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Mobile Monitoring of Physical States of Indoor Environments for Personal Support

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***Abstract*— Mobile service robots are expected to operate in our daily life soon, as mobile robot technologies such as SLAM are rapidly developing. As a new application area of the technologies, we propose mobile monitoring and support robot (MMSR), which maintains a residential environment to be comfortable, safe, and secure. A key to realizing MMSRs is monitoring the physical state of the environment. By using a mobile robot as a mobile sensor base, an MMSR can efficiently obtain only necessary environmental information such as the temperature of the location of a person. It can then do supporting actions such as controlling appliances to make the environment more comfortable. We have developed and tested a prototype of MMSR to show the potential feasibility of MMSR concept.**

***Index Terms*— Mobile monitoring and support robot, physical state monitoring, personal service robot.**

I. Introduction

Mobile robots has been one of the most active and important research areas in robotics for years. Especially, many sophisticated mapping and localization techniques have been developed [1]. Based on such techniques, mobile robots can recently be used for various applications. One of the promising applications is a robot which lives with and takes care of the elderly. Such an assistive robot usually has mobility, object recognition and manipulation skills, and interaction abilities, and assists residents in various ways (e.g., [2], [3], [4], [5]). These works mainly focus on robot operations and human robot interaction. For appropriate and timely assists, a robot needs to monitor the physical state of the environment as well as residents' state. The robot then takes actions for maintaining the environment to be comfortable, safe, and secure. We call such a robot a mobile monitoring and support robot (MMSR).

Keeping a residential environment in a comfortable state (comfortable temperature, moderate illuminance, air cleanness etc.) has been recognized to be effective not only for resident's health but also for energy savings. Various comfort assessment methods and resident's comfort indices have been proposed (e.g., [6], [7], [8], [9]), with lots of standarization efforts. An efficient and precise measurement of the physical state of an environment is a key to realizing an effective assessment.

Monitoring people at home has been a popular topic in sensor network and ubiquitous systems research. There are many works on so-called *intelligent room*, which puts many sensors in a room and observes the room and people for activity modeling, activity prediction, and anomaly detection [10], [11], [12], or further providing services through human-computer interaction abilities and/or robotic devices [13], [14], [15]. These systems rigorously use built-in sensors for reliable monitoring, and cannot be immediately applied to normal houses. Moreover, it is sometimes difficult to monitor the physical state at the very location where a person exists. To obtain data at desired locations, we need to move around with carrying sensors.

Using a robot as a mobile base for environmental sensing is an interesting research area with many potential applications. Marques et al. [16] use multiple mobile robots with an odor sensing capability for making environmental odor maps. Hernandez et al. [17] developed a mobile robot that can generate a gas distribution map using an optical remote gas sensor, and can localize a leak position. Nagatani et al. [18] developed a method of integrating range and thermal data for generating a 3D thermography map. Such an approach is effective when we cannot place many sensors at many locations.

Maintaining an environment to be comfortable, safe, and secure entails knowing the current state of the environment as well as people's states, detecting potential risks and hazards, and taking (mostly) preventive actions. Realizing MMSRs that can do such tasks will effectively be developed based on various mobile robot technologies. This paper discusses the expected tasks and the development of MMSRs, with focusing mainly on the physical state monitoring. We develop a prototype MMSR and conduct experiments on physical state monitoring and personal support. In this paper, we deal with thermal and illuminance states as physical states to monitor which directly affect the resident's health in usual daily living.

The rest of the paper is organized as follows. Sec. II discusses expected tasks of MMSRs with related mobile robot technologies. Sec. III briefly surveys physical state monitoring, and Sec. IV describes a prototype MMSR and an experimental room. Sec. V describes mobile monitoring of physical state and visualization of monitoring results. Sec. VI shows an example monitoring and support scenario. Sec. VII concludes the paper and discusses future work.

