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K-ICNP: a Multi-Robot Management Platform

Tao Zhang¹, Christophe Agueitaz¹, Yun Yuan¹ and Haruki Ueno²

¹*Department of Automation, Tsinghua University,*

²*Intelligent Systems Research Division, National Institute of Informatics*

¹*China, ²Japan*

1. Introduction

As robots are bound to greatly grow in importance in a not-so-far future's everyday life, the question of their integration within their environment naturally arises as one of major importance. One cannot expect random users to adapt themselves to complex system beyond a certain level, this statement becoming even truer if elderly users are to be involved. Generally speaking, the more intuitive the system is to use, the better. In the ideal case, users would interact with a group of domestic robots using only natural language and gestures, and would then be able to communicate with them without virtually needing any prior knowledge about the devices involved. Such a system is recently nominated by a symbiotic autonomous human-robot system (Ueno, 2002). As of today, such an approach is not realistic, as it would require a human-like intelligence in order to resolve ambiguities and guess intentions. A more feasible approach would be putting stronger constraints on the interaction protocol, that is, for instance, asking the user only to use simple language structures and words. That is what we chose to do, trading user learning time for feasibility.

To aim at implementing such a multi-robot system with intelligent interaction, coordinative control of robots is one of crucial issues. So far, there are many researches proposing various approaches facing to different requests. For example, Huntsberger (Huntsberger, 2003) proposed a software/hardware framework for co-operating multiple robots performing tightly coordinated tasks, such as exploration of high-risk terrain areas. Yoshida (Yoshida, 2003) 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 with low-level human-robot intelligent interaction and coordination. Hence, this paper proposes a novel multi-robot management platform, called Knowledge-Based Intelligent Coordinative Network Platform (K-ICNP).

The K-ICNP was created with the intent of integrating a group of domestic robots as well as possible within its environment. It is a java-based platform aimed at providing 'symbiotic' integration to different robots with different features and ways of interacting with the user. These features may include vision, mobility, speech synthesis, textual input and output, providing the final user with a great range of capabilities. The platform aims at making these various features accessible in a unified way, be it for the third party programmer or for the final user, as well as providing inference mechanisms for mixing knowledge with empirical data.

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Since the core of this kind of network platform is a knowledge model, a multi-robot system is firstly modeled by means of frame-based knowledge representation (Minsky, 1974). With this knowledge model, a multi-robot system can be clearly defined in the developed K-ICNP by use of XML format. K-ICNP can 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 behaviours of robots for each service to human, etc. It not only can explain the knowledge model of multi-robot system, but also integrate several techniques, such as distributed software agents, tele-operation via wireless network, etc. The coordinative control of robots can be therefore implemented according to human commands. The effectiveness of K-ICNP was verified by the experiments considering actual scenarios of activities of multi-robot system comprised of humanoid robots, mobile robot and entertainment robot.

2. Modeling of Multi-Robot System

2.1 Multi-robot system

A multi-robot system discussed in this research comprises many different types of robots for various purposes. According to their functions, all robots in the multi-robot system can be classified into two groups. One group is to communicate with human in order to obtain human requests through human-robot interface. The robots in this group have the ability of conducting intelligent interaction with human by means of vision, speech, body movement, etc. Another group is consisted of robots which will perform the task according to human commands. These robots have various specific functions, such as holding something, autonomously moving, etc. Therefore, such a kind of multi-robot system is a complex system, whose construction must be depended on the integration of various techniques, such as robotic technique, pattern recognition, software engineering, tele-operation, communication, etc.

2.2 Knowledge representation of multi-robot system

As mentioned in the Introduction, the core of K-ICNP is a knowledge model of multi-robot system. The knowledge model is constructed by use of the frame-based knowledge representation approach. The frame structure is originally proposed by M. Minsky (Minsky, 1974). Considering the complexity of the multi-robot system, the frame structure is re-defined comparing the original case (Zhang, 2005). The structure of a frame defined in this research is therefore consisted of the following items, such as Name, Type, A-kind-of, Descendants, Slots, etc. As the element of a frame, each slot has the items of Name, Type, Values, Conditions, etc. The meanings of each item in a frame are as given in Table 1 and the meanings of each item in a slot are given in Table 2.

