Knowledge Model-Based Intelligent Coordinative Control by Use of Network Platform

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Abstract—This paper presents a knowledge model-based intelligent coordinative control approach for heterogeneous multi-robot system (HMRS) by use of network platform. A HMRS comprised of different types of robots is a primitive prototype of a future symbiotic autonomous human-robot system. Different features of these robots for various purposes always cause difficulty to implement their cooperative operation. Particularly, behaviors of robots in this system are required to follow human commands. In the proposed approach, with frame-based knowledge representation, a HMRS is modeled clearly, including features of different types of robots, activity of human-robot interaction, operations of robots, etc. Based on this knowledge model, the HMRS is defined in a Knowledge Model-Based Intelligent Coordinative Network Platform (K-ICNP) by use of XML format. With the use of K-ICNP and the support from several techniques, such as distributed software agents, tele-operation via wireless network, local robot control programs, etc., the coordinative control of HMRS can be implemented according to human commands. In this paper, an actual HMRS comprised of humanoid robots (Robovie, PINO), mobile robot (Scout) and entertainment robot dog (AIBO) is constructed and the effectiveness of coordinative control is verified by experiment.

Index Terms—Coordinative control, heterogeneous multi-robot system, knowledge representation, network platform

I. INTRODUCTION

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owadays, many types of robots with various functions have been developed and employed in wide areas, such as industrial robot, mobile robot, medical robot, entertainment robot, etc. Particularly, robotic techniques are gradually entering into the human life. Future welfare society requests more supports from different robots, which can be possibly operated according to human request. Ueno [1] proposed the concept of symbiotic autonomous human-robot system recently. In such a system, various types of robots coexist with human at the places of everyday life, communicate with, and aim in helping human. In order to implement this system, coordinative control of robots according to human commands is definitely one of important research topics. Therefore, this paper proposes a framework of knowledge model-based intelligent coordinative control approach for heterogeneous multi-robot system (HMRS).

Since coordinative control of robots is very significant for fulfilling complex tasks, there have some literatures that proposed different control approaches for multi-robot system. For instance, Wang [2] presents a general framework for the analysis and design of the control system with multiple robots handling a common object based on the decomposition of the combined system dynamics into motion-control and internal force-control subsystem. Huntsberger [3] proposed a software/hardware framework for cooperating multiple robots performing tightly coordinated tasks, such as exploration of high-risk terrain areas. Yoshida [4] developed a system for sharing a common coordinate system so that multiple robots can be operated in the same environment. Unfortunately, most of all contributions on coordinative control of robots are only concerning identical type of robots and they have loose relations with human request. Hence, the approaches given in these literatures have limitations to the case of coordinative control of HMRSs.

In this paper, a knowledge model-based intelligent coordinative control approach is proposed for HMRS. In the proposed method, a HMRS is firstly modeled by means of frame-based knowledge representation. It is well known that frame representation systems are currently the primary technology used for large-scale knowledge representation in Artificial Intelligent (AI) [5]. A frame is a data-structure for representing a stereotyped situation [6]. Attached to each frame are several kinds of information. Collections of related frames are linked together into frame-systems.

With this knowledge model, a HMRS can be defined in a network platform by use of XML format, which could be responsible for exchanging messages of communication among robots and human, generating control instructions of robots, responding the information from each member of this system, scheduling behaviors of robots for each service to human, etc. For this research, we have developed a network platform, called Knowledge Model-Based Intelligent Coordinative Network Platform (K-ICNP). With K-ICNP and the support from several techniques, such as distributed software agents,
tele-operation via wireless network, local robot control programs, etc., the coordinative control of HMRS can be implemented according to human commands. In this paper, an actual HMRS comprised of humanoid robots (Robovie, PINO), mobile robot (Scout) and entertainment robot dog (AIBO) is constructed and the effectiveness of coordinative control is verified by experiment.

The remainder of this paper is organized as follows. In section II, modeling of HMRS using frame-based knowledge representation is explained firstly. This knowledge model is then defined in the K-ICNP in section III. Section IV presents the implementation of intelligent coordinative control of HMRS. Finally, an actual HMRS is constructed and its experimental results demonstrate the effectiveness of the proposed method in section V.