II. Tasks of MMSR and Related Mobile Robot Technologies

A. Physical state monitoring and control

To keep a residential environment to be comfortable, monitoring and control of its physical state is most important. A mobile robot with various sensors can move to measurement locations and collect data for evaluating the physical state. If the current state is different from a satisfactory one, the robot may operate, for example, an air conditioner to adjust the room temperature. A mapping and localization function (mostly in 2D) is needed for such an autonomous movement.

For people-aware monitoring, it is desirable to monitor the physical state at the very location where people exist as well as monitoring people conditions. Therefore, functions for detecting people and recognizing their conditions are necessary for the robot. Various interaction capabilities (e.g., voice interface) would also be desired.

B. *Safety assessment and response*

Preventing accidents is important for realizing a safe environment. A possible accident is a tumble of the elderly. To prevent tumbling accidents, even small obstacles on the floor must be detected and removed; 3D mapping function will thus be useful. A more flexible people recognition will also be required such as recognizing people in various postures (e.g., falling on the floor) and detecting vital signs [5], [19].

Other accidents such as fire and water leakage must also be avoided. Mobile robot technologies for localizing various physical sources such as heat source, odor source, or sound source will be effectively utilized for this purpose.

C. *Security maintenance*

Confirmation of lock of doors and windows is one of possible supports for security. Object recognition techniques will be utilized for such confirmation as well as generating walk-around robot paths. Detection of an intruder would also be necessary. This will require a human identification ability for discriminating intruders from residents.

III. Physical State Monitoring in Architecture Domain

This section briefly surveys established methods for measuring physical states of houses in architecture domain. In thermal state monitoring in Japan, for example, we are expected to observe the following guideline [20]:

- A living space is defined as the one surrounded by the floor, the plane at the height of $180cm$, and vertical planes $60cm$ apart from walls, windows, and fixed air conditioners (see Fig. 1).
- The measured position is the center of the floor in the space, and the measured height is $110cm$. This height corresponds to that of either the head position when sitting or the abdomen position when standing. It is desirable to additionally measure the temperature at the heights of $10cm$ and $60cm$ when sitting, and at the heights of $10cm$ and $170cm$ when standing.
- More measured points should be added and a desired degree of accuracy should be assured according to the purpose of measurement.

In illuminance measurements [21], the following guidelines are established:

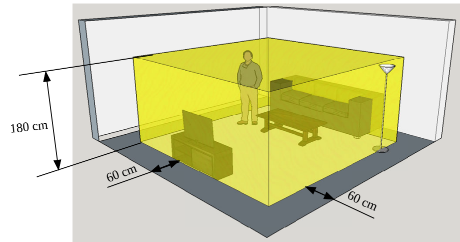


Fig. 1. Definition of a space for measuring a thermal state.

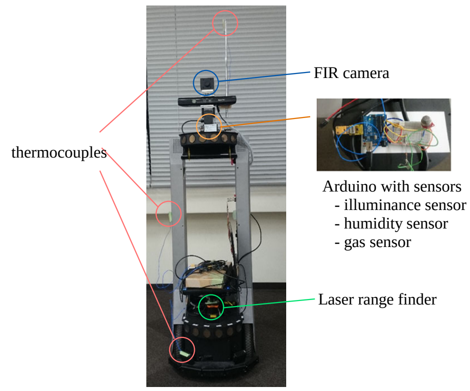


Fig. 2. The mobile monitoring and support robot prototype.

- The measured height is normally set at $80{\pm}5cm$.
- The measured positions are determined according to the objective of the room to measure, usually distributed to sufficiently cover the whole area.
- The measured positions are placed on grid points and the number of the positions are between 10 to 50.

