Human-Robot Cooperation in Virtual Assembly Using Augmented Reality

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Abstract- **This research presents an implementation of human-robot cooperation system using augmented reality technique. In this research, human operator and robot arm share the common workspace in virtual object assembly task. The technique of augmented reality is used for creating virtual objects and providing necessary information to the human operator. The virtual objects are in the form of 3D computer graphics superimposed on the real video images. The ARToolKit software library is used in the vision manager to process captured video image and obtain the positions and orientations of targeted objects. The task manager is responsible for generating action plans using STRIPS planning algorithm in assembly task and control system states. The robot manager takes care of computing forward/inverse kinematics of the developed robot arm, reading robot's joint angles, and sending commands to control the robot. Graphics manager is used to generate 2D and 3D computer graphics rendered on the real video images. The graphics present all guidance information and virtual objects to the operator. The system can generate assembly plans for human and robot step by step. The robot arm is responsible for assisting the human operator by transferring virtual objects to the loading area. Furthermore, a task planner controls all robots' operations accordingly to human actions. Human operator can accept or decline robot's assistance. Human operator also receives robot's task plan in the form of computer graphics during the operation. The computer-generated information will support human operator's decision for a suitable next step action. Therefore, the augmented reality can enhance the cooperation between human operator and the robot effectively.**

Keywords- Human-Robot Cooperation; Augmented Reality; Task Planning

I. INTRODUCTION

For the past years, the technique of presenting computer graphics information superimposed on the real time video images, which is called augmented reality, gains more interests. Some previous research works implemented augmented reality to provide necessary information in the form of computer graphics to the operator during working with the real objects. Wolfgang [1] chose augmented reality technique to present the operation guidance to human operator in a complicated task. N. Pathomaree and S. Charoenseang [2], implemented the skill transferring system in assembly task by presenting the assembly procedure with augmented reality technique. M.L. Yuan and colleagues [3] presented augmented reality technology for assembly guidance using virtual interactive tool called Virtual Interaction Panel. T. N. Kengo Akaho and team [4] developed navigation system using augmented reality called AR-Navi. Furthermore, augmented reality is also used in human-robot cooperation task. Human operator will receive the augmented task information while working with the robot. S. Otmane and companions [5] presented the development of virtual reality and augmented reality with internet-based teleoperation system. They used active virtual guide to assist human operator in performing simple or complex tasks. P Nunez and colleagues [6] also proposed the human-robot interaction by using augmented reality to allow the user to help the robot for building map and correct robot's path planning. Scott A. Green and companions [7] presented that the use of augmented reality technique to provide information to the operator while working with robot will increase the system's accuracy and performance by 30%. A. Ameri E. and team [8] chose augmented and virtual reality techniques for presenting a visual feedback of robot's view while the user operates or programs robots. However, in the previous related research works, human and robot do not share the same workspace. Hence, this research presents the development of shared space human-robot cooperation by using augmented reality technique for creating virtual objects and providing necessary information to the human operator. In this implementation, human operator and a robot arm share the same workspace in the virtual object assembly task. During human-robot operation, human will obtain virtual objects, graphics instruction, and robot's action information through augmented reality technique. Moreover, robot will receive control commands from human operator to assist in transferring virtual objects.

The paper is organized as follows. Section II covers details of the whole system operation. Section III shows the experimental results. Finally, conclusions and future works are presented in Section IV.

II. SYSTEM OVERVIEW

The human-robot cooperation system with augmented reality in assembly task is proposed in this research. A single video camera is used to capture the workspace's image. All tracked marker plates are on the workspace. The virtual objects used in this task are in the form of 3D computer graphics and rendered on the detected marker plates. During assembly process, workspace's video image is captured and sent to the computer for computing the marker plates' positions and orientations. The system will then generate a task plan for assembling virtual objects and controlling the robot arm. It also presents all graphics information which is 2D guidance texts, 3D symbols, and 3D virtual objects to the operator through LCD display. Moreover, the operator can allow or declining the assistance from robot in transferring marker on where virtual objects are superimposed.

A. *System Configuration*

Fig. 1 shows the system configuration developed in this research. It consists of an operator, in-house developed 5-DOF robot arm, computer, LCD screen display, video camera, and maker plates.

