Research article

Automatic planning and coordinated control for redundant dual-arm space robot system

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Abstract

Purpose – The purpose of this paper is to present a novel automatic planning and coordinated control method of redundant dual-arm space robot for inner space-station operation based on multiple sensors information by stages.

Design/methodology/approach – In order to improve the coordinated control capability of dual-arm robot system, a four-layer hierarchical control structure is designed based on the theory of centralization and decentralization. At the high-level planning of dual-arm system, a task decomposition strategy based on task knowledge and a task allocation strategy in terms of the robotic capability are proposed, respectively. Moreover, a control method by stages based on the information of multiple sensors is introduced to object recognition, task planning, path planning and trajectory planning. Finally, a 3D simulation and experiment of screwing nut and bolt are implemented on a dual-arm robot system, and the feasibility and applicability of this control strategy are verified.

Findings – The automatic planning can be accomplished by means of sensors information by stages, and by this method, the autonomy and intelligence of dual-arm space robot system can be further improved.

Practical implications – A new automatic planning strategy integrated with multiple sensors information by stages is proposed, and can be implemented on a dual-arm robot system for inner space-station operations. This method specializes in heterogeneous dual-arm robot system.

Originality/value – A task decomposition strategy based on task knowledge and a task allocation strategy in terms of the robotic capability are proposed, respectively. Moreover, a control method by stages based on the information of multiple sensors is introduced to object recognition, task planning, path planning and trajectory planning of dual-arm robot system.

Keywords Robotics, Control systems, Hierarchical control, Space technology, Sensors

Paper type Research paper

1. Introduction

In recent years, the technology of redundant dual-arm robot system for space-station operation has got considerable attention. The NASA, Deutsches Zentrum fuer Luft-und Raumfahrt, the Space Bureau of Russia, the Humanoid Robot National Research Center of Japan and the Space Technology Research Plan of European Economic Community all have invested on development of dual-arm space robot systems (Ding, 2003). At present, the task planning of dual-arm space robot is achieved mostly relying on the tele-operation from the earth. The tele-operation control system, which combines human intelligence with robotic control, is responsible for not only the perceptive comprehension, task planning in high level by means of human intelligence, but also the sensor system, information fusing, path planning and robot control in low level. Therefore, the automatic planning capability of dual-arm space robot system urgently need be improved at present. In order to realize the autonomy of dual-arm space robot system, first of all, the automatic planning problem must be solved. Up to now, a great deal of researches and some important achievements on this field have been obtained. For typical instances, Freund *et al.* (1996, 1997) introduced the automatic action planning system to virtual reality based on man-machine-interfaces of an autonomous multi-robot-system for space-laboratory servicing. The action planning and task deduction capabilities were well suited for the control and supervision of dual-arm space robot. Moreover,

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Freund *et al.* (2000) proposed a new resource-based action planning approach to manage robot manipulators and other automation components for the robot arm ETS-VII Robot Arm onboard the satellite ETS-VII. The action planning system also took care of the "real" robot onboard the satellite and the "virtual" robot in the simulation system. By means of the simulation system, the operator can do the task planning beforehand as well as analysis and demonstration of different strategies. Ding *et al.* (1992) developed a dual-arm robotic simulation system (DRSS), it was used mainly for multi-manipulator simulation study of robotics trajectory planning, cooperative control method, typical task and off-line programming. In order to obtain a general method to describe different kinds of tasks, a set of general variables according to D-H rule was defined. Hormann (1992) also set up an online task-level planning system for an advanced assembly robot consisting of two manipulators. The planning system took an implicit description of the assembly task, planed a sequence of explicit robot commands and monitors the execution by the real-time robot control system. And it also presented an overhead camera and a force-torque sensor.

From above instances, the research centre is the knowledge building to the environment and object, task method with robot working. It needs the task procedure knowledge, objects knowledge and denoting framework knowledge, so most of these algorithms are complicated and the establishment of task knowledge base is very difficult. Furthermore, the two manipulators are absolutely identical in these dual-arm robot systems, so the performance and capability of the two arms are same and the task allocation can be executed identically. However, in our dual-arm space robot system, these two arms (PA10 robot and Modular robot) are heterogeneous and completely different. The advantage of heterogeneous type over homogeneous type lies in the operation flexibility during executing task and two arms can make up for the deficiency of arm function each other. So, the task allocation strategy should be accomplished according to the different performance and capability of robot arm. In our system, the knowledge base is set up simply and mainly includes the operation sequences and action sequences of decomposed task, the capability description of tasks and robots. Moreover, during automatic planning, a novel method to control by stages based on multiple sensors information is applied.

The aim of this paper is to describe the automatic planning and coordinated control strategy of redundant dual-arm space robot system with a certain degree of autonomy according to some typical tasks in space-station. This paper is organized as follows: Structure of dual-arm space robot system section introduces the structure of dual-arm space robot system, including system hardware structure and system control structure; the automatic planning strategy of dual-arm robot system and its implementation are explained in Automatic planning section. In this chapter, a control method by stages based on multiple sensors information is presented and applied to object recognition, task planning, motion planning and robotic force control; Section 4 describes the environment modeling and some algorithms on task decomposition and task allocation of dual-arm robot are demonstrated. The simulation and experiment of screwing nut and bolt on a dual-arm robot system are shown in Simulation and experiment section, so the feasibility and applicability of control strategy in this paper are verified. Finally, the summary and conclusion are given in Conclusion and future work section.

2. Structure of dual-arm space robot system

2.1 System hardware structure

In order to imitate the operation function of human arm, the dual-arm robot system with heterogeneous mode is built with PA10 and Modular redundant robot, as shown in Figure 1. The specifications of two robots are listed in Table I.

The experiment platform of dual-arm space robot is composed of several components:

- *PA10 and Modular Redundant robot.* Two robots have seven degrees of freedom and belong to redundant arm.
- *Global vision.* A charge coupled device (CCD) camera (SONY, Japan) locates on the ceiling. This global vision monitors the entire work-space, recognizes the object and then measures its approximate position and orientation.
- *Local vision.* It is made up of a CCD camera (WATEC, Japan) and an ultrasonic sensor (BANNER, USA), and situated on the tip of arm (fixed on the wrist), moving with the arm. Under the guidance of global vision, the local vision follows and accurately orients the object for achieving the vision-servo grasping task.
- *Vision processing unit.* It is used to recognize the object and process the image information.
- *Wrist force sensor.* The force sensor (ATI, USA) is fixed on the top of arm wrist. During manipulator moving, it can collect the force and torque information real-time.
- *Motion control unit.* In virtue of vision information and planning information, it is applied to control the robots.