IV. Prototype System and Experimental Room

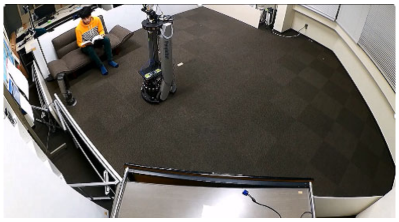
A. *Prototype system*

We developed an MMSR prototype system with a mobile robot and various sensors. Fig. 2 shows the robot. The mobile base is PeopleBot by MobileRobots Inc. The robot is equipped with two Hokuyo range sensors (UTM-30LX and UHG-08LX) for covering 360° view, two Kinects, and a far-infrared (FIR) camera; these are for mapping, localization, and human detection. Environmental sensors are three thermal sensors (thermocouples) an illumination sensor, a humidity sensor, and a gas sensor. The robot accesses these environmental sensors through Arduino Uno. The thermocouples are set on the heights of $10cm$, $70cm$, and $170cm$ considering both the requirement in architecture and the robot structure.

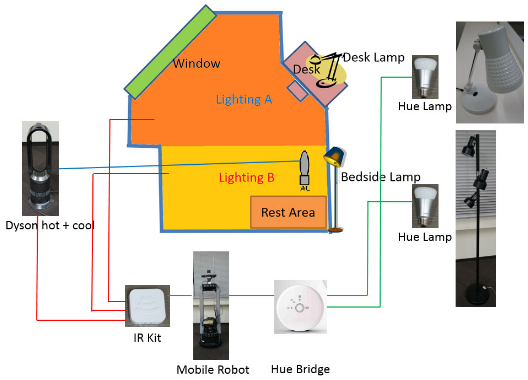
This prototype robot deals with physical state monitoring, human monitoring, and actions for keeping a room comfortable. Maintaining a safe and secure environment is not considered.

B. *Experimental Room*

Our experimental room is shown in Fig. 3. The room has one window. A subject is either at a desk or on a sofa bed. Lights on the ceiling are divided into two groups which cover

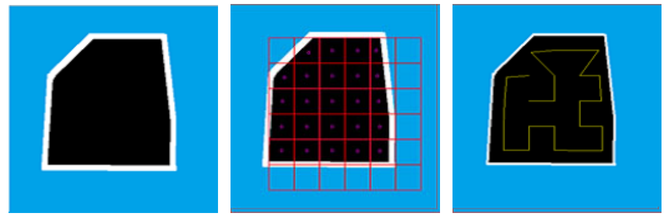


(a) View of the experimental room.



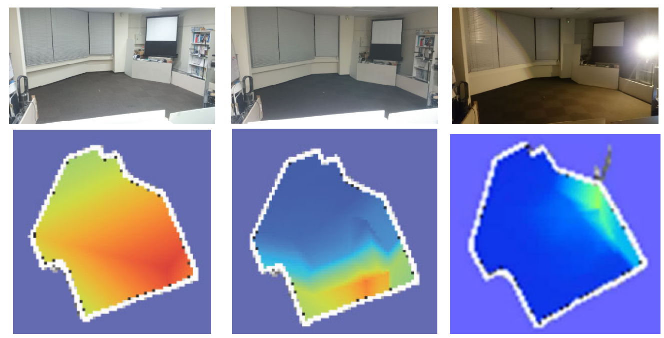
(b) Floor plan of the room and remote-controlled devices.

Fig. 3. Experimental room.



(a) Input free space map. (b) Viewpoint candidates. (c) Generated path.

Fig. 4. Path planning for a whole space measurement.



(a) normal lighting (b) partial lighting (c) spot lighting

Fig. 5. Examples of illumination distribution measurements. The top row shows actual scenes and the bottom row shows the corresponding measured illumination distributions. Red regions show high illuminance while blue regions low illuminance.

different areas of the room. We also have desk lamp and bedside lamp, and a heater.

Operation of the room lights and appliances is done through IR Kit [22]. IR Kit has an HTTP-based API and accepts GET and POST commands for learning IR codes for remote controllers and for submitting the codes, respectively. The robot also controls the desktop and bedside lamp by using the Philips hue system [23].

V. Physical State Monitoring and Visualization

A. *Planning a viewpoint sequence for physical state monitoring*

Monitoring the physical state of an indoor space is composed of two steps: (1) planning a path for monitoring and (2) movement on the path with collecting sensor data. Considering the measurement requirements in architecture domain (see Sec. III), we represent a path by a sequence of viewpoints where the robot has to obtain sensor data.