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

- **Robot frames:** are the frames for describing the features of various robots, including types, spatial positions, components, functions, etc.
- **User frames:** are the frames for describing different users who are distinguished by their names, occupations, 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. Each frame describes a atomic action series for one purpose. The third type is to describe the intelligent interaction between human and robot, by means of vision, speech, etc. In addition, 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 multi-robot system can be easily defined by use of behavior frames. Table 3 shows an example of the frame “AskUserName”, which is to define the robot behavior to ask user’s name.

Items	Meanings
Frame name	Identification for frame
Frame type	Type of frame
A-kind-of	Pointer to parent frame for expressing IS_A relation
Descendants	Pointer list to children frame
Has-part	Components of this frame
Semantic-link-from	Links from other frames according to their semantic relation
Semantic-link-to	Links to other frames according to their semantic relations
Slots	Components of the frame

Table 1. Meanings of each item in a frame

Items	Meanings
Slot name	Identification for slot
Role	Purpose of slot
From	Source of slot
Data type	Explain the attribute of information recorded into the value
Value	Slot value
Condition	Condition of slot
Argument	Argument for slot
If-required	If slot is required, check this item.
If-shared	If slot can be shared with other frames, check this item.
If-unique	If slot is unique from other slots, check this item.
Frame-related	A frame related with slot
Frame-list-related	Several frames related with slot
Default	If the slot value is not determined, the default value can be recorded. But the value and default value cannot be given at the same time.

Table 2. Meanings of each item in a slot

Items	Contents
Name:	AskUserName
Type:	Instance
A-kind-of:	Speech
Descendants:	NULL
Has-part:	NULL
Semantic-link-from:	NULL
Semantic-link-to:	NULL
Slot #1	
Slot name:	mUser
Data type:	Instance
Value:	NULL
Condition:	Any
Argument:	NewUser
If-required:	Checked
If-shared:	Checked
If-unique:	Checked
Slot #2	
Slot name:	mMouth
Data type:	Instance
Value:	NULL
Condition:	Any
Argument:	Mouth
If-required:	Checked
If-shared:	Checked
If-unique:	Checked
Slot #3	
Slot name:	mfunction
Data type:	String
Value:	sendmsg
Condition:	Any
Argument:	NULL
If-required:	No Checked
If-shared:	Checked
If-unique:	Checked

Table 3. Definition of frame “AskUserName”

Therefore, the knowledge model of a multi-robot system is consisted of various frames which forming a frame system. All these frames 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, except some concrete features that are not defined in the upper frame. Some lower frames can be also regarded as instances of upper frames. Fig.1 illustrates the organization structure of all frames in the knowledge model of a multi-robot system.