II. MODELING OF HETEROGENEOUS MULTI-ROBOT SYSTEM

A. Heterogeneous multi-robot system

A HMRS comprises of many different types of robots for various purposes. According to the difference of their intelligence, all robots are classified into two groups. One group is consisted of advanced robots which can communicate with human in order to obtain human request through human-robot interface. Another group is consisted of robots with specific functions, such as walking, holding something, moving along a trajectory, etc. In addition, this HMRS integrates various techniques, such as robotic technique, pattern recognition, software engineering, tele-operation, communication, etc.

B. Knowledge representation of heterogeneous multi-robot system

A knowledge model of HMRS is constructed based on the frame-based knowledge representation approach. The structure of a frame defined in this paper is consisted of several items, such as Name, Type, A-kind-of, Descendants, Slots, etc. [7]. The meaning of each item in a frame is explained in Table I. As the element of a frame, each slot has the items of Name, Type, Values, Conditions, etc. The meaning of each item in a slot is explained in Table II.

With frame-based knowledge representation, features of different types of robots, activity of human-robot interaction, operations of robots, etc., in this HMRS can be defined by the following types of frames. This frame system is regarded as the knowledge model of HMRS.

- Robot frames: are the frames for describing the features of different types of robots, including types, spatial positions, components, functions, etc.
- User frames: are the frames for describing different users who are distinguished by their name, occupation, etc. They can be classified into frames for new users and known users.
- Behavior frames: are the frames for describing the behaviors of robots. There have following three types of behavior frames. The first type is about the atomic actions of each type of robot, such as walking, sitting, standing, etc. The second type is about the combination behaviors of robots. The third type is about the interaction between human and robot, such as speech, image analysis, etc. With the items of "Semantic-link-from" and "Semantic-link-to" in a frame, the relations among behavior frames can be defined, including relations of synchronization, succession, restriction, etc. Therefore, the activities of HMRS can be easily defined by use of behavior frames.

All frames for a HMRS are organized by the ISA relation corresponding to the item of A-kind-of in a frame. The ISA relation means that the lower frame inherits all features of the upper frame, but with some concrete features that are not defined in the upper frame, or the lower frame is an instance of the upper frame.

III. DEFINITION OF HETEROGENEOUS MULTI-ROBOT SYSTEM IN NETWORK PLATFORM

A. Features of Knowledge Model-Based Intelligent Coordinative Network Platform

The Knowledge Model-Based Intelligent Coordinative Network Platform (K-ICNP) provides a central module, which acts as blackboard, knowledge processing brain, memory, and do the judgment, task planning and execution. It also provides software tools necessary for integration of various existing actions of each type of robot, such as walking, sitting, standing, etc. The second type is about the combination behaviors of robots. The third type is about the interaction between human and robot, such as speech, image analysis, etc. With the items of "Semantic-link-from" and "Semantic-link-to" in a frame, the relations among behavior frames can be defined, including relations of synchronization, succession, restriction, etc. Therefore, the activities of HMRS can be easily defined by use of behavior frames. All frames for a HMRS are organized by the ISA relation corresponding to the item of A-kind-of in a frame. The ISA relation means that the lower frame inherits all features of the upper frame, but with some concrete features that are not defined in the upper frame, or the lower frame is an instance of the upper frame.
modules over a TCP/IP network.