Figure 1 The experiment platform of dual-arm space robot system

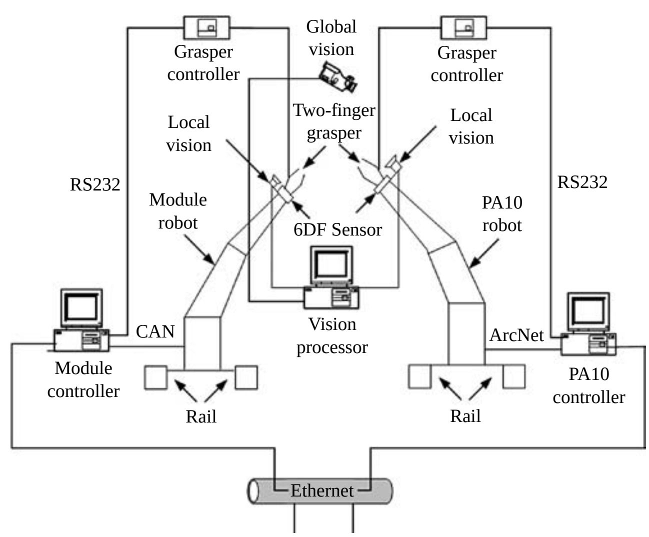


Table I The specifications of dual-arm robot

	PA10 robot	Modular robot
Manufacturer	Mitsubishi, Japan	Amtec, Germany
Payload	10 kg	3 kg
Length	1,345 mm	1,016 mm
Velocity (max)	1,550 mm/s (terminal)	216 deg/s (joint)
Repeatability	0.01 mm (terminal)	± 0.02 deg (joint)

- *Network communication interface*. It cannot only accomplish the communication between the simulation platform and the robot controller, but also transmit the instruction and data between the two robots.
- *End-effector*. The end-effector is a two-finger gripper which has the control ability of force feedback. It composes an arm-hand integration system with the manipulator.

2.2 System control structure

The coordinated control system of dual-arm robot should have the higher layer for planning and simulating, the medium layer for coordinating control and dealing with the sensor information, and the lower layer for controlling the robots. However, the same as other commercial robots, PA10 robot and Module robot are designed for single application. So, these robot controllers lack the abilities of coordination and communication with other robot controller, it is difficult to achieve the coordination control using the present robot control system. Therefore, a four-layer hierarchical structure is designed based on the theory of centralization and decentralization control (Qu and Tan, 1991; Meng *et al.*, 2004), shown in Figure 2.

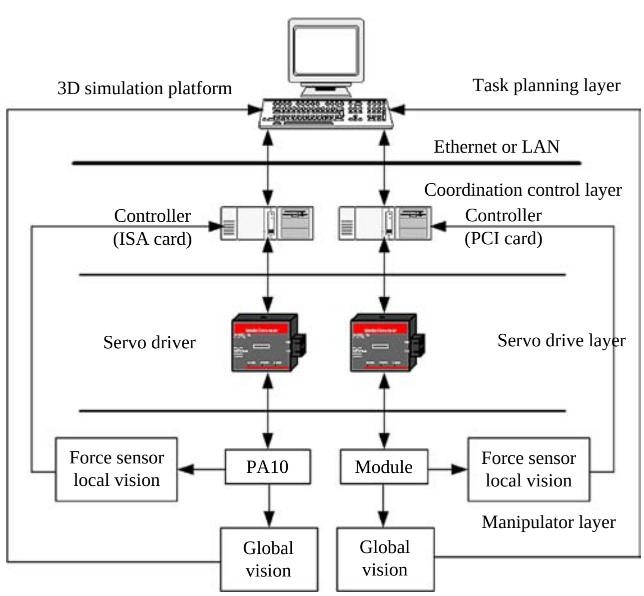
The higher layer is the task planning layer. This layer is responsible for task input, task decomposition, task allocation, path planning and trajectory planning. A 3D (three dimensional) dynamic simulation platform of redundant dual-arm robot system is developed and can achieve programming and simulating. Moreover, it connects with lower layer through the internet or local area network.

The second layer is the coordination control layer. It mainly achieves the coordination control of dual-arm robot and deals with the sensors information real-time. This layer is composed of two industrial computers installed separately the motion control card of ISA(MHID6780) and PCI(IXXAT IPC-I320), they can receive the commands from the upper layer to robot controller and also program by itself to control the robot.

The third layer is the servo driver layer. This layer can accurately carry out the servo control of robot and it also is responsible for position close-loop control and velocity excess protection.

The last layer is the mechanical manipulator layer. It is made up of PA10 robot, Modular robot, two-finger gripper and some external sensors.

Figure 2 The hierarchical control structure of dual-arm robot system



3. Automatic planning

In our system, the methodology of automated planning and coordinated control of dual-arm space robot is generic for typical inner space-station. It includes several processes. First is task decomposition. In this step, a series of operation sequences and action sequences of subtasks will be obtained. Second is task allocation. According to compare the capability of decomposed subtasks with the capability of robots, the subtasks will be allocated to the corresponding robot. The third step is path planning and trajectory planning. The planed joint value and joint velocity value will be transmitted to the robot controller through network. Finally, it is the process to coordinated control of dual-arm robot. In these processes, the global vision, the local vision, the wrist force sensor and the finger force sensor are implemented in different stages. That is the control method by stages based on multiple sensors information.

3.1 Task decomposition

The dual-arm robot system for inner space-station operation mainly performs some typical and not very complicated tasks, such as replacing rod, inserting and drawing circuit chips, conveying objects and screwing nut and bolt, and so on. In task planning layer, there is a task knowledge base, which includes these typical operation tasks. When an appointed task is chosen, the system will decompose the chosen task according to the task knowledge and then produces a series of subtasks and its ability matrixes, and at the same time brings a series of actions corresponding to subtasks (Cheng *et al.*, 1991; Hormann and Rembold, 1991; Shao *et al.*, 2001).

As an instance for screwing nut and bolt, there are two ways to screw nut and bolt according to common sense. One way is that the two arms move synchronously in the course of screwing nut, and this demands a very higher synchronization of two arms. Another way is that one arm pauses after grasping bolt, and another arm screws nut not only rotating but also transferring motion. This way does not need a very higher synchronization of two arms and can be controlled easily. So, in terms of the control characteristic of our dual-arm robot system, the second way is chosen.