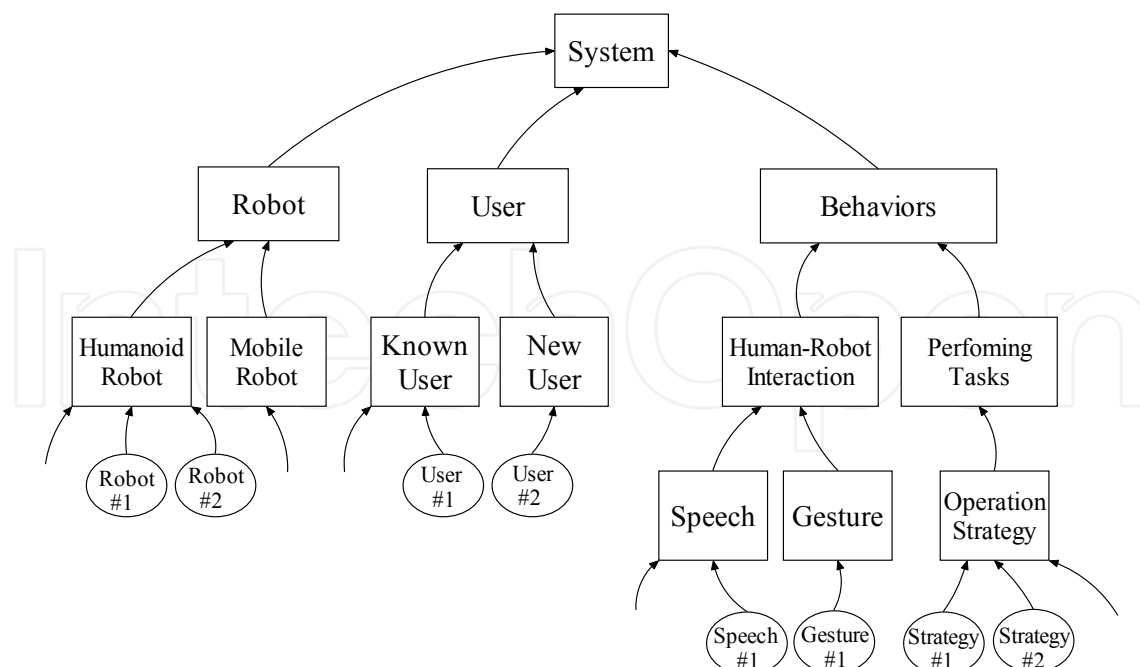


Figure 1. Organization structure of all frames in the knowledge model of a multi-robot system

3. Knowledge Model-based Intelligent Coordinative Network Platform

3.1 Features of K-ICNP

One of the key ideas underlying K-ICNP's design was abstraction. The platform aims at unifying different features and capabilities provided by different robots, and collecting them into a frame-based knowledge base where they will be processed in a uniform way. Abstraction is made of any hardware and software specificity, starting with networking. This implies, of course, that a bit of code specific to the platform has to be run on the robot itself, at least for interfacing the robot on a network. Indeed, the platform is network-based and designed to manage remote devices in a transparent fashion. More specifically, K-ICNP consists of a central management module, typically run on a computer, handling all of the management tasks as well as the intelligence aspects detailed later. This central module handles the task of agents synchronization over a TCP/IP network, reacts to input stimuli and distributes appropriate reaction directions. The attractive 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 cooperative robots (or their agents) operate on top of frame knowledge.

The mechanism that transforms perceived stimuli into these appropriate reactions is the inference mechanism. As stated before, it is modeled using a frame-based knowledge representation. In this representation, functionalities offered by the different robots are represented by frame classes and processed the same way as any knowledge present in the knowledge base is. This way, linking features presented by a robot with semantic content for instance becomes a straightforward task involving frames manipulation only. The knowledge base has of course to contain prior knowledge about the world robots will roam in, but the system is also capable of filling the knowledge base with learned frames coming from user interaction, from simple questions asked by the system for example.

K-ICNP is a platform, and as such is designed to be used as a development base. As we saw before, the use of K-ICNP requires the embedment of some codes on the robots' side. This can be done using Agent Base Classes, which are java classes provided with the platform. More generally, the whole platform bears an easily extendible, plastic structure providing system designers with a flexible base. That is why K-ICNP includes a graphic knowledge base editor as well as a java script interpreter, the combination providing powerful behaviour control for the developer to use.

K-ICNP consists of six software components:

- GUI interface: It is 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 engine: Inference engine is to 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: It is adopted to interpret 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: It provides 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.

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 (Bruce, 1975).