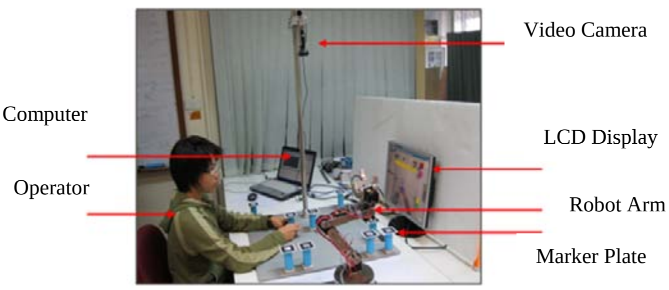


Fig. 1 System Configuration

During virtual object assembly, the operator and robot will move virtual objects on marker plates accordingly to system guidance. A video camera is used to capture image of the workspace. The computer is responsible for image processing, task planning, rendering all graphics on LCD screen, and controlling the robot's operation. The robot performs as an operator's assistance. Its operations depend on task plan and operator's decision commands.

B. *Robot Design and Development*

A 5-DOF robot is designed and developed in the research. The first three joints of this robot arm have the same pose as Yasukawa Motoman L-3 robot's [9]. The last two joints have the same origin and provide pitch and yaw configurations as shown in Fig. 2. Robot's structures, links, and base, are made of aluminium. To control this robot, USB2dynamixel device [10] is selected. It provides a communication between a computer and dynamixel motors on the robot by converting signals from USB port on the personal computer into serial port communication for controlling the robot as shown in Fig. 3.

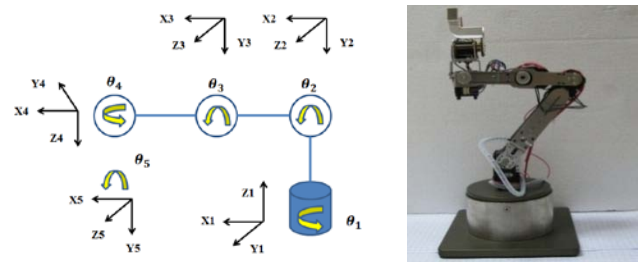


Fig. 2 Robot Arm's Configuration

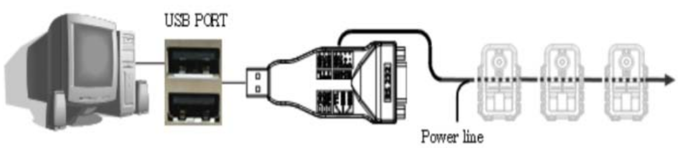
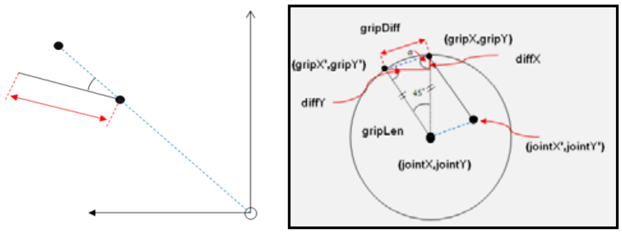


Fig. 3 Dynamixel Control by Personal Computer [10]

C. *Robot's Inverse Kinematics*

The robot's inverse kinematics is used to determine all possible and feasible sets of the joint variables which achieve the goal position and orientation of the manipulator's end-effector with respect to the base frame [11]. In this research, the robot's gripper at the end of the 4th joint is set to 45 degrees from the normal pose. The configuration of robot is shown in Fig. 4.



(a) (b)

Fig. 4 Adjustment of Robot's Gripper for Finding Inverse Kinematics

In Fig. 4(a), the dash line shows the configuration of the robot arm in the normal pose and the bold line with 45 degrees tilted from the dash line shows the specified orientation of the robot's gripper. Fig. 4(b) shows the details of the robot gripper's configuration at the end of the 4th joint. If the robot's end effector is in the goal position (gripX, gripY) at the normal pose, the position of the 4th joint should be at (jointX, jointY) which is solved by the robot's kinematics. The gripper needs to be tilted from the straight pose and retained at the same target at (gripX, gripY). Therefore, the 4th joint at (jointX, jointY) must be shifted along X and Y axes to (jointX′, jointY′). The offsets between (gripX, gripY) and (gripXgripY′) are diffX and diffY. Hence, the solution for the 1st, 2nd, 3rd and 5th joints can be determined using geometric method as shown in Equations (1) – (4) where the 4th joint is always fixed at 45 degrees from the normal pose.

$$\theta_1 = Atan2(jointX', jointY') \tag{1}$$

$$\theta_3 = Atan2\left(\sqrt{1 - cos\theta_3{}^2}, cos\theta_3\right) \tag{2}$$

$$\theta_2 = -Atan2\left(z, \sqrt{jointX'^2 + jointY'^2}\right) - Atan2(L3 \sin\theta_3 + L2L3 \cos\theta_3) \tag{3}$$

$$cos\theta_3 = \frac{\left(jointX'^2 + jointY'^2 + z^2 - L2^2 - L3^2\right)}{2L2L3} \tag{4}$$

In Fig. 4, robot's gripper should be paralleled with the workspace on the table. The solution of the 5th joint (θ_5) can be then computed as in Equation (5).

