Intelligent Ambience-Robot Cooperation
— Door-Closing Tasks with Various Robots —

Takeshi Sakaguchi, Takeshi Ujije, Shinichi Tsunoo, Kazuhiro Yokoi, and Kazuyoshi Wada

Abstract—A large amount of information involving human beings is available on the Internet; however, only little information that involves robots is available. We believe that having ambient intelligence provides helpful information for robots under ubiquitous computing technologies. The purpose of our research is to describe common environmental information in order to enable a robotic system to execute target tasks in a variety of ambient conditions. This system can correspond to various robots and various objects when we design the task information, which does not depend on the types and structures of these robots. In this paper, we focus on the door-closing task performed by robots among various other tasks and propose a robot control method that integrates the ambient intelligence. The effectiveness of the proposed system is experimentally confirmed using a refrigerator with two types of doors: a door status sensor, which we developed; a humanoid robot; and a mobile manipulator.

I. INTRODUCTION

In the future, it is expected that robots will participate in our daily environments. However, few robots are being used in offices and houses. This is because the ambience of industrial robots in factories is constant, whereas the target objects for robots that are outside these factories, namely, offices and houses, are continuously changing. It is almost impossible to define all the models of these objects to a robot. When an object is replaced, persons developing each robot should redefine a new model for the robot. It is impossible to install these updated models in all the robots whenever an object is replaced. A home robot like the iRobot RoomRat has no map of the workplace and it only moves on the floor while automatically redirecting itself when it bumps into obstacles.

Structuring methods of ambient intelligence are becoming important issues in the robotics field; such ambient intelligence can enable robots to adopt ubiquitous computing technologies by using GPS and RFID tags, and acquire the necessary information for working in offices and houses, thereby working accordingly [1]. There are two merits in putting information into an environment. Firstly, persons who develop each robot can minimize the installation of knowledge of the objects that the robot might use. The new knowledge of objects is provided by the object manufacturers and the owners, designers, architects, or removers who structure the environment whenever the ambience changes. Secondly, in case of different robots, the same ambient intelligence can handle different kinds of robots, as shown in Fig. 1. No one needs to customize each robot. Each robot can execute tasks using the common ambient intelligence.

There have been some researches to support persons and robots by arranging sensors in the environment. Saio et al. [2] have proposed the robotic room that measured human actions by arranging sensors and actuators in a room and tried applications toward medical welfare. Hashimoto et al. [3][4] have networked ceiling cameras, special sensors, and computers arranged in space and have investigated the intelligent space that recognized human gestures and promoted the efficiency of robot control. Hasegawa et al. [5] have suggested a robot town comprising robots with the RFID tags, sensors, and street corner cameras arranged both indoors and outdoors. Irie et al. [6] have investigated an intelligent room enabling the operation of home electric appliances by recognizing hand waving and the number of fingers using ceiling cameras. From the viewpoint of service-oriented robots, Koide et al. [7] have investigated an interactive exhibition guide robot using ubiquitous sensors embedded in an exhibition room or attached to people in the room. Fukuda et al. [8] have proposed human activity recognition systems based on human actions dealing with items labeled by IC tags and have developed a cooking-support robot that suggests subsequent tasks to humans by means of voice and gestures. Ha et al. [9] have proposed a service-oriented ubiquitous robotic framework and implemented Web services for robots, networked sensors, and devices as a unified interface method.