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

3.2 Definition of multi-robot system in K-ICNP

In K-ICNP, a multi-robot system is described in XML format according to its knowledge model. XML is a markup language for documents containing structured information (<http://www.xml.com>). 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 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 multi-robot system can be defined in K-ICNP and the coordinative control of robots can be implemented as the following explanation. Table 4 is an example of frame definition in K-ICNP by use of XML.

```
<FRAME>
  <NAME>Greeting</NAME>
  <ISA>Speech</ISA>
  <ISINSTANCE>FALSE</ISINSTANCE>
  <SLOTLIST>
    <SLOT>
      <NAME>mUser</NAME>
      <TYPE>TYPE_INSTANCE</TYPE>
      <CONDITION>COND_ANY</CONDITION>
      <ARGUMENT>KnownUser</ ARGUMENT>
      <VALUE></VALUE>
      <REQUIRED>TRUE</REQUIRED>
      <SHARED>TRUE</SHARED>
      <UNIQUE>TRUE</UNIQUE>
    </SLOT>
    <SLOT>
      <NAME>mMouth</NAME>
      <TYPE>TYPE_INSTANCE</TYPE>
      <CONDITION>COND_ANY</CONDITION>
      <ARGUMENT>Mouth</ ARGUMENT>
      <VALUE></VALUE>
      <REQUIRED>TRUE</REQUIRED>
      <SHARED>TRUE</SHARED>
      <UNIQUE>TRUE</UNIQUE>
    </SLOT>
    <SLOT>
      <NAME>onInstantiate</NAME>
      <TYPE>TYPE_STR</TYPE>
      <CONDITION>COND_ANY</CONDITION>
      <ARGUMENT></ ARGUMENT>
      <VALUE>Sendmsg(s.mMouth, "Hi! Nice to meet you. Welcome to visit my
room!");</VALUE>
      <REQUIRED>FALSE</REQUIRED>
      <SHARED>TRUE</SHARED>
      <UNIQUE>TRUE</UNIQUE>
    </SLOT>
  </SLOTLIST>
</FRAME>
```

Table 4. Definition of frame “Greeting” in K-ICNP by use of XML format

3.3 Coordinative control of multi-robot system by means of K-ICNP

(1) Human-robot interaction

In order to implement coordinative control of multi-robot system according to human requests, human-robot interaction is an essential because the results of human-robot interaction can trigger the behaviours 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 K-ICNP, cooperative operations of multiple robots have been defined by behavior frames. Each behavior frame has a command or a command batch about 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 basically including synchronization, succession and restriction. The synchronization relation means that several robots can be operated simultaneously for a specific task. Their control instructions are generated referring to a same time coordinate. The succession relation means that one action of a robot should start after the end of another action of the same robot or other robots. The actions of several robots should be performed successively. The restriction relation means that as one robot is conducting a certain action, other robots can not be conducting any actions at the same time. With these behavior 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 adopted 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, and 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.

In addition, local control programs of robots are always put to the robot sides. When performing cooperative operation of multiple robots, the instruction from K-ICNP will be converted to the command of local control program by software agents so that local robot controllers can execute. Thus, as developing software agents the features of local controllers should be understood. But when defining any human-robot systems in K-ICNP, it is no need to take into account the local robot control programs.

Besides, when performing coordinative control of robots, feedback signals on activities of multi-robot system should be easily obtained. In the environment where user and robots are staying, several sensors (camera, etc.) can be set up to observe the actions of robots. Based on the user's judgment on the actions of robots, K-ICNP can adjust its control instructions or generate new tasks. Another way to get the feedback signals is by robots themselves. As robots ended their actions, they should automatically send back responses corresponding to their actions. Moreover, since there are many sensors in robot bodies, they can also send some signals detected by these

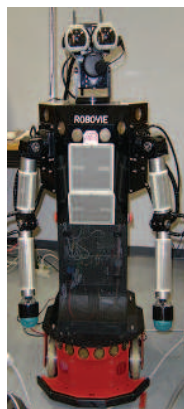
sensors to K-ICNP, which could be useful for K-ICNP to know the status of activities of multiple robots. These feedback signals can be defined in the frame as the conditions of slots. Finally, the coordinative control of multi-robot system can be carried out successfully.

4. Experiments

In order to verify the effectiveness of K-ICNP, experimental work was made by employing actual different types of robots, such as humanoid robots, mobile robot, entertainment robot, etc., meanwhile considering actual scenarios of activities of multi-robot system.

4.1 Experimental components

In the experimental work, the following four types of robots are employed, as illustrated by Fig.2.