According to the task knowledge, the screwing nut and bolt task should be divided into two subtasks, that is rotating nut and grasping bolt, and then the two subtasks also can be divided into more subtasks. These subtasks can be denoted with a series of operation sequences in Table II.

In Table II, each operation sequence corresponds to a subtask. Because the step 1 to 6 is very easy, so we only plan the step 7 and step 8. The action command corresponding to the step 7 and 8 as follows:

Do: Close jaw;
Move $L^{*}\alpha/2\pi$ along a;
  While turn wrist α;
Open jaw θ_j;
Turn wrist $-\alpha$;
If torque $<$ T then continue;
Else Halt

Table II The operation sequences for screwing nut and grasping bolt of dual-arm robot

	Screwing nut	Grasping bolt
1	Near nut	Near bolt
2	Arrival nut	Arrival bolt
3	Grasp nut	Grasp bolt
4	Lift nut	Lift bolt
5	Preassembly	Preassembly
6	Pause	Touch nut
7	Rotate and transfer	Pause
8	Release	Pause
9	Pause	Leave
10	Home	Home

where L is the bolt pitch; T is the restriction torque; α is the rotation angle of wrist; a is the approach vector of gripper's orientation vector; θ_j is the opening angle of gripper.

In 3D simulation, the two robots have four motion modes:

- *Move_T(T_f)*. The position and orientation control mode corresponds to the robot base coordinate.
- *Move_XYZ(dX, dY, dZ, dγ, dβ, dα)*. The six dimensional vector control mode corresponds to the robot base coordinate.
- *Move_xyz(dx, dy, dz, dγ, dβ, dα)*. The six dimensional vector control mode corresponds to the mechanical interface coordinate.
- *Move_axs(q1, ..., q7)*. The joint angle control mode. The two-finger gripper has two control modes.
- *Close(θc)*. Closed gripper and θ_c is changed according to the finger force.
- *Open(θo)*. Opened gripper and θ_o is the initial angle.

Therefore, the robot action commands are made up of the six motion control functions. For instance, the process of screwing nut one time can be denoted by:

Close(θ_c);
Move_xyz(0,0, L$*\alpha/2\pi$,0,0,α);
Open(θ_o);
Move_xyz (0,0,0,0,0, $-\alpha$);

3.2 Task allocation

It is well known that human beings have only one cerebrum, which deals with task decomposition and task allocation, to control his dual-arm to move and work. The control mode of human being cerebrum is centralization. Because the dual-arm robot system has only two robots, it does not require the very higher communication performance, computation rate and disposal ability. At the same time, in order to improve the system operation efficiency, a task allocation method based on the "centralization trader" is presented by means of simulating the human being's control principle. Through defining the capability vector used in multi-robot task allocation, a formal description method is applied to describe the capability of tasks and robots (Liu *et al.*, 2006; Dong *et al.*, 2007).

A. Capability classified of robot

In general, robot has some different capabilities, such as the vision capability, the force capability, the execution capability, the communication capability, and so on. For a task, Completed it should also require many different robot capabilities and these capabilities can form a capability group which denoted by equation (1):

$$\boldsymbol{C} = \{c_j\}, \quad 1 \le j \le m \tag{1}$$

In this paper, the capability group of dual-arm robot is given by equation (2):

$$\boldsymbol{C} = \{G, L, W, F, E, C\} \tag{2}$$

where these symbols, respectively, denotes the global vision capability, the local vision capability, the wrist force capability, the finger force capability, the execution capability and the communication capability.

B. Capability description of robot

There are n different robots r_i, $1 \le i \le n$. In our system, $n = 2$. For robot r_i, the capability parameter P_{ij} is set and it is a variable. In the course of executing task, the P_{ij} varies continually. If robot has the c_j item capability, the P_{ij} is 1, otherwise the P_{ij} is 0. That is denoted by equation (3):

$$\boldsymbol{P}_i^r = diag\{P_{i1}, P_{i2}, \ldots, P_{ij}, \ldots, P_{im}\} \tag{3}$$

For robot r_i, the capability level parameter L_{ij} of c_i item capability is set and it is a constant, and its range is $0 \le L_{ij} \le 1$. For robot r_i, the capability level is higher, the L_{ij} is larger. That is given in equation (4):

$$\boldsymbol{L}_i^r = diag\{L_{i1}, L_{i2}, \ldots, L_{ij}, \ldots, L_{im}\} \tag{4}$$

C. Capability description of task

There are l different tasks t_k, $1 \le k \le l$. For task t_k, the demanded parameter N_{kj} for the c_j item capability of robot is set and it is a variable. If subtask demands the c_j item capability of robot, the N_{kj} is 1, otherwise the N_{kj} is 0. That is written in equation (5):

$$\boldsymbol{N}_k^t = diag\{N_{k1}, N_{k2}, \ldots, N_{kj}, \ldots, N_{km}\} \cdot \tag{5}$$

For task t_k the demanded intensity parameter W_{kj} for c_j item capability of robot is set and it is a constant, and its range is $0 \le W_{kj} \le 1$. For task t_k, the demanded intensity is higher, the W_{kj} is larger. That is denoted in equation (6):

$$\boldsymbol{W}_k^t = diag\{W_{k1}, W_{k2}, \ldots, W_{kj}, \ldots, W_{km}\} \cdot \tag{6}$$

D. Task accomplishment condition

Task sequences. These tasks generally have some restriction relations of sequences. For instance, the task t_q should be performed after the task t_p completed. This task restriction relation can be denoted by equation (7):

$$t_p > t_q, \quad 1 \le p, \quad q \le l \tag{7}$$

So, the task t_p is regarded as fore condition and the task t_q is considered as back condition. An operation priority parameter P_j $(1 \le j \le l)$ of each subtask is defined. This parameter is a constant and should be confirmed before performing task. Sometimes, many subtasks have the same priority in order to complete a task, so the operation schedules of these subtasks are same, that is these subtasks priority P_j are same.

Task accomplishment capability condition.