K-ICNP is a frame-based knowledge engineering environment. The features of this network platform are "platform-independent" as existing robots and software modules often rely on different platforms or operation systems, "network-aware" as the modules must interact on a network, supporting "software agent" and being "user friendly". K-ICNP is targeted to be the platform on which a group of co-operative robots (or their agents) operate on top of frame knowledge. K-ICNP consists of the following software components:

- GUI Interface: A user-friendly graphical interface to the internal knowledge manager and the inference engines. It provides the users direct access to the frame-based knowledge.
- Knowledge Database and Knowledge Manager: This is the K-ICNP core module that maintains the frame systems as Java class hierarchy, and performs knowledge conversion to/from XML format.
- Inference Engines: Verify and process information from external modules that may result in instantiation or destruction of frame instances in the knowledge manager, and execution of predefined actions.
- JavaScript Interpreter: Interprets JavaScript code which is used for defining conditions and procedural slots in a frame. It also provides access to a rich set of standard Java class libraries that can be used for customizing K-ICNP to a specific application.
- Basic Class for Software Agent: Provide basic functionality for developing software agents that reside on networked robots.
- Network Gateway: This is a daemon program allowing networked software agents to access knowledge stored in K-ICNP. All K-ICNP network traffics are processed here.

B. Definition of heterogeneous multi-robot system in K-ICNP

In K-ICNP, a HMRS is described by XML format according to its knowledge representation. XML is a markup language for documents containing structured information [8]. With text-based XML format, frame hierarchy can be serialized and stored in a local file. It can be also transmitted over the network to a remote K-ICNP. In addition, the frame system can be illustrated in the K-ICNP Graphic User Interface. Corresponding to XML file, there is an interpreter to translate XML specification into relative commands.

With the XML format, the knowledge model of HMRS can be defined in K-ICNP and the coordinative control of robots can be implemented as the following explanation.

IV. IMPLEMENTATION OF INTELLIGENT COORDINATIVE CONTROL OF HETEROGENEOUS MULTI-ROBOT SYSTEM

A. Intelligent Coordinative control by means of K-ICNP

1. Human-robot interaction

In order to implement coordinative control of HMRS according to human request, human-robot interaction is an essential because the results of human-robot interaction can trigger the behaviors of multiple robots. Human-robot interaction can be implemented by many kinds of techniques, such as image recognition, speech, sentence parsing, etc. In K-ICNP, human-robot interaction is defined by use of behavior frames, such as greeting, face detection, etc. In the behavior frames, many independent programs for performing various functions of robots are adopted by the specific slot of "onInstantiate". If these behavior frames are activated, these functions will be called and robots will conduct their relative actions.

2. Cooperative operation of robots

In a HMRS, the coordinative control is implemented by means of K-ICNP. In K-ICNP, cooperative operations of multiple robots have been defined by behavior frames. Each behavior frame uses a command or a command batch on actions of robots. The organization of these frames is based on the ISA relation so that the relations of robot behaviors can be known, which including synchronization, succession and restriction. The synchronization relation means that several robots can be operated together at the same time for a specific task. Their control instructions are generated referring to a same time coordinate. The succession relation means that the action of one robot should start after the end of the action of another robot. The actions of several robots should be performed successively. The restriction relation means that as one robot is conducting a certain action, another robot can not be conducting any actions at the same time. With these relations, even a complex task could be undertaken by cooperative operation of multiple robots. Besides, before activating a behavior frame, the conditions given in the slots should be completely satisfied. Therefore, we can define many safe measures to guarantee the reliability of robot behaviors, such as confirming the feedback of robot actions, checking the status of robots in real-time, etc.

The execution of these frames for cooperative operation of multiple robots is by use of the inference engines defined in K-ICNP. The inference engines are for doing forward and backward chaining. The forward chaining is usually used when a new instance is created and we want to generate its consequences, which may add new other instances, and trigger further inferences. The backward chaining starts with something we want to prove, find implication facts that would allow us to conclude it. It is used for finding all answers to a question posed to the knowledge model.

B. Technical supports

1. Distributed software agents

In K-ICNP defines many kinds of Java classes representing the agents, such as server, user, robots, etc. The server agent serves as a message-switching hub, a center for relaying messages among robots and user agents. A user agent represents each user on the system, relays commands from the user to other agents, queries states of the robot agents, and provides the user with enough feedback information. A robot agent represents each robot under control.
There are also some other software agents, e.g. a software agent to parse a sentence. K-ICNP generates the commands to robots relying on key words. We have developed a simple sentence parser for K-ICNP using the technique of Case Grammar taking into account the features of the operation of robot arm [9].