Robovie



PINO



Scout



AIBO

Figure 2. Robots employed in the experimental work

- **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 (Turk, 1991)(Rowley, 1998), the festival speech synthesis system developed by CSTR (<http://www.cstr.ed.ac.uk/projects/festival>), 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.

4.2 Scenario of task

With this multi-robot system, a simple task can be fulfilled. The scenario of this task is shown in Table 5.

User A	(User A appears before the eye cameras of Robovie.)
Robovie	(Robovie is looking at the user A’s face and trying to recognize it.) How are you! I have never seen you before. What is your name?
User A	My name is XXX.
Robovie	Hi, XXX. Nice to meet you. Welcome you to visit my room. (Robovie A shakes its both hands.)
Robovie	This is my friend, PINO.
PINO	(PINO walks to user A and shake its hand with user A.)
Robovie	What do you want to drink?
User A	Tee, please.
Scout	(Scout brings a cup of tee for user A.)
Robovie	This is a robot dog AIBO. Please enjoy yourself with it.
AIBO	(AIBO walks to user A and lies down near user A.)
	...

Table 5. A scenario of multi-robot system

4.3 Modeling of multi-robot system and its definition in K-ICNP

With frame-based knowledge representation, this multi-robot system can be modeled and defined in K-ICNP. Fig.3 is the K-ICNP knowledge editor showing the frames hierarchy for the multi-robot system. Each frame is represented by a click-able button. Clicking on the frame button brings up its slot editor. Fig.4 is a slot editing table for “AskUserName” frame. Each row represents a slot in this frame. For this frame, if two instances (“NewUser” and “Mouth”) are set up, this frame will be created and execute the JavaScript codes written in “onInstantiate” slot. In this slot, special functions “sendmsg()” for Robot A speech is defined as the values of this slot.