If robot r_i can accomplish the task t_k, it should be equation (8):

$$\boldsymbol{L}_{ij} \ge \boldsymbol{W}_{kj}, \quad 1 \le j \le m \tag{8}$$

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That is equation (9):

$$\boldsymbol{L}_i^r \geq \boldsymbol{W}_k^t \tag{9}$$

For robot r_i and task t_k, if there is c_j item capability, then equation (10):

$$\boldsymbol{L}_{ij} < \boldsymbol{W}_{kj}, \quad 1 \leq j \leq m \tag{10}$$

So, the robot r_i cannot accomplish the task t_k and denoted by equation (11):

$$\boldsymbol{L}_i^r < \boldsymbol{W}_k^t \tag{11}$$

If all subtasks can be accomplished by any one robot, the total capability value of the task and robot are, respectively, computed. The subtask with larger capability value is allocated to the robot with better capability, vice versa.

3.3 Path and trajectory planning

For one task, the outputs of task planning are n subtasks, and there are n action sequences corresponding to the n subtasks. According to the initial and target position and orientation of each task, and the priority of action sequence, the centralized manager "trader" carries out the path planning and trajectory planning of dual-arm robot. A differential motion control method is applied to the motion planning of dual-arm robot (Joonhong and Dong, 1985, 1987). The joint value and joint velocity value are produced and saved in a text file, respectively, during each sample time. After planning, the high planner then transmitted the value file to the robot controller through network. The planning flow chart of dual-arm robot system is shown in Figure 3.

3.4 Control method by stages based on multiple sensors information

The multiple sensors system of dual-arm robot is composed of the global vision, the local vision, the ultrasonic sensor, the wrist force sensor and the finger force sensor. The sensors information is solely used according to the sensor's accuracy and effective action range in our system. Because the global vision can survey the extensive range and its precision is not high, so it is fit for lower accurate measuring in extensive range. However, the local vision is opposite to global vision, it has the high accuracy in some range but the measure range is more limited, the local vision is fit for the high accurate measure in some range. The wrist force sensor and finger force sensor should act after the touch force is produced, so the force control is applied to small regulation during robot motion.

Therefore, a control method by stages based on multiple sensors information is presented. That is the first stage to approximately measuring with global vision, the second stage to accurately measuring with local vision and the third stage to small regulating with force sensor (Zhang, 2003). The structure of control by stages based on multiple sensors information is shown in Figure 4.

The control process by stages includes several steps.

Task selection

The operation task can be selected through 3D simulation platform at the task planning layer. After that a task ID is produced corresponding to the selected task, the planner triggers the global vision to start work.

Figure 3 The planning flow chart of dual-arm robot system

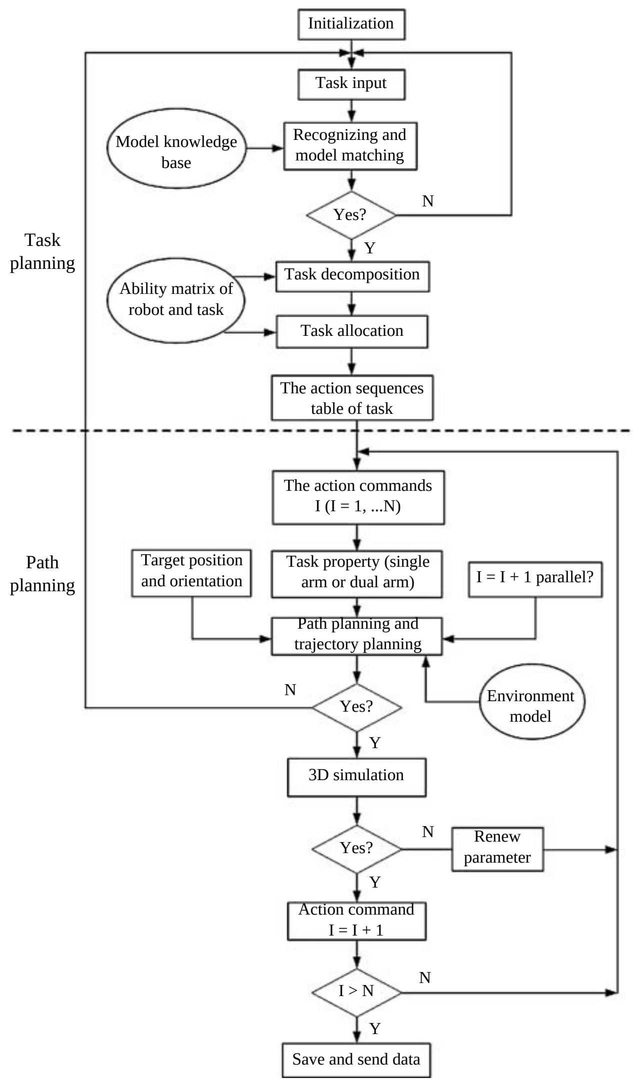
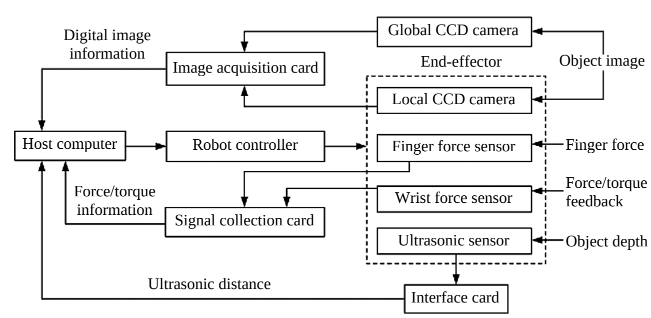


Figure 4 The structure of control by stages based on multiple sensors information



Object recognition

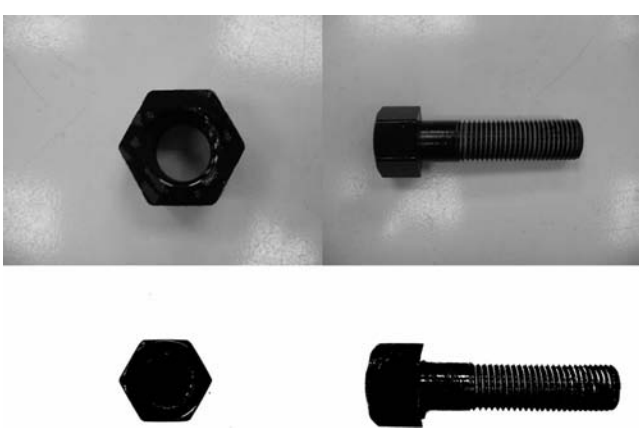
The global vision uses a 2D camera system to recognize the object and determine its appropriate position and orientation. Because the object recognition depends on planar feature, as a consequence, the objects are restricted to regular parts so far. The global vision begins to recognize the grasped object according to the selected task ID. If the object recognition is successful, the planner will take for the grasped object existing and continue to measure its position and orientation. Otherwise, the planner will notify the operator that the grasped object do not exist at all and the operation task will also be stopped.