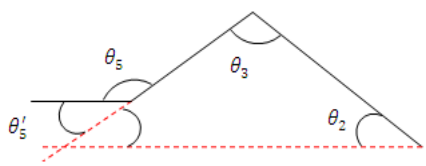


Fig. 5 Relation of θ_2, θ_3, and θ_5

$$\boldsymbol{\theta_5 = \theta_2 + \theta_3} \tag{5}$$

D. *Electronics Design and Development*

The RX model of Dynamixel motor is selected to drive the robot arm in this research. Because of the different load of each joint, variant motor series are chosen. RX-64 motor series are chosen for the first and second joints since they can provide the maximum torques at 77.8 kgf.cm with 18 volts. For the third joint, RX-28 motor is selected to provide the maximum torques at 37.7 kgf.cm with 16 volts. RX-10 motors are used for the last two joints. They can provide the maximum torques at 12.1 kgf.cm with 12 volts. The wiring diagram for this robot's motors is shown in Fig. 6.

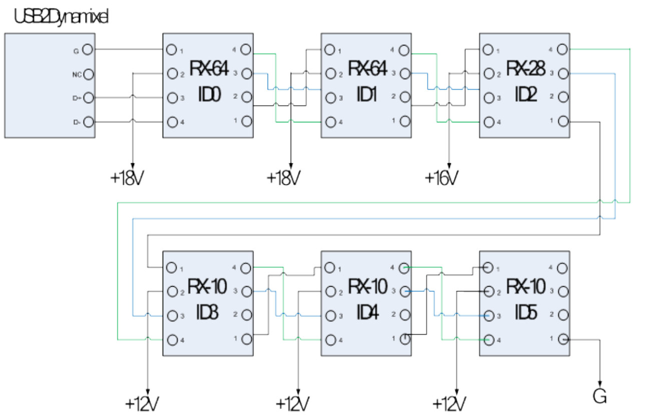


Fig. 6 Dynamixel Motor's Supply Circuit Design

E. Programming Design and Development

This proposed system contains four main software components, which are vision manager, graphics manager, task manager, and robot controller.

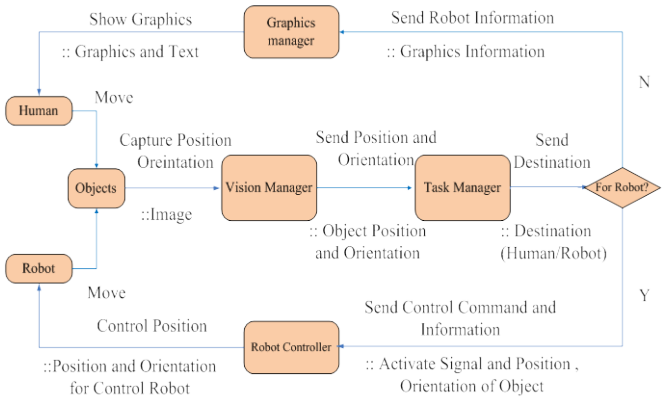


Fig. 7 System Data Flow Diagram

From the data flow diagram in Fig. 7, ARToolKit [12] software library is used in the vision manager to process captured video images and obtain positions and orientations of the targeted marker plates. Then, it sends targeted objects' positions and orientations to the task manager. The task manager is responsible for generating action plan using STRIPS [13] planning algorithm for the assembly task. Next, the robot manager computes forward/inverse kinematics, reads robot's joint angles, and sends commands to control the robot's movement. The last component is the graphics manager which generates 2D and 3D computer graphics to present all guidance information and virtual objects on the LCD display to the operator.

1) Vision Manager:

After the vision manager obtained video image of the workspace from the video camera, this module will find the marker plates from the received image and calculate the position and orientation of each marker plate. Vision manager sends calculated position and orientation to task manager. The computer graphics objects are then generated and superimposed on the markers' in the video image. Flowchart of this module is shown in Fig. 8.