Fig. 1. Importance of Ambient Intelligence

Takeshi Sakaguchi and Kazuhiro Yokoi are with JRL, AIST, Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki, Japan (email: {sakaguchi.t, kazuhito.yokoi}@aist.go.jp), and Takeshi Ujije, Shinichi Tsunoo, and Kazuyoshi Wada are with Graduate School of System Design, Tokio Metropolitan University, 6-7 Ashigakoka, Hino, Tokyo, Japan (email: {ujije-t, tsunoo-shinchi, k_wada}@sd.tmu.ac.jp).
for access. We showed application examples to support persons by putting information into an environment, but there have been many researchers investigating navigation assists using embedded information in an environment from the viewpoint of supporting a robot. Hiratsuka et al. [10] and Moon et al. [11] have focused on the navigation of robots in large working areas or rooms. Kodaka et al. Alankus et al. [12] have proposed a new approach for wireless-sensor-network-assisted navigation while avoiding moving dangers. Their approach relied on adaptive embedded roadmaps in the sensor networks that always contained safe paths. Shenoy et al. [13] have described range-free localization and navigation of mobile robots in a hybrid sensor network, which consisted of a large number of static wireless sensors and relatively small number of mobile robots. Some researches have focused on assisting object recognition in a working space. Asama et al. [14] have proposed autonomous robotic systems that communicate with their environments via intelligent data carriers (IDC). Shihuta et al. [15] have developed an intelligent mark and its recognition system to obtain information about the working space for service robots. Miyauchi et al. [16] have proposed a collaborative monitoring system using active RFID tags (UFAM) and monitoring mobile robots. These researches involved object recognition and workspace recognition by robots. In fact, these robots did not operate upon objects in the working space. There have been some researches on the assistance of object manipulation using visual marks, RFID tags, and so on. Ota et al. [17] have proposed an environmental support method for mobile robots using visual marks and Katsumi et al. [18] have prepared a fixed manipulator handle for three objects that were occluded or were close to each other. The robot could select suitable motion using object information in QR codes and signals from proximity sensors. Nagatani et al. [19] have developed optical communication marks for mobile robots to recognize their environments and handle objects. They developed a mobile robot that could accurately recognize a target in the working space and grasp it. Chong et al. [20] have proposed a new design of distributed knowledge networks to deploy easy-to-use robot systems into day-to-day activities with minimal programming effort. In this robotic system, a manipulator cleared the dinner table autonomously without any significant human intervention.

As mentioned above, many related works have used environmental structuration technologies and some researchers have actually developed a robot to manipulate objects. However, most of these researches focus on manipulation by a specific robot. It is expected that various kinds of robots will be introduced in the future so that there are various cars depending on performances, sizes, prices, and so on. It is essential to establish the formulation of common task information for all kinds of robots.

The purpose of this research is to specify a structuring method of ambient intelligence that is independent of the kind of robot. We have focused on the door-closing tasks by robots and studied the communication of common task information with the server so far [21]. Each robot cannot perform the door-closing task only by knowing the target door model, unlike the door-opening task, because the robot needs information about the current state of the target door. Therefore, we think that the door-closing task is an appropriate target that can employ environmental structuration technologies. In this paper, we prove that the humanoid robot and another type of robot can perform the door-closing task against a hinged door and a drawer based on the common task information.

The rest of this paper is organized as follows. In Section II, we present an overview of the door-closing system. In Section III, we describe the task information independent of the types and structures of robots. In Section IV, we describe robot motion planning based on the common task information. In Section V, we substantiate the experiments of the door-closing task using a humanoid robot “HRP-2,” a mobile manipulator “UFMRP-02,” and a refrigerator with two types of doors. Finally, we conclude this research.

II. STRUCTURING METHOD OF AMBIENT INTELLIGENCE FOR DOOR-CLOSING TASKS

We propose a robotic system where each robot acquires the task information from the ambience. Fig. 2 shows an example of the door-closing system, which detects an open-hinged refrigerator or cupboard door in the room and drives a robot to close the door. This system uses our proposed method of environmental structuration.

Each door has a sensor to detect the door status. The status is defined using the open angle in the case of a hinged door and the open distance in the case of a sliding door. Each door is distinguished with an ID number by the sensor. The detected value is transmitted to the environmental state server as ambient intelligence. The environmental information other than the door status is described by the server beforehand.

The server creates the task information for the door-closing task by matching the door status to the environmental information and transmits it to the robot.

This system can correspond to various robots and various doors when we design the task information, which does not depend on the robot types and robot structures.

![Image](https://example.com/figure2.png)

**Fig. 2. Door-Closing System**
III. COMMON TASK INFORMATION INDEPENDENT OF ROBOT TYPES

A. Task Information

When we design the task information, independent of the types and structures of robots, various robots can execute the target tasks in a variety of ambient conditions. Because each robot needs a mathematical description of the ambient intelligence for the door-closing task, we set the objects’ coordinates as follows (shown in Fig. 3): the world frame set on the floor by architects or designers as $\Sigma_w$; the object frame set under the corner by removers or owners as $\Sigma_o$; the door axis frame set under the door corner along the sliding direction by the manufacturers as $\Sigma_d$; and the contact point set on the door by the manufacturers as $\delta_T^{(id)}$. The $x$-$y$ coordinate plane of $\Sigma_w$ is set on the floor and the $z$ axis is set on the vertical direction. The $x$-$z$ coordinate plane of $\Sigma_o$ is set on the door side of the target object and the $y$ axis is set on the depth direction. In case of the hinged door, the $z$ axis of $\Sigma_d$ is set on the axis of rotation and the $x$ axis is set on the door surface. In case of the drawer, the $y$ axis of $\Sigma_d$ is set on the axis of translation and the $x$-$z$ coordinate plane is set on the door surface.