The global vision is shown in Figure 5 and the recognition image of object is shown in Figure 6.

Object orientation
If the grasped object exists on the operation platform, the next step is to make certain the position and orientation of object. The initial position and orientation of object is acquired using the global vision. However, only the position and orientation of X and Y axis are measured, the object height of Z axis will be estimated and the object orientation of Z axis will not be considered. The central point coordinates of object is regarded as its position, the angles to two coordinates axis (X and Y) and one straight-line (such as the best short diameter) of object are denoted its orientation (Xie *et al.*, 2005). The position and orientation of object is denoted a four-dimensional vector and this vector can be directly used by robot planning system.

Figure 5 The global vision

Figure 6 The recognition image of object



3D model
After getting the object's position and orientation, the 3D models of objects should be shown in 3D simulation platform. The 3D models of objects are produced by VC++ and OpenGl, 3DMAX. The dimensions of model are strictly in proportion with the real dimensions of object. These 3D models should be shown at the position of determined by global vision. It is shown in Figure 7.

Motion planning
At first, only the global vision information is applied to the path planning and trajectory planning of robot; After the object comes into the measuring range of local vision under the guidance of global vision, the local vision information, which comprises the ultrasonic information, is used to the path and trajectory planning of robot. The two local visions are shown in Figure 8. The central point coordinate of projective object is taken for the object position, the angles to the three coordinate axes and the best short diameter of projective object are taken as the object orientations (Xie *et al.*, 2005). Therefore, the position and orientation of object is denoted with a six-dimensional vector and this vector can be directly applied to the robot planning system.

Finger force grasping
The two-finger gripper can steadily grasp object by means of finger force sensor.

Wrist force judging
The wrist force sensor is used to judge the initial tight force when the bolt and nut contacting and the safe torque during screwing bolt and nut.

4. Environment modeling

The simulation environment modeling is programmed in VC++6.0 development environment with the Matcom, OpenGl, 3Dmax and Proe. The purpose of 3D simulation is to verify the validity and reliability of the task decomposition, task allocation and the measured data by visions, nipping in the bud. For the task planning, a task capability class including several membership functions is defined, as follows:

Figure 7 The 3D model of objects

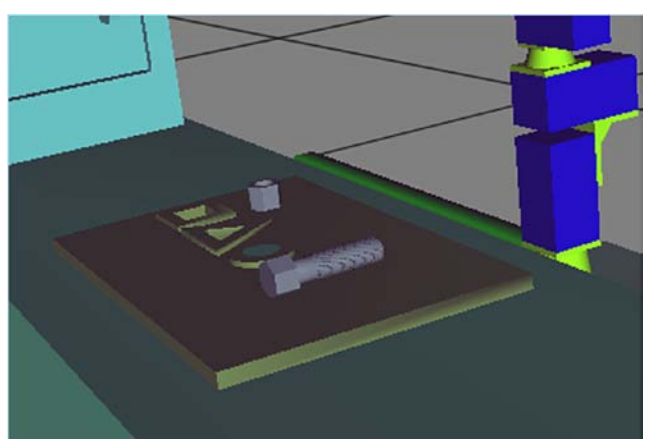
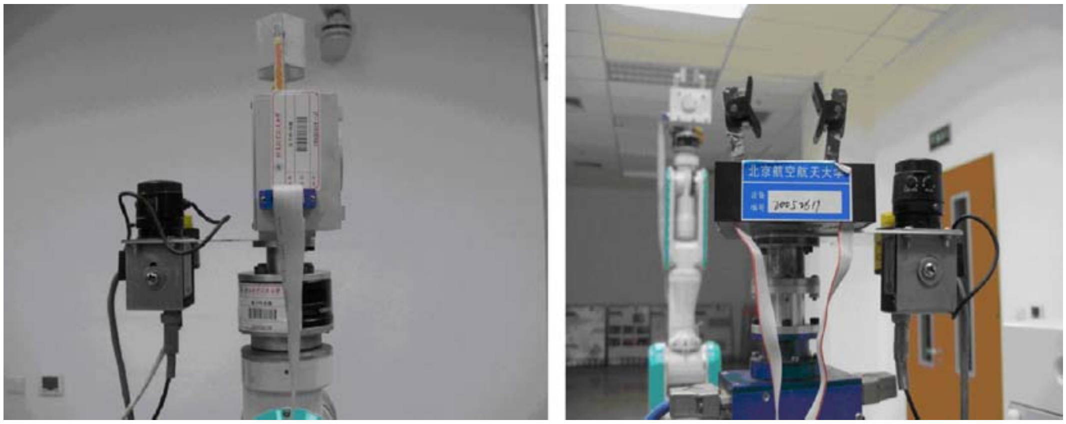


Figure 8 The local vision



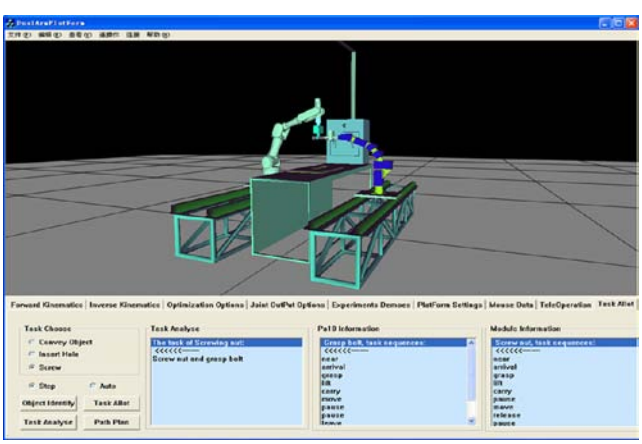
Mm Task_capability(); Task capability matrix
Mm PA_capability(); PA10 robot task capability matrix
Mm Module_capability(); Module robot task capability matrix
Int Priority(); Task priority function
BOOL Compare(); The capability comparing function
BOOL KS(); Activating function

The 3D simulation of automatic planning is shown in Figure 9. The part plan algorithms of dual-arm robot are written in the following.