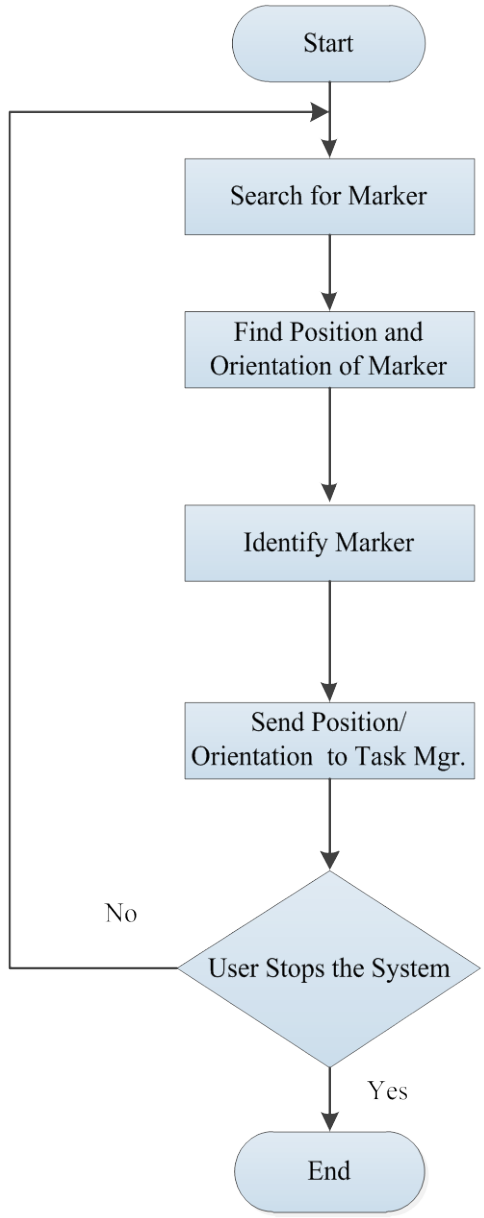


Fig. 8 Flowchart of Vision Manager

2) Task Manager:

Task manager is responsible for controlling all system processes. This module receives information, which is position and orientation of object, from the vision manager to do further process. In the task manager, process can be separated into many states and each state has substates. Flowchart of task manager is shown in Fig. 9.