Fig. 4 illustrates the steps of path planning in monitoring the whole space. We set a regular grid in the space and generate a path connecting the centers of cells. Cells with low free space ratios are not included in the path for avoiding collisions. Planning a shorter path is so-called traveling salesman problem (TSP). We use 2-opt method [24], a popular local search-based method, for solving the TSP. The trajectory connecting subsequent viewpoints is generated by our local path planner [25]. Note that the robot continuously collect data as it follows the generated trajectories, not collect data only at the viewpoints.

B. *Visualization*

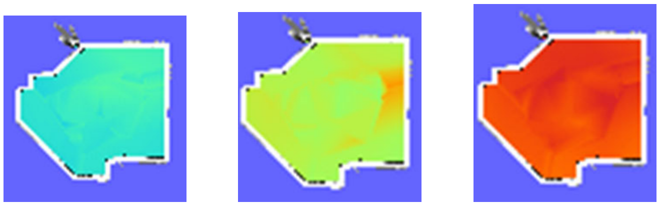
Visualizing the measured data is useful for us to recognize the state of the room. Since we currently suppose relatively static scenes where the changes of physical states is slow enough, and since the robot can collect data sufficiently densely in the space, we take a simple interpolation approach for visualizing the distributions of physical states. We use the Delaunay triangulation [26] for partitioning the whole space into local triangle regions; vertices of triangles are positions where the sensor data are collected. A linear interpolation is then applied to each triangle.

C. *Monitoring examples*

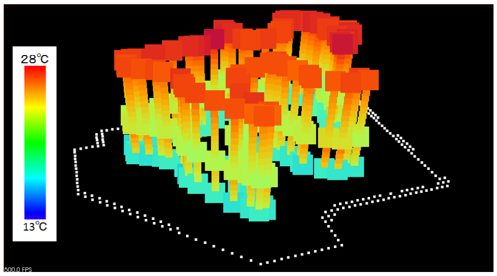
1) Monitoring illumination conditions: Fig. 5 shows examples of measuring illumination distributions in the room under three different conditions. This room has two groups of ceiling lights; they are indicated as *Lighting A* and *Lighting B* in Fig. 3. In (a), both groups were turned on, while in (b), only one group in the front side (*Lighting B*) was turned on. In (c), both groups were turned off while one spotlight (bedside lamp in Fig. 3) was turned on. The illumination distributions are properly measured and visualized.

2) Monitoring thermal conditions: Figs. 6 and 7 shows examples of thermal condition monitoring in the room. The figures use two different visualization methods. One is 2D visualization triplet corresponding to the three sensor heights. The other is 3D visualization, showing three sensor data at once at each measured position. The value for an intermediate height is calculated by a linear interpolation.

Fig. 6 is the case where the air conditioner is set to 24°C. Since the air conditioner is on the ceiling, there is a large temperature gradient from the ceiling to the floor. Fig. 7 is the case where the air conditioner is turned off



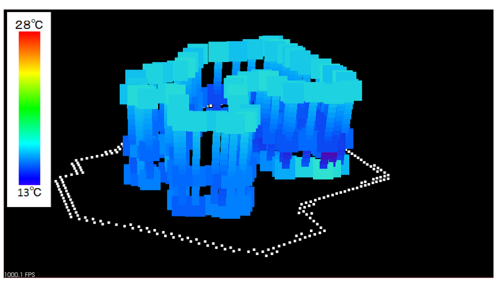
(a) $10cm$. (b) $70cm$. (c) $170cm$.



(d) 3D visualization.

Fig. 6. Thermal condition when the air conditioner is set to 24°C.

(a) $10cm$. (b) $70cm$. (c) $170cm$.

