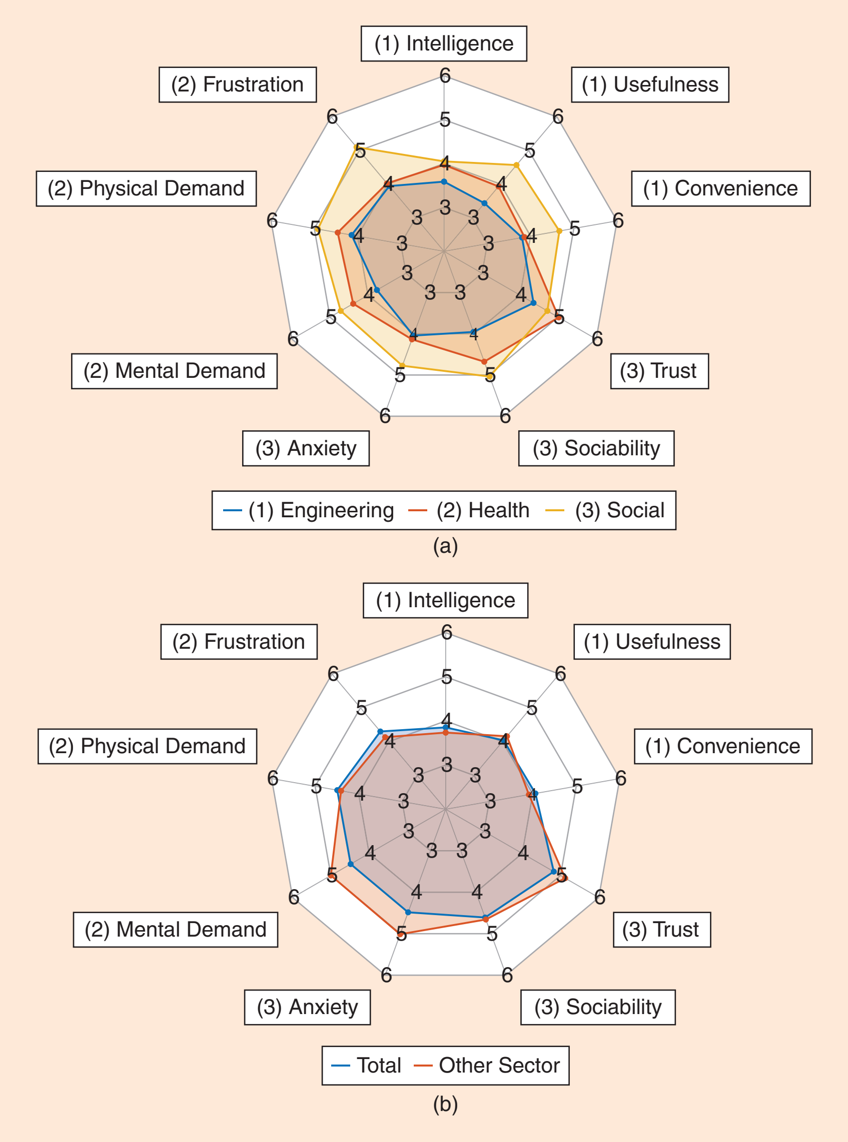

FIGURE 12. The nine-point questionnaire results. (a) Scores considering experts in engineering, healthcare, and social fields. (b) Scores considering all the experts.

Data protection and information privacy is another issue where an informed consent-based evaluation of a user's request by the AI is made. On the side of the AI, the problems can be focused on the global intelligence: improving robot understanding of high-level instructions from a user in human-friendly ways. For example, in a scene where not only patients but also everyday people and other professionals are participants, the AI should be able to respond and react based on a person's intention, occupation, and interaction with counterparts.

ACKNOWLEDGMENT

This work was partially supported by the Japan Science and Technology Agency (Moonshot Research & Development Program), under grant JPMJMS2034. Before the experiment, our

research purpose, method, and data handling were fully explained to participants, and we obtained their informed consent. All the research has taken place with the approval of the Ethics Committee on Research Involving Human Subjects, Graduate School of Engineering, Tohoku University. This article includes supplementary downloadable material available at https://doi.org/10.1109/MRA.2022.3223256, provided by the authors. Ankit A. Ravankar, Seyed Amir Tafrishi, and Jose V. Salazar contributed equally to this article.

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