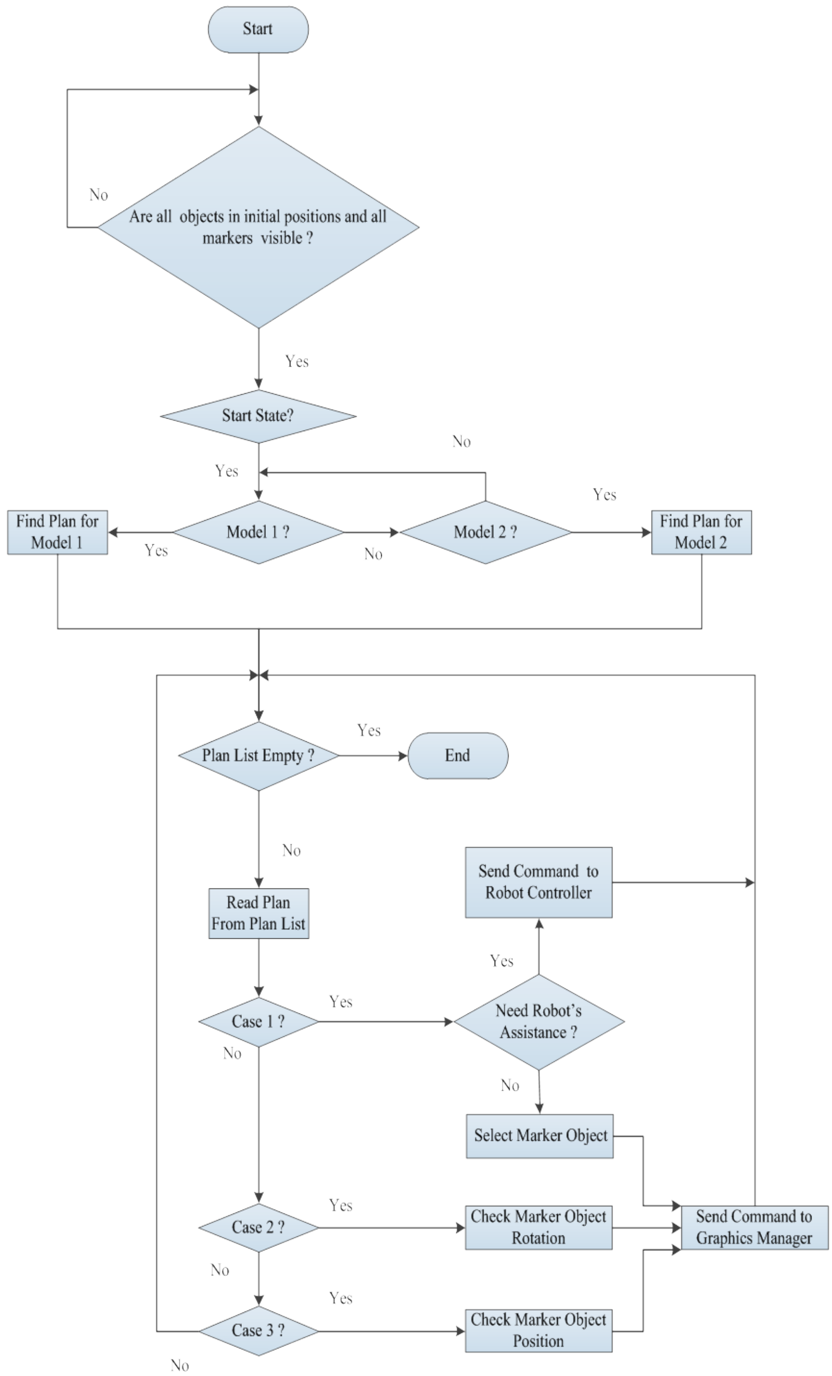


Fig. 9 Flowchart of Task Manager

Fig. 9 shows the main operation of Task Manager. This task operation starts with checking all markers in workspace.If markers of virtual object are in the loading area, it means that the system is ready. The system has 2 models for virtual assembly. After state is ready, the system will verify the virtual assembly model selected by the operator and wait for checking 'START' marker. The virtual assembly task starts after the 'START' marker is selected. The system then checks the selected virtual assembly model and goes to the planning state. At this state, the system will call 'Planner' module to generate the virtual assembly task plan. The planner module consists of World state, Goal state, and plan list. It uses the 'Delete' and 'ADD' operators of virtual objects to modify the World state to achieve the target which is Goal state.

The planner is called when 'START' marker is selected. During the process, if the user and/or robot choose incorrect virtual objects for assembling, this module will regenerate a new task plan. This new task plan is generated based on the information of the current positions and orientations of virtual object markers. The system state will be changed to the reading plan state to read task plan from the 'Plan List' which consists of all operations, which are SELECT, PUTRIGHT, PUTLEFT, PUTTOP, PUTDOWN, and ROTDIR, to achieve the goal. The system will examine the planning case which is separated into 3 cases as described below.

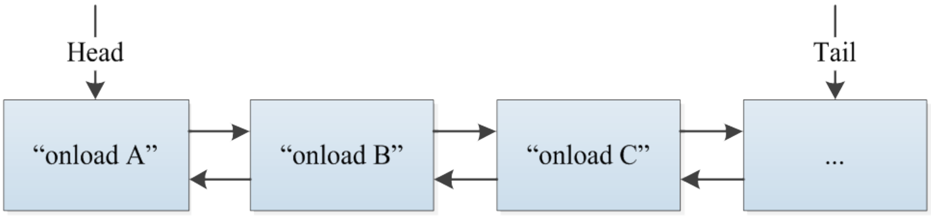


Fig. 10 Structure of World State: World state contains current state of virtual objects in workspace. At the beginning, all virtual assembly objects must be in 'Loading area'