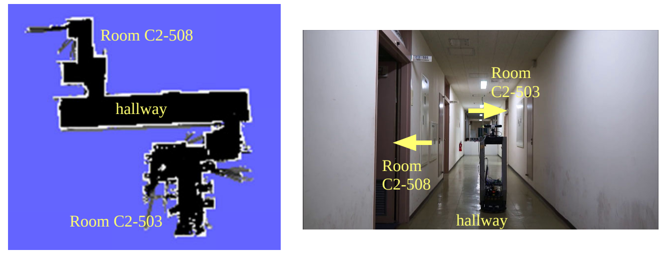


(d) 3D visualization.

Fig. 7. Thermal condition when the air conditioner is off and a heater is on.

and a small heater at the right-bottom corner of the room is turned on (marked by a red circle). After turning off the air conditioner, the overall temperature becomes low, with a temperature gradient still remaining. It can also be seen that at $10cm$ near the heater is warmed up a little (around 20°C). Thermal conditions can be intuitively perceived by either of the visualization methods.

Fig. 8 shows another example of thermal condition monitoring. The robot moved from one room to another through a hallway by manual control and collected thermal data during the movement. In the figure, we can see that air conditioners were operating in the two rooms, while we had a lower temperature in the hallway.



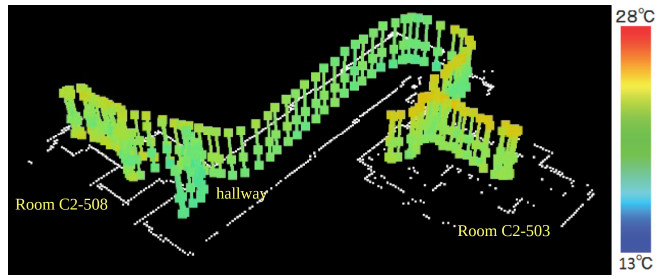


Fig. 8. Measurement of thermal distribution over rooms and hallway. Top left: the map generated by a SLAM method. Top right: the experimental scene. Bottom: the thermal distribution.

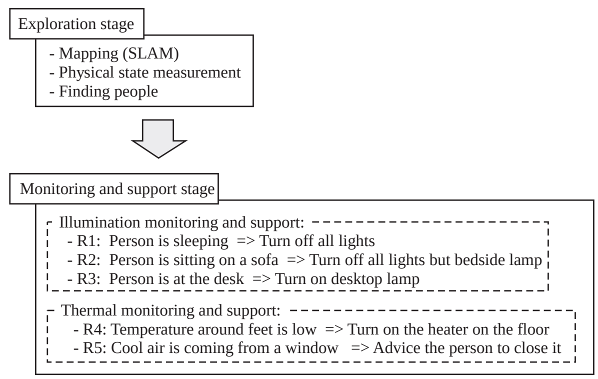


Fig. 9. An experimental scenario.

VI. Personal Support Application Example

A. Supporting action generation

The ultimate goal of MMSRs is to keep the environment comfortable, safe, and secure. This is done by monitoring the physical state of the environment, by monitoring the state of people, and then by taking appropriate actions such as controlling appliances, giving people advice to do some actions, and reporting the status to an outside caregiver.

In general, there are a large variety of personal support scenarios, depending on various factors such as the robot's ability in sensing and operation, equipments of the room, ages and health state of people, and so on. Extensive analyses will be, therefore, required on what factors to consider and what supporting actions are really useful and necessary. In this paper, as a starting point, we deal with a small but essential scenario in which all elements of MMSR, namely, monitoring physical state, monitoring human state, and supporting actions, are included. We expect to show the potential usefulness of MMSRs using this example scenario.

Fig. 9 illustrates the scenario. It starts when the robot is entering the space to monitor. If the space is not known before, the robot explores and makes a map of the environment, while searching for people in the space. Then, the robot monitors physical and people states and takes appropriate supporting actions when it detects some condition to react. We prepare five condition-action rules shown in the figure. The first three rules (R1-R3) are about illumination conditions and the last two (R4-R5) are about thermal conditions. The robot moves and monitors the physical and person states autonomously to verify the conditions of the rules.

B. Experiments

Two actual operations of the robot are presented. Each shows a sequence of monitoring and support actions.