![Fig. 3. Objects’ Coordinates](image)

With regard to the task information for the door-closing task, we put the following information into the environment, such that it can be accessed by the robot:

1) position and orientation of the target object in work space $\mathcal{Y}_w$
2) position and orientation of the target door on the target object $\mathcal{Y}_d^{(id)}(\mathcal{F}_d^{(id)})$
3) contact point on the target door to execute the door-closing task $\delta_T^{(id)}$
4) door-open distance $\mu^{(id)}$

The door-open distance is a scalar variable and is detected by the door status sensor attached to each door. The remaining three parameters, called the environmental information, are stored in the environment state server beforehand.

B. Door Status Sensor

In order to detect the open angle/distance of the door, we developed wireless sensor network nodes with an inertial sensor as the door status sensor [21]. This sensor detects the door status (open angle/distance) by measuring the acceleration and integrating it twice. It transmits the calculated information to a dedicated access point by using a feeble radio wave (distance: $10$ [m]). Because this device is small (case dimensions: $57$ [mm] $\times$ $41$ [mm] $\times$ $14$ [mm]), lightweight (24 [g]), and battery-driven (button type, 3 [V]), we can easily install it on different doors using a double-faced tape. Fig. 4 shows the apparatus for the sensor. This sensor has a relay switch as the closed-door confirmation switch, which turns on with a magnet in order to detect whether the door is completely opened or closed.

![Fig. 4. Apparatus of Door Status Sensor](image)

IV. ROBOT MOTION PLANNING BASED ON TASK INFORMATION

In this section, we describe the robot motion planning for the door-closing task. Each robot has to calculate the target position for moving and the hand trajectory for closing the door.

A. Motion to Close Doors

There are various motions to close doors, for example, grasp the knob of the door and shut the door, hang the door, clap the door, and so on. In this research, we made each robot push the target door in a straight line from the contact point (start) to the contact point (goal), as shown in Fig. 5. This motion does not need the redundancy of each robot and any robot can execute it easily.

![Fig. 5. Trajectories of Contact Point](image)

B. Information Measurable by Robots and Known Beforehand

We set the robot's coordinates as follows (shown in Fig. 6): the robot frame set on the robot by developers as $\Sigma_{re}$ and the hand frame set on the end-effector of the robot by developers as $\Sigma_{he}$.

![Fig. 6. Robot's Coordinates](image)
Each robot can constantly detect the position and orientation of the robot in the world frame $W_r T$ and the position and orientation of the end-effector in the robot frame $h_{start} r T$. Each robot knows beforehand the initial position and orientation of the end-effector against the contact point before the end-effector pushes the contact point (start) $h_{start} r T$ and the final position and orientation of the end-effector against the contact point when the end-effector reaches the contact point (goal) $h_{goal} r T$. $h_{start} r T$ is the safety gap to prevent the end-effector from striking the door.

C. Motion Planner for Each Robot

In order to prove that various robots can perform the door-closing task based on the common task information, we used two kinds of robots. One was a humanoid robot “HRP-2” (Fig. 7 (a)) [22] and the other was a mobile manipulator “UFMRP-02” (Ubiquitous Function Mobile Robot Platform No. 2)” (Fig. 7 (b)) [23]. Each robot possesses a locomotion mechanism to move toward the vicinity of the target door, arm mechanism with an end-effector to push it, and a wireless LAN function to receive the task information from the environmental state server.

1) Description of Robot Motion in the World Frame: As the position and orientation of the contact point in the world frame $W_r T(id)(p(id))$ is

$$\begin{align*}
\begin{bmatrix} W_r T(id)(p(id)) \end{bmatrix} & = \begin{bmatrix} \theta T \end{bmatrix} \begin{bmatrix} T(id)(p(id)) \end{bmatrix} \begin{bmatrix} \thetaT(id) \end{bmatrix}, \end{align*}
\tag{1}
$$

the initial position and orientation of the end-effector in the world frame for the door-closing trajectory $h_{start} W_r T$ can be written as follows:

$$\begin{align*}
\begin{bmatrix} W_r T(id)(p(id)) \end{bmatrix} & = \begin{bmatrix} \theta T \end{bmatrix} \begin{bmatrix} T(id)(p(id)) \end{bmatrix} \begin{bmatrix} \thetaT(id) \end{bmatrix} h_{start} C_r T. \end{align*}
\tag{2}
$$