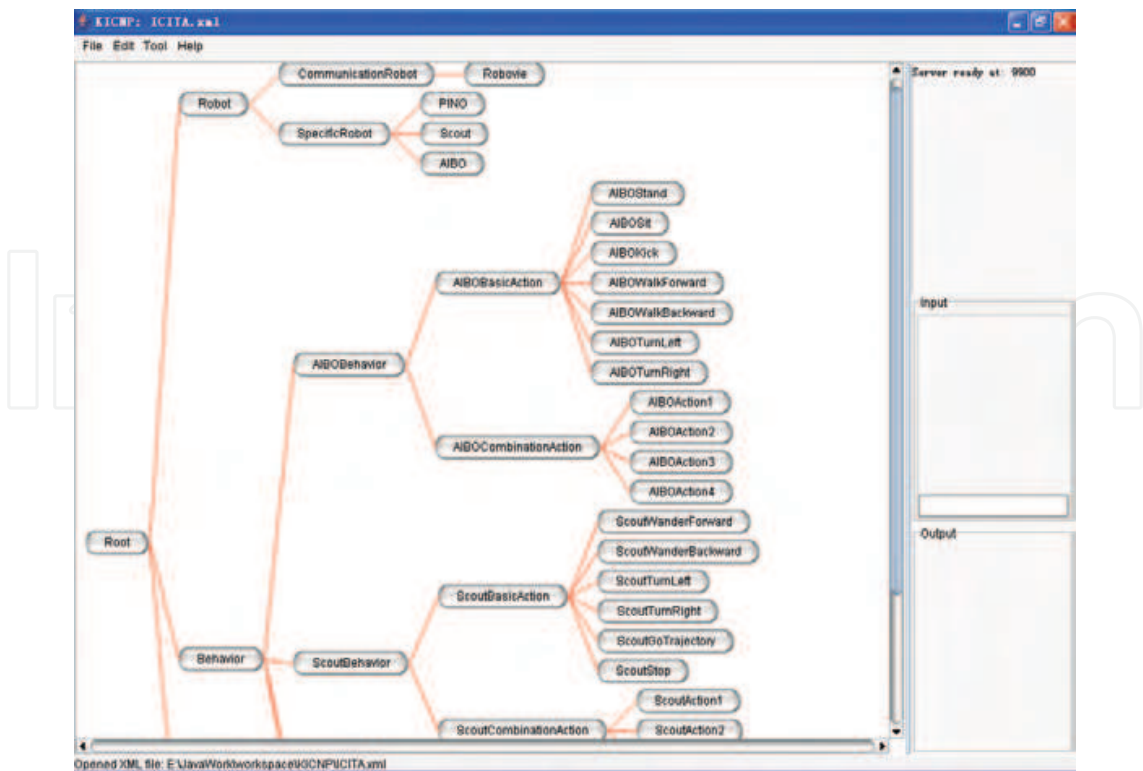


Figure 3. K-ICNP knowledge editor showing the frames hierarchy for multi-robot system

Property of AskUserName							
File Edit							
Name	Type	Value	Condition	Argument	Required	Shared	Unique
Name	String	AskUserN...	ANY		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
mUser	Instance		ANY	NewUser	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
mMouth	Instance		ANY	Mouth	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
onInstantiate	String	sendmsg(...	ANY		<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>

Figure 4. Slot editing table of “AskUserName” frame

4.4 Implementation of coordinative control of robots

Based on the above definition, the cooperative operation of multiple robots can be carried out according to the scenario. The cooperative operation of multiple robots in multi-robot system is firstly activated by human-robot interaction. For example, the human-robot interaction conducted by Robovie can be linked with frames of “GotNewName”, “FirstMeet”, “FaceDetection” and “Greeting”. When a face is detected by Robovie, an instance of “User” frame is created. This instance will be checked whether it belongs to any subclasses of “KnownUser” classes. If there is a match and this face is a known user, the “Greeting” 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”. Based on human-robot interaction, cooperative operation of multiple robots can be implemented. For example, in this scenario there are several different tasks performed by different robots. Each task is fulfilled by several actions of each robot. Each action of robot is conducted as the following example. Concerning about the “AIBOAction1” frame, if three instances (“RobovieToAIBOCommand1”, “Mouth” 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, "Mouth" frame can be automatically activated. As Robovie is performing the interaction with user, "RobovieToAIBOCommand1" frame can be activated. Before performing actions of robots, it needs to indicate the operation object of robots. With interpreting the speech of Robovie, "AIBO" frame can be activated. Then, the first action of AIBO can be conducted. Similarly, other actions of robots can be conducted. Therefore, multiple robots in a multi-robot system can perform more complex planned activities for users.

5. Conclusions

The Knowledge Model-based Intelligent Coordinative Network Platform for multi-robot system is proposed in this paper. In K-ICNP features of robots in multi-robot system as well as their operations can be described by frame-based knowledge representation. By means of K-ICNP, coordinative control of multi-robot system can be implemented. The effectiveness of K-ICNP was verified by the experimental work considering actual scenarios of activities of multi-robot system comprised of humanoid robots Robovie and PINO, mobile robot Scout and entertainment robot AIBO.

Further developments will improve the system's capacity of learning from possibly incomplete or erroneous data, of guessing optimal strategies and responses from prior knowledge and will extend the system's overall capacity to deal with complex orders. Hardware abstraction will be brought to the next level and standardized via the use of UPnP as a means for robots, even unknown, to expose their available features.

These improvements will make the platform a powerful tool on which to base practical multi-robot applications, another step towards the goal of real symbiotic robotics.

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To design a team of robots which is able to perform given tasks is a great concern of many members of robotics community. There are many problems left to be solved in order to have the fully functional robot team. Robotics community is trying hard to solve such problems (navigation, task allocation, communication, adaptation, control, ...). This book represents the contributions of the top researchers in this field and will serve as a valuable tool for professionals in this interdisciplinary field. It is focused on the challenging issues of team architectures, vehicle learning and adaptation, heterogeneous group control and cooperation, task selection, dynamic autonomy, mixed initiative, and human and robot team interaction. The book consists of 16 chapters introducing both basic research and advanced developments. Topics covered include kinematics, dynamic analysis, accuracy, optimization design, modelling, simulation and control of multi robot systems.

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InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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