2. Tele-operation via wireless network

All robots are connected with server computers in which K-ICNP and distributed software agents system are respectively running, over a wireless TCP/IP network. Any information exchange among robots, K-ICNP and software agents are through wireless network. Therefore, tele-operation is an important means for implementing coordinative control of HMRS.

3. Local robot control programs

All robots have their local control programs that can control their behaviors. When performing cooperative operation of multiple robots, the instruction from K-ICNP will convert to the command by software agents so that local robot controllers can execute. Thus, as we develop software agents we should understand the features of local controllers. But when we define any human-robot systems in K-ICNP, it is no need to take into account the local robot control programs.

4. Feedback of status

Basically, coordinative control of robots is performed with feedforward pattern according to its definition in K-ICNP. However, feedforward control is not enough to perform a complex task. Feedback from robots is definitely necessary to evaluate activities of robots as well as instruct the next actions of robots. We could get the feedback signals on activities of HMRS by two ways. In the environment where user and robots are staying, we set up several sensors (camera, etc.) to observe the actions of robots. Based on the user's judgment on the actions of robots, K-ICNP can adjust its control signals or generate new tasks. Another way to get the feedback signals is by robots themselves. As robots finished their actions, they should send back responses corresponding to their actions. Moreover, since there are many sensors in robot bodies, they could also send some signals detected by these sensors to K-ICNP, which could be helpful for K-ICNP to know the status of activities of multiple robots. These feedback signals can be defined in the frame as the conditions of slots. Finally, the coordinative control of HMRS can be carried out successfully.

V. EXPERIMENT

With the proposed approach, we constructed an actual HMRS consisted of different robots, illustrated by Fig.1.

A. Experiment setup

This HMRS is comprised of K-ICNP and the following four types of robots:

- **Robovie**: is a humanoid robot with human upper torso placed on an ActivMedia wheel robot. The movements of both arms and the head can be controlled from the software. It has two eye cameras, which connect through a video source multiplexer, to the frame grabber unit of a Linux PC inside the ActivMedia mobile unit, and a speaker at its mouth. Thus, Robovie can interact with user by gesture of its arms and head, or by using voice, like a kind of autonomous communication robots. A wireless microphone is attached to Robovie head so that we can process user voice information as well. Since Robovie has capability to realize human-robot communication, therefore, in this system Robovie plays the role for human-robot interaction. We also installed some programs for human-robot interface in the Linux PC of Robovie by means of the techniques of image analysis, speech, etc., such as face processing module using the algorithms described in [10],[11], the festival speech synthesis system developed by CSTR [12], etc.

- **PINO**: is another kind of humanoid robots. It has 26 degrees of freedom (DOFs) with the low-cost mechanical components and well-designed exterior. It can act stable biped walking, moving its arms and shaking its hands like human.

- **Scout**: is an integrated mobile robot system with ultrasonic and tactile sensing modules. It uses a special multiprocessor low-level control system. This control system performs sensor and motor control as well as communication. In Scout, there are differential driving systems, 16 sensors, 6 independent bumper switches, CCD camera, etc.

- **AIBO**: is a kind of entertainment robots. It can provide high degree of autonomous behavior and functionality. In our experimental system, we use AIBO ESP-220, which is able to walk on four legs. It has a total of 16 actuators throughout its body to control its movements, and 19 lights on its head, tail, and elsewhere to express emotions like happiness or anger and reactions to its environment.

All robots are connected with K-ICNP via wireless TCP/IP network. In the environment, there are several cameras product by Sony Co. of Japan. By running the software of Windows NetMeeting developed by Microsoft Co., we can see the status of robots from the server monitor captured by cameras. If there are any errors of robot actions, we can interrupt them from K-ICNP for security.
B. Scenario of task

With this system, a simple task can be fulfilled. The scenario of this task is shown in Table III.