On the other hand, the goal position and orientation of the end-effector in the world frame $h_{goal} W_r T$ can be calculated by equating (2) with 0 [m] as follows:

$$\begin{align*}
\begin{bmatrix} W_r T(id)(0) \end{bmatrix} & = \begin{bmatrix} \theta T \end{bmatrix} \begin{bmatrix} T(id)(0) \end{bmatrix} \begin{bmatrix} \thetaT(id) \end{bmatrix} h_{goal} C_r T. \end{align*}
\tag{3}
$$

Then, the robot calculates the target position and orientation of the robot in the world frame $R_{goal} W_r T$, which can be used by the robot to execute the door-closing task.

$$\begin{align*}
\begin{bmatrix} W_r T(id)(p(id)) \end{bmatrix} & = \begin{bmatrix} \theta T \end{bmatrix} \begin{bmatrix} T(id)(p(id)) \end{bmatrix} \begin{bmatrix} \thetaT(id) \end{bmatrix} h_{goal} C_r T. \end{align*}
\tag{4}
$$

Here, $h_{start} r T$ is the position and orientation of the end-effector in the robot frame $\Sigma_r$. In this research, we set the data as the posture in which the end-effector is moved to the height of the contact point from the initial posture of the robot.

2) HRP-2: The locomotion command of HRP-2 is the target position and orientation of the robot in the robot frame. As the robot can get the initial position and orientation of the robot in the world frame $R_{start} W_r T$, the target position and orientation of the robot $R_{goal} T$ can be written as follows:

$$\begin{align*}
\begin{bmatrix} R_{goal} W_r T \end{bmatrix} & = R_{start} W_r T^{-1} R_{goal} T. \end{align*}
\tag{5}
$$

Since the manipulation command of the end-effector is the position and orientation in the robot frame, the initial position and orientation $h_{start} r T$ and the final position and orientation $h_{goal} r T$ of the end-effector in the robot frame are given as

$$\begin{align*}
\begin{bmatrix} h_{start} W_r T \end{bmatrix} & = R_{start} W_r T h_{start} C_r T, \end{align*}
\tag{6}
$$

$$\begin{align*}
\begin{bmatrix} h_{goal} W_r T \end{bmatrix} & = R_{goal} W_r T h_{goal} C_r T. \end{align*}
\tag{7}
$$

Substituting (2)–(4) for (5)–(7), HRP-2 can calculate $(R_{goal} T, h_{start} r T, h_{goal} r T)$ by using the task information $(\theta T, \thetaT(id), \thetaT(id), \thetaT(id), \thetaT(id), \thetaT(id))$ and its own and measurable information $(h_{start} W_r T, h_{goal} W_r T, h_{start} C_r T, h_{goal} C_r T)$.

3) UFMRP-02: The locomotion command of UFMRP-02 is the target position and orientation of the robot in the world frame. Therefore, the robot can use $R_{goal} W_r T$ as is. This robot can measure its own position and orientation in the world frame with a high degree of accuracy using the StartLIFE system. Since the manipulation command of the end-effector is the relative position and orientation from the present position and orientation, the initial position and orientation $h_{start} r T$ and the final position and orientation $h_{goal} r T$ of the end-effector in the hand frame can be given as

$$\begin{align*}
R_{start} C_r T & = h_{start} C_r T, \end{align*}
\tag{8}
$$

$$\begin{align*}
R_{goal} C_r T & = h_{goal} C_r T. \end{align*}
\tag{9}
$$

Substituting (6), (7), and the initial posture $h_{start} W_r T$ of the end-effector at the target point of the robot for (8) and (9), UFMRP-02 can calculate $(R_{goal} W_r T, h_{start} W_r T, h_{goal} W_r T)$ by using the task information and its own and measurable information.
V. EXPERIMENTS ON DOOR-CLOSING TASKS

Various doors are encountered in our day-to-day environments. In our research, we selected a hinged door and a drawer among various doors and then used a refrigerator having such doors as the target object (Fig. 8). In this paper, we investigated the door-closing task by using a top-hinged door and a center drawer of the refrigerator. We installed the door status sensor with an ID number on each door and made two kinds of robots, as shown in Fig. 7, that were close to each door of the refrigerator.