Algorithm 1. Procedure of task capability
Input: Task ID
Output: Task capability matrix
1: Choose task according to Task ID
2: Decompose the task to some subtasks;
3: Designate the capability parameter and intensity parameter to subtasks
4: for i = 1,…, 6 do
5: Obtain the whole task capability matrix
6: Return the capability matrix of task
7: End

Algorithm 2. Procedure of robot capability
Input: Robot ID
Output: Robot capability matrix
1: Choose robot according to Robot ID

Figure 9 The 3D simulation of task planning



2: Obtain the capability group of robot;
3: Designate the capability parameter and intensity parameter to capability group
4: for i = 1,…,6 do
5: Obtain the whole robot capability matrix
6: Return the capability matrix of robot
7: End

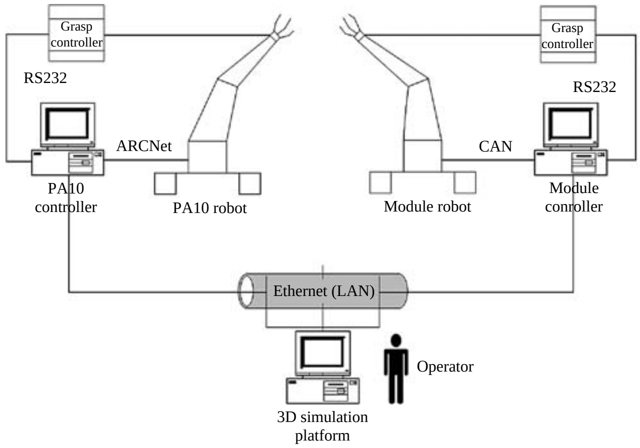
Algorithm 3. Procedure of comparing capability
Input: Task ID and Robot ID
Output: Judgement ID
1: Choose task capability matrix and robot capability matrix according to Task ID and Robot ID
2: Compared the task capability matrix with the robot capability matrix
3: for i = 1,…,6 do
4: Obtain the Judgement ID
5: Return the Judgement ID
6: End

Algorithm 4. Procedure of path planning
Input: Subtask ID
Output: Joint value file of subtask
1: Obtain the priority according to the subtask ID
2: Obtain the initial and target position and orientation of subtask
3: Trajectory planning through a differential motion control method
4: Get the joint value file
5: Save the file
6: End

5. Simulation and experiment

In order to validate the feasibility and applicability of automatic task planning strategy, the simulation and experiment for the screwing nut and bolt of dual-arm robot are separately executed. Moreover, a network communication structure based on client/server mode is established (Ding *et al.*, 2006), shown in Figure 10. This communication structure is more important, because it a bridge which connects the simulation platform with the robot controller. Through the network, the produced data in 3D simulation are transmitted to the robot controller to control the robot moving. During whole control, only one operator can

Figure 10 The network communication structure of dual-arm space robot system based on C/S mode



complete the operation task through the 3D simulation platform.

According to the characteristic of dual-arm robot and the capability vector of tasks and robots, a series of subtasks of screwing nut and grasping bolt are, respectively, given to Module robot and PA10 robot. In 3D simulation platform, the task for screwing nut and bolt of dual-arm robot is planned and simulated by virtue of planning method in Figure 3. During the two robots grasp the nut and bolt, the robot will be pause two times (move above object, near object, about 10 s). For the sake of ensuring the continuity of whole experiment process, the process of robot grasping nut and bolt can be removed and the dual-arm robot directly grasps the nut and bolt at first and then moves to the preassembly position. The task condition of screwing nut and bolt is listed in "The task condition" below:

bolt : C-level (GB5780-86), metric diameter M30, length 150 mm, bolt pitch 3.5 mm;
nut : length 35 mm;
initial tight force : 2 N;
safe torque : 2 Nm;
nut rotation angle each time : 2π rad;
nut rotation time each time : 10 s;
nut going ahead length each time: 3.5 mm; and
accomplish condition : screwing one time.

The task accomplishment time of PA10 robot and Module robot are both 80s, listed in Table III.

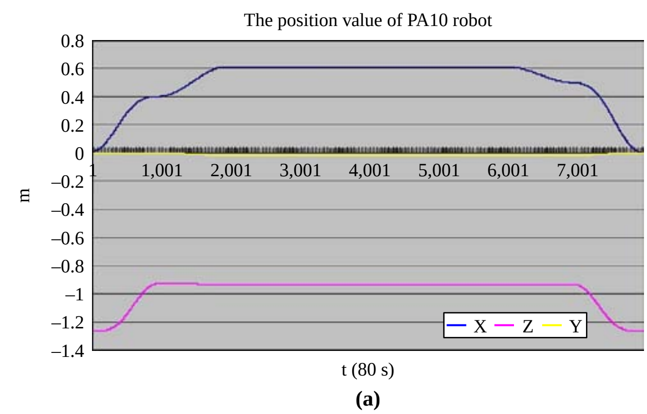
The planned position values of two robots in 3D simulation platform are shown in Figure 11 and the process of simulation and experiment are, respectively, shown in Figures 12 and 13.

From Figures 13 and 14, it can see that the actual experiment generally accorded with the 3D simulation. So, it verified the validity and reliability of planning and coordinated control of dual-arm robot system in this paper. The safe torque value is 2 Nm and if exceeding the value, the robots will stop at once. We implemented the experiment of screwing nut and bolt five times and the position of end-effector and angular of joint are measured real-time. Through compared planning value with real value, the error between actual results and simulation results is obtained. The errors between simulation data and real data are small. The maximal position error is 0.2 mm and the maximal angle error is 0.3 deg. The errors are mainly derived from the system errors, including calculation error, robot control error, sensor data disposing and transmitting error, and so on. In the course of screwing nut and bolt, the wrist force sensor measures the force and the torque of six orientations, and the graphs of the force and torque are shown in Figure 14. The time of screwing nut (one times) is 10 s and the sampling time of force sensor is 0.1 s.