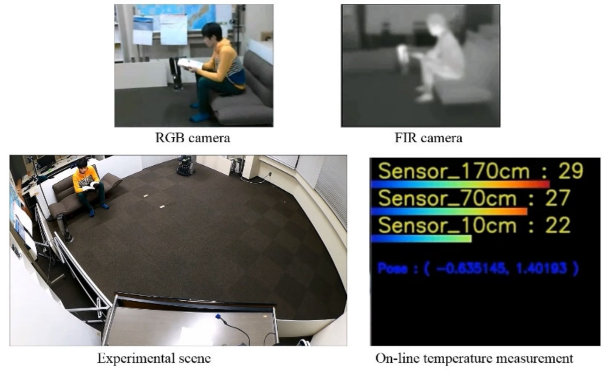
1) Experiment 1: A person was first sitting on a sofa bed and then went to sleep there. The robot detected the person's state from his posture and appropriately controlled the illumination. It also detected that it was a little cool around his feet and turned on a heater. Detailed steps are shown in Fig. 10.

2) Experiment 2: A person was sitting on the desk. The robot first turned on the desktop lamp and then went to a window to measure the temperature. It detected a cool air coming from the window and gave the person an advice to close it. Detailed steps are shown in Fig. 11.

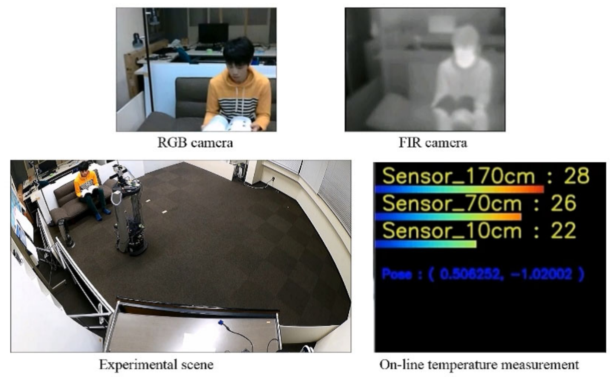
VII. Conclusions and Future Work

This paper has dealt with mobile monitoring and support robot (MMSR), a new research area in mobile robotics. We have described expected tasks of MMSRs and related mobile robotics technologies which will be utilized in developing such robots. A prototype MMSR was developed as a proof-of-concept, with referring to physical state monitoring in architecture. The robot can explore a space autonomously while collecting sensor data and generate a distribution map of physical entities, which is then visualized for intuitive understanding of the situation. The robot also achieved a monitoring-and-support scenario, which includes monitoring physical state, monitoring human state, and supporting actions.

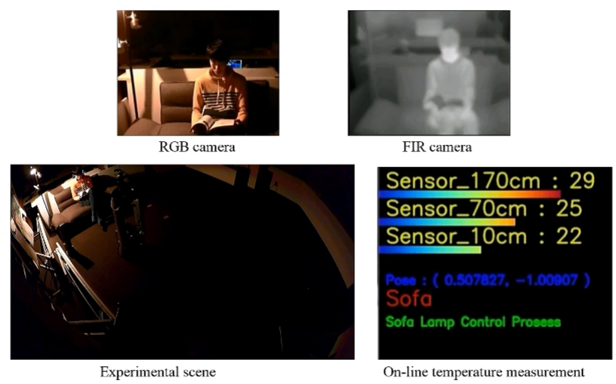
There are many things to do for future deployments of MMSRs. First, an extensive survey of actual needs is necessary. The needs will be different from case to case, depending not only on the characteristics of a residential environment but also the state of residents including ages, health, family relations, jobs, and many others. Finding a small but important coverage of tasks will be a key to developing useful MMSRs. Second, we need to improve mobility and object recognition ability to cope with a large variety of residential environments. Last but most importantly, the ability of recognizing human state must be improved. Current state-of-the-art computer vision techniques can deal with human detection, face recognition, posture estimation but still have difficulties in recognizing human hedonics (comfort or not) and health. These factors are, however, important for assessing the environment. Although these could be measured by wearable devices, remotely sensing them will be desirable.