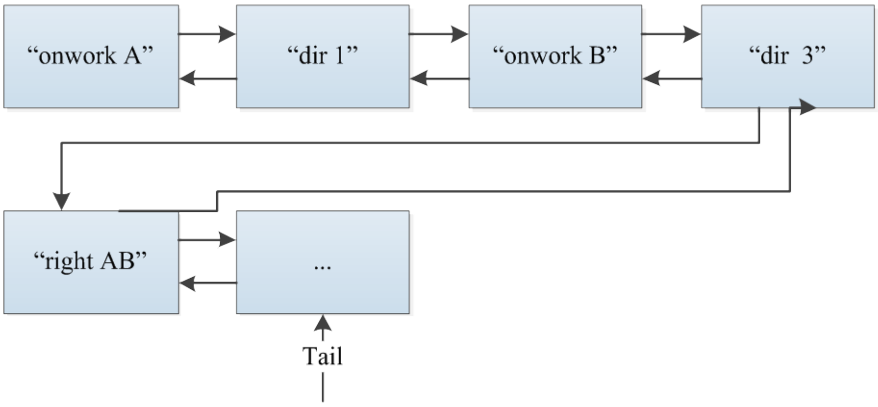


Fig. 11 Structure ofGoal State: Goal State contains target of assembly task

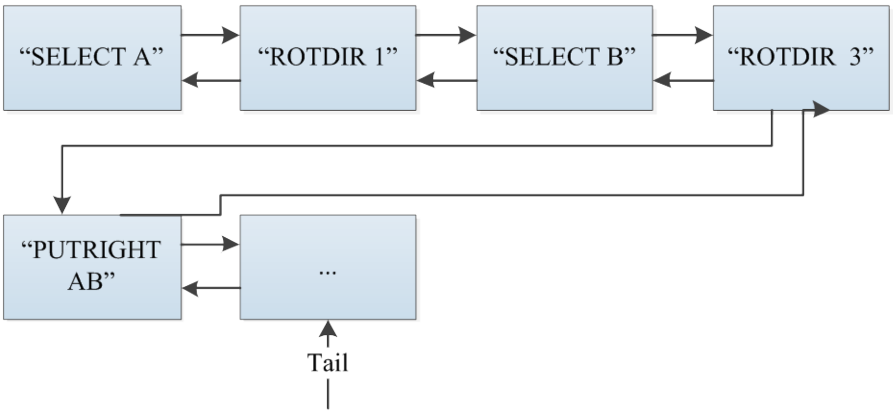


Fig. 12 Structure of Plan List: Plan List contains all operations to achieve target

Case 1 At the plan reading state, this case concerns about choosing virtual objects for assembling in workspace. When this case is started, it will send *Graphics ID* to the graphics manager for asking human operator whether he/she needs the robot to help in transferring virtual object or not. If the operator needs the robot's assistance, the task manager will send command to the robot controller to control the robot arm. After that, task manager will inspect the selected virtual object. If this virtual object is the same as one in generated plan, World state will be updated by adding this correct current virtual object state. If the selected object is incorrect as one in the suggestion plan, the current object's information will be added into the World state and this program module will regenerate a new plan from the modified World state.

Case 2 considers about the orientations of virtual objects. It will check whether selected virtual object is in the correct orientation or not. If the orientation of virtual object is in the wrong direction, the task manager will send *Graphics ID* to the graphics manager for showing computer graphics of rotating guidance.

Case 3 is responsible for checking the position of virtual object. If its position is incorrect, *Graphics ID* will be sent to the graphics manager for showing computer graphics of position guidance.

This module mainly updates the graphics according to the current system state from the task manager. It will choose the suitable *Graphics ID* for presenting system status' information. This chosen computer graphics are virtual objects, 2D computer graphics texts, and 3D computer graphics symbols. The graphics are rendered and superimposed on the video image displayed on the screen. The flowchart of its operation can be shown in Fig. 13.

3) Graphics Manager:

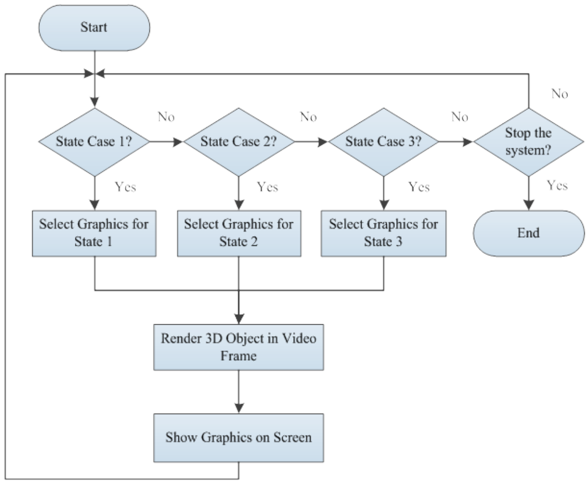


Fig. 13 Flowchart of Graphics Manager

4) Robot Controller:

Robot Controller is responsible for solving the inverse kinematics and controlling the robot arm. The robot control command is sent to the robot by using USB2Dynamixel through RS485. The flowchart of its operation is shown in Fig. 14.

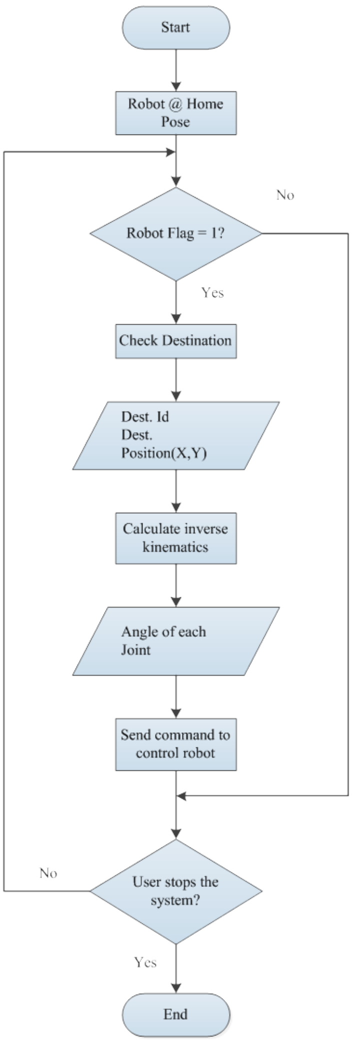


Fig. 14 Flowchart of Robot Controller

5) Graphics User Interface(GUI):

Graphics user interface is designed for communication between human, system, and robot by implementing augmented reality technique. There are nine marker plates presented on the workspace. The 3D computer graphics are overlaid on the markers. The user is able to interact through this GUI by placing his/her hand over the marker which he/she needs. Graphics user interface consists of components as shown in Fig. 15.