Table III The task accomplishment time

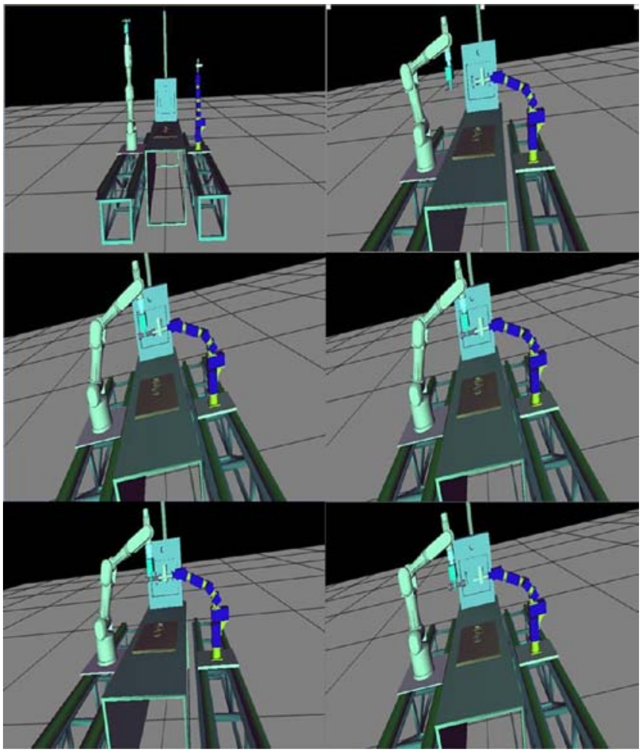
Steps	PA10 (s)	Module (s)
1	Preassembly 10	Preassembly 10
2	Approach 10	Pause 10
3	Pause 10	Screw nut 10
4	Pause 5	Open grasper 5
5	Pause 5	Wrist rotate 5
6	Pause 5	Close grasper 5
7	Pause 10	Screw nut 10
8	Pause 5	Open grasper 5
9	Leave 10	Pause 10
10	Home 10	Home 10

Figure 11 The position value of PA10 robot and Module robot



From the above graphs, it can find that the force values of X orientation are larger than the Y, Z orientation, reaching 2-3 N, it is the main force orientation and the torque values of Y orientation are larger than X, Z orientation, reaching

Figure 12 The 3D simulation for screwing nut and bolt of dual-arm robot



0.4-0.5 Nm, it is the main torque orientation. Moreover, the curve shapes of the two orientations are more similar, so it illuminates the torque of Y orientation is proportional to the force of X orientation. The force value and the torque value of other orientation are very small, therefore, it is shown that the produced force and torque are within the permissible range. Thus, the feasibility and applicability of our control strategy are verified.

6. Conclusion and future work

As an example of typical task of dual-arm robot system for inner space-station operation, the strategy of automatic task planning is studied. This strategy includes task decomposition and task allocation of the higher layer, the path planning and trajectory planning of the lower layer, and the control by stages based on multiple sensors information. In our heterogeneous dual-arm robot system, the task planning is executed automatically in terms of this method, and the intelligence of dual-arm robot system is improved during the collaborative operations. The practicality of the automatic planning method is also verified by simulations and experiments. Our study convinces that it is a very efficient automatic planning method of dual-arm robot system for inner space-station operation.

Our future research will be focused greatly on reducing the running time of some subsystem, such as the time of task planning, the time of disposing sensors information, the time of transporting data, and so on. The motion efficiency of dual-arm robot system can be further increased. In order to achieve this purpose, some strategies are illustrated as follows:

- applying more advanced controller of sensors (especially in vision sensor);
- reducing the computing time of kinematics and inverse kinematics of redundant robot; and
- improving the speed of transmitting data through the network.

Figure 13 The experiment for screwing nut and bolt of dual-arm robot system

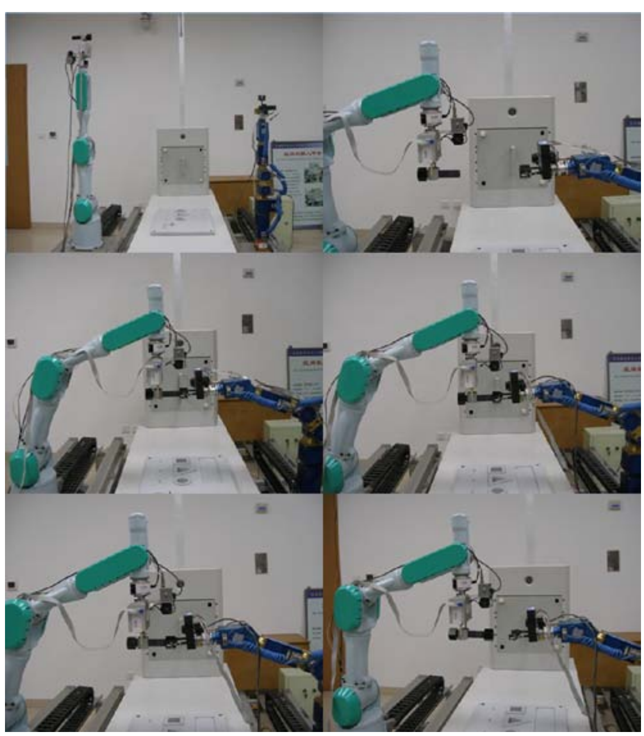
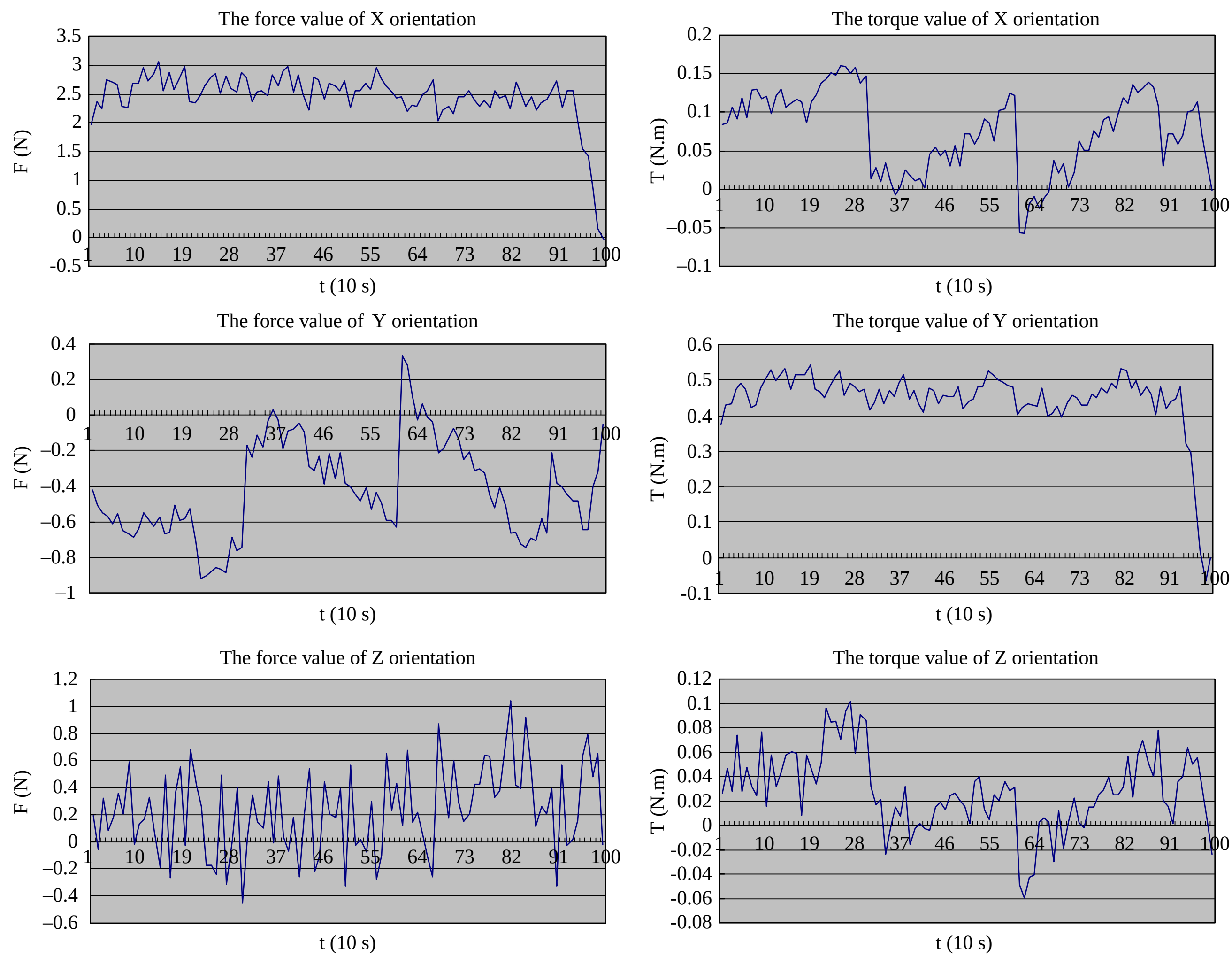