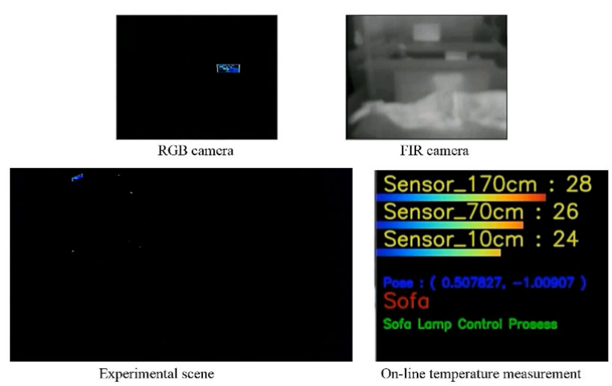
(a) Initial state. The robot was at the top in the image. A person was detected using an FIR camera.



(b) The robot moved to the person's position and recognized the person's posture (i.e., sitting) and measured the temperature near the person.

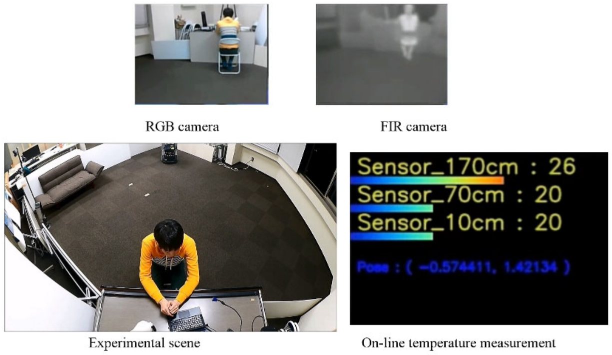


(c) The robot turned on the sofa-side lamp and turned off the others using Rule R2, and turned on the heater using Rule R4.

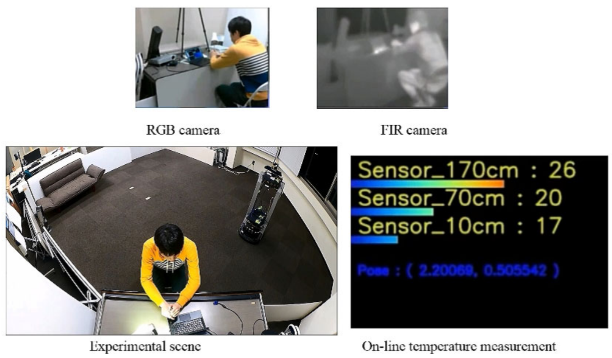


(d) The robot detected the person to go to sleep and turned of all lights using Rule R1.

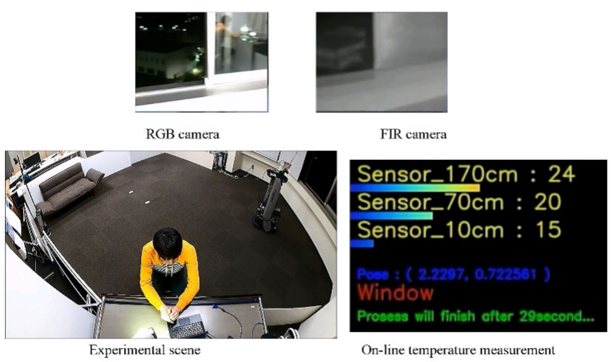
Fig. 10. Experiment 1: supporting actions of controlling lights and a heater.



(a) Initial state. The robot was at the top in the image. A person was detected using an FIR camera.



(b) The robot moved to the person's position to find the person was sitting at the desk. It then turned on the desktop light using Rule R3.



(c) The robot moved to a window and measured the temperature. It found that a cool air is coming from the window, and gave the person an advice by voice to close it using Rule R5.

Fig. 11. Experiment 2: supporting actions of controlling a light and giving an advice.

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