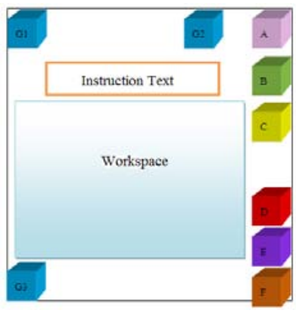


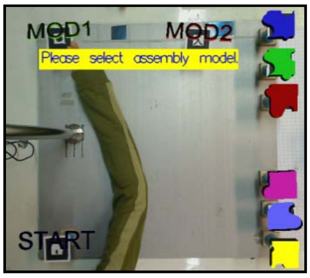
Fig. 15 Layout of Graphics User Interface

where,

G1 and G2	show 3D computer graphics. The user can select assembly mode through these markers.
G3	shows 3D computer graphics. The user can confirm to start assembly procedure through this marker.
A-F	show 3D computer graphics of virtual objects accordingly to the selected mode.
Instruction Text	shows 2D computer graphics in the form of text for assembly guidance and robot's information.

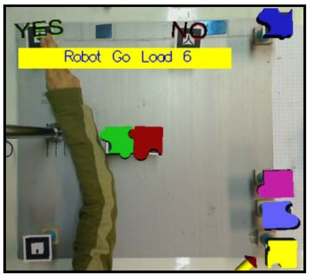
6) System Operation:

Fig. 16 (a) shows the first state of this system operation. At the initial state, the graphics instructions are presented to offer two virtual assembly models. The operator must choose which model he/she wants to operate on. After virtual assembly model is selected, various virtual objects are rendered and superimposed on the marker plates. A task plan for selected assembly model is then generated to arrange all system states, present graphics information, and controls the robot. The suggestion texts and information related to robot’s actions are showed in the form of 2D graphics. The 3D graphics presenting assembly guidance arrows such as appropriate position and orientation of virtual object are superimposed on the real video image on the LCD screen as shown in Fig. 16(b). While human operator and robot arm work together in virtual assembly task, the robot has responsibility to assist human operator by transferring a selected object after the operator selected the “Yes” virtual object as shown in Fig. 16(c) and 16(d). The operator can refuse any robot action while workings together by choosing “No” virtual object. The sysem will generate a new task plan for the assembly task automatically when the operator does not follow the suggested task plan.



(a) Model Selection

(b) Rotation Guide



(c) Robot Selection

(d) Robot Operation

Fig. 16 System Operation

III. EXPERIMENTAL RESULTS

Three experimental sets are conducted to evaluate the efficiency of human robot cooperation with augmented reality system. They cover the system performance, usability, and the values for specific task. The system performance test presents the robot’s repeatability and the system’s ability of updating graphics on the display. The system usability test shows the user’s satisfaction level after using this system. The last experimental set is to find the values for specific task which are related to ability of assisting the operator in the proposed operation.

A. System Performance

The first test of system performance is to evaluate the robot’s repeatability. There are at least 6 targeted positions in robot workspace that are tested for robot’s repeatability evaluation in both x and y axes.

Table I shows that the averaged repeatability errors are 0.52 and 0.35 millimetres in x and y axes, respectively. In addition, the system’s ability in updating graphics is about 17 fps with the image resolution of 640 x 480 pixels. The system can track the targeted markers which are moved with velocity less than 10 centimetres/second.

TABLE I MEAN VALUES OF ROBOT’S REPEATABILITY AT 6 POSITIONS

Position	Mean Values of Robot’s Repeatability at 6 Positions	
	X(cm)	Y(cm)
1	0.06	0.018
2	0.042	0
3	0.042	0.032
4	0.04	0.09
5	0.067	0.054
6	0.07	0.018

B. Usability

The user’s satisfaction on system’s usability is collected by questionnaire after using this system to do virtual assembly task as shown in Fig. 17. The system results are also used to identify some interested points need to be improved in the future.