Figure 14 The force and torque graphs of six orientations



References

Cheng, X., Kappey, D. and Schloen, J. (1991), "Elements of an advanced robot control system for assembly tasks", *Fifth International Conference on Advanced Robotics, Piscataway, NJ, June 19-22*, Vol. 1, pp. 411-16.

Ding, X.L. (2003), *Coordinating Control and Teleoperation of Fault-tolerance Redundant Dual Arm Space Robot System*, Beijing University of Aeronautics and Astronautics, Beijing, pp. 1-5.

Ding, M., Sun, Z.Q. and He, B. (1992), "A general dual-arm robotic simulation system and cooperative control research of multi-manipulator", *Proceedings of the IEEE International Symposium on Intelligent Control, Glasgow, UK, August 11-13*, pp. 23-8.

Ding, X.L., Li, H.T. and Xie, Y.W. (2006), "Research on internet-based dual-arm robotic teleoperation system", *High Technology Letters*, Vol. 16 No. 8, pp. 808-12.

Dong, Y.B., Jiang, J.P. and He, Y. (2007), "Fitness-based task allocation strategy for multi-robot system", *Journal of Zhejiang University (Engineering Science)*, Vol. 41 No. 2, pp. 272-7.

Freund, E., RoBmann, J. and Hoffmann, K. (1996), "Automatic action planning as a key to virtual reality based man-machine-interfaces", *Proceedings of the IEEE/SICE/RSJ International Conference on Multi-sensor Fusion and Integration for Intelligent Systems, Piscataway, NJ, USA, December 8-11*, pp. 647-54.

Freund, E., Hahn, D.L. and Rossmann, J. (1997), "Cooperative control of robots as a basis for projective virtual reality", *International Conference on Advanced Robotics, Piscataway, NJ, USA, July 7-9*, pp. 753-8.

Freund, E., Hoffmann, K. and Rossmann, J. (2000), "Application of automatic action planning for several work cells to the German ETS-VII space robotics experiments", *Proceedings of the IEEE International Conference on Robotics and Automation, Piscataway, NJ, USA, April 24-28*, pp. 1239-44.

Hormann, A. and Rembold, U. (1991), "Development of an advanced robot for autonomous assembly", *IEEE International Conference on Robotics and Automation, Piscataway, NJ, USA, April 9-11*, Vol. 3, pp. 2452-7.

Hormann, A. (1992), "On-line planning of action sequences for a two-arm manipulator system", *Proceedings of IEEE International Conference on Robotics and Automation, Nice, France*, pp. 1109-14.

Joonhong, L. and Dong, H.C. (1985), "On a control scheme for two cooperating robot arms", *Proceedings of the*

24th IEEE Conference on Decision and Control, Fort Lauderdale, FL, USA, December 11-13, Vol.1, pp. 334-7.

Joonhong, L. and Dong, H.C. (1987), "A control scheme for two cooperating robot arms", *IEEE Control Systems Magazine*, Vol. 7 No. 1, pp. 65-8.

Liu, L., Ji, X.C. and Zheng, Z.Q. (2006), "Multi-robot task allocation based on market and capability classification", *Robot*, Vol. 28 No. 4, pp. 337-43.

Meng, Q.X., Li, P. and Guo, L.B. (2004), "Analysis and experimental design of multi-robot cooperation", *Manufacturing Automation*, Vol. 26 No. 11, pp. 43-7.

Qu, D.K. and Tan, D.L. (1991), "A control system for two robots coordination", *Robot*, Vol. 13 No. 3, pp. 6-11.

Shao, P.M., Li, C.G. and Wu, H.S. (2001), "An intelligent task scheduling and control system based on object model for robot arm", *China Mechanical Engineering*, Vol. 12 No. 4, pp. 451-5.

Xie, Y.W., Ding, X.L. and Liu, Y. (2005), "Position and orientation measurement using monocular camera-ultrasonic sensor configuration mounted on robot", *Journal of Beijing University of Aeronautics and Astronautics*, Vol. 31 No. 7, pp. 809-13.

Zhang, W. (2003), "Slide-motion redundancy manipulator kinematics planning and control technology research based on multi-sensor fusing", working paper, School of Mechanical Engineering and Automation Science, Beijing University of Aeronautics and Astronautics, Beijing, March 14.

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