Fig. 9 shows the system architecture for the door-closing tasks. Each door is distinguished with an ID number by the door status sensor. The detected value by the door status sensor is transmitted to the environment state server through the dedicated access point. In this server, the program “Sensor Monitor” determines whether the door is kept open and then the program “Converter” creates the common task information for the door-closing task by matching the door-open distance to the environmental information and transmits it to the robot through the wireless LAN. In the robot, the program “Motion Planner” creates the target trajectory of the locomotion and the end-effector by using the common task information and the robot’s own information.

The scenario for executing the door-closing task in this system is as follows:

1) The door status sensor set on each door transmits the door status \( p^{(d)} \) (e.g., open distance) to the environment state server every 0.38 [s].

2) The server receives the current door status from the sensor, concludes the target door is left open when the door status is a constant value (not equal to 0) for more than a fixed period (30 counts in this experiment), and then transmits the door-closing command and task information for the door-closing task to the robot.

3) The robot plans and executes the door-closing task based on the given task information and its own information.

In each experiment, we assumed that some persons forgot to close the door. We arranged for some persons to open the hinged door at the target angles of approximately 30 [deg] and 60 [deg] and to open the drawer at the target distance of approximately 0.15 [m] and 0.35 [m]. We repeated each motion five or more times. Each robot was able to execute the door-closing task based on our proposed common task information in all of these cases.

Fig. 10 shows the photographs of the experiments for a target angle of approximately 60 [deg] and for a target distance of approximately 0.35 [m]. In these experiments, the positions of each robot and refrigerator are shown in Fig. 11. For HRP-2, we set the origin of the object frame as \((x, y) = (2.0 \text{ [m]}, 1.5 \text{ [m]})\) in the world frame and rotated the object frame at 270 [deg] against the world frame. We made the initial robot frame correspond to the world frame. For UFMRP-02, we set the origin of the object frame as \((x, y) = (1.165 \text{ [m]}, -0.363 \text{ [m]})\) in the world frame and rotated the object frame at 180 [deg] against the world frame. We set the origin of the initial robot frame as \((x, y) = (0.672 \text{ [m]}, 1.376 \text{ [m]})\) in the world frame and did not rotate the initial
robot frame against the world frame. Each setting depends on the corresponding owner.

In both cases, we set each contact point on the hinged door as \((x, y, z) = (0.35 \text{ m}, 0 \text{ m}, -0.5 \text{ m})\) and on the drawer as \((x, y, z) = (0.25 \text{ m}, 0 \text{ m}, 0.2 \text{ m})\) along each door axis frame. We set the door axis frame of the drawer as shown in Fig. 11 (a) and the door axis frame of the hinged door as shown in Fig. 11 (b). In each experiment, it took approximately 1 minute for each robot to close each door.

The detected value by the door status sensor was 59 [deg] in Fig. 10 (a)-(I), 55 [deg] in (a)-(II), 0.28 [m] in (b)-(I), and 0.28 [m] in (b)-(II). These values are not the actual values, but each robot system can handle some errors: this is possible because of the stability control system of HRP-2, high-accuracy positioning afforded by the SurLaITE system of UFRMRP-02, rigidity of each door, or a normal function according to which each door of a refrigerator closes automatically when it is ajar by a few centimeters.

In this experiment, we did not use the visual recognition of the working space and force control of the end-effector. The purpose of this experiment was to confirm the effectiveness of our proposed common task information and to confirm whether a robot with low-level functions could execute the door-closing task or not. If we consider the measurement errors relating to the door status sensor, dead-reckoning, trajectory of the end-effector, and so on, we will have to use visual recognition or force control. On the other hand, when the robot moves in a dynamic environment where there are some moving objects or persons and a complex environment where there are a lot of obstacles, it will be necessary to use visual recognition, obstacle avoidance by a laser range finder, SLAM, and so on. This problem is the future work.

VI. CONCLUSIONS

In this paper, we focused on the door-closing task and a structuring method for ambient intelligence is specified, which is independent of the different kinds of robots. This method can correspond to various robots and various doors when we design the task information, which does not depend on the structures and types of robots. We proved that the humanoid robot HRP-2 and mobile manipulator UFRMRP-02 can perform the door-closing task against a hinged door and a drawer based on common task information obtained from the environmental state server in the room. We confirmed the effectiveness of our proposed method experimentally.

In the future, we will use the visual recognition of doors and force control of the end-effector, and make various robots move in a wide environment (several rooms) and manipulate various objects integrating the ambient intelligence.

REFERENCES