C. Modeling of heterogeneous multi-robot system and its definition in K-ICNP

With frame-based knowledge representation, this HMRS can be modeled. This knowledge model comprises of plenty of frames. The following Table IV is the definition of “FirstMeet” frame by use of XML format. Fig.2 is the K-ICNP knowledge editor showing the frames hierarchy for HMRS. Each frame is represented by a click-able button. Clicking on the frame button brings up its slot editor. For this frame, if three instances (“Scout”, “MouthIO” and “ScoutWanderForward”) are set up, this frame will be created and execute the JavaScript codes written in “onInstantiate” slot. In this slot, special functions “sendmsg()” for Robovie speech and “scout(“f”)” for Scout forward wandering movement are defined as the values of this slot.

D. Implementation of coordinative control

Based on the above definition, the cooperative operation of multiple robots can be carried out according to the scenario.

The experimental work has two steps. First step is the activation of activities of this system by human-robot interaction. As illustrated by Fig.4(a), the human-robot interaction can be carried out by “RobovieBehavior” frame, which linking with frames of “GotNewName”, “FirstMeet”, “FaceDetection” and “Greet”. When a face is detected by the image processing module in Robovie, face location and eigenvalues corresponding to that face will be sent to K-ICNP and an instance of “User” frame is created. This instance will be checked whether it belongs to any subclasses of “KnownUser” classes by comparing the eigenvalues slots. If there is a match and this face is a known user, the “Greet” behavior will be fired to greet the user. Otherwise, the new user instance will be treated as “NewUser” and “FirstMeet” behavior will be triggered to ask user of this name. The user's response will be sent to “GotNewName” frame which will register the new name as a sub-frame of “KnownUser”. Besides, with special slot “onInstantiate” some special functions defined in Robovie itself or in other server computers developed by different software languages can be executed by incorporating with functions of Robovie, such as face recognition, speech, action, etc.

The second step is the behaviors of other robots instructed by K-ICNP. Fig.4(b) illustrates the behaviors of AIBO. In the “AIBOAction1” frame, if three instances (“Greet”, “MouthIO” and “AIBO”) are set up, the first action of AIBO will be performed with the corresponding functions existed inside of AIBO. When making the connection between K-ICNP and Robovie, “MouthIO” frame can be automatically activated. As Robovie is performing the interaction with user, “Greet” frame can be activated. Before performing actions of robots, it needs to indicate the operation object of robots. With the prompting by the speech of Robovie, user can type into the name of AIBO to activate the sub-frame “AIBO” of “SpecialRobot” frame. Then, the first action of AIBO can be performed. Continuously, the second action and third action of AIBO will perform after the former action is finished. In the frames of “AIBOAction2” and “AIBOAction3”, the relative actions for AIBO are defined.
In this experiment, the first action of AIBO is standing. The second is walking and the third is turning to left. With the same way, PINO and Scout can also perform their behaviors according to the control of K-ICNP. Although this is a simple task by use of HMRS, with this approach, multiple robots can perform a more complex planned activity for human in the future.

![Image](image1)

**Fig.2** K-ICNP knowledge editor showing the frames hierarchy for heterogeneous multi-robot system

![Image](image2)

**Fig.3** Slot editing table of “ScoutAction1” frame

![Image](image3)

**Fig.4** Relation network defined in K-ICNP

(a) Human-robot interaction  (b) Behaviors of AIBO

VI. CONCLUSIONS AND FUTURE RESEARCH

The knowledge model-based coordinative control for HMRS is proposed in this paper. With this approach, features of robots in HMRS as well as their operations can be described by frame-based knowledge representation. With this model, this system can be defined in the K-ICNP. By means of K-ICNP and several techniques, coordinative control of HMRS can be implemented. In this paper, an actual HMRS is constructed and its coordinative control is implemented. In the further research, we want to integrate more functions for human-robot interface and improve the performance of HMRS, such as designing a general behavior manager for HMRS, taking into account security measurement, etc. Additionally, we will apply this system for performing more complex tasks, especially using it for welfare enterprise. Since this HMRS is open to any kinds of robots as well as human-robot interfaces, it can be extended widely for many kinds of applications. In the future, we expect to create an actual high-intelligent, human-friendly symbiotic autonomous human-robot system.

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