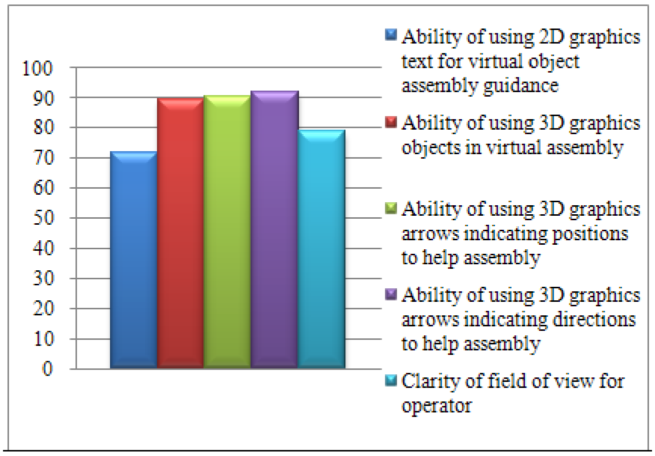


Fig. 17 Satisfaction of System’s Usability

The results indicate that most of users are satisfied with the purposed system’s usability. The ability of using 3D graphics arrows indicating direction of virtual object in assembly task helps the user to understand the virtual object’s correct direction better. Therefore, the usability of 3D graphics arrows indicating virtual object’s direction obtained the highest satisfaction score with 92 percent. During virtual assembly, most users did not pay much attention to the suggestion texts. As the result, the ability of using 2D graphics text for virtual object assembly guidance got the lowest satisfaction score with 74 percent.

C. Values for Specific Task

This proposed human-robot cooperation system is applied in virtual object assembly task. It should give high values for specific task which is to reduce the operation’s time and provide the ease for virtual assembly with augmented information and the robot’s assistance. In virtual assembly task, the users are asked to assemble the virtual objects as shown in the given picture in instruction sheet. The assembly experiments can be divided into 3 types which are assembly with/without any system's information and assembly with system's information along with robot's assistance. In all experiments, the tasks are not easy for the users who do not have enough skills in complicated 3D graphics assembly. Therefore, it is very difficult to assemble virtual objects without any system's information and it took the most averaged assembly time at 182 seconds. With the system's graphics guidance information, the operation time is reduced to 64 seconds or 35.16 percent of assembly time obtained from system without graphics guidance information. The averaged assembly time is about 144 seconds or 79.12 percent of assembly time obtained from system without graphics guidance information when assembly with system's guidance and robot's assistance. However, this operation time also depends on robot's speed. The questionnaire is used to collect the user's satisfaction after this experiment.

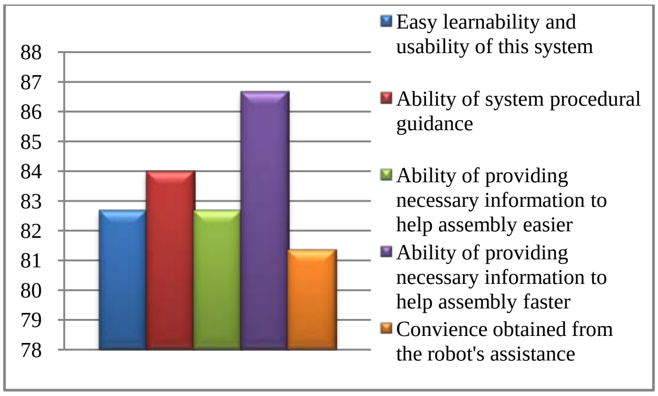


Fig. 18 Satisfaction of System Value for Specific Task

The results in Fig.18 show that the ability of providing necessary information to accelerate assembly obtains the highest satisfaction score with 87 percent. The easy learnability, ability of system procedural guidance, and ability of providing necessary information to help assembly easier got 82.67 84.0 and 82.67 percents, respectively. Because of working with human operator, the robot's operation speed is set at the low speed. A few users were not satisfied with this operation's speed so the satisfaction of convenience obtained from the robot's assistance got the lowest score with 81.33 percent.

IV. CONCLUSIONS AND FUTURE WORKS

The human-robot cooperation in virtual assembly using augmented reality system was presented. The system was developed by taking the advantage of augmented reality technique to generate computer graphics information and superimpose them on the real video image. This unique virtual object assembly system presents the cooperation between human operator and robot arm in the common workspace. The virtual object, graphics symbols, and text information, which are in the form of 3D and 2D computer graphics, are presented to the human operator through LCD screen display. The virtual object assembly task plan is generated for controlling the system's operation. The user interface is developed by using augmented reality technique. The experimental results indicate that the system's assistance using augmented reality and the robot can reduce the operation time and mostly users were satisfied with the system usability and values for specifics task of this proposed system. The virtual objects can be changed into various object models by importing them from any CAD applications. This proposed augmented reality in the virtual assembly task will lead to save cost and training time since the users gain more understanding of the virtual assembly task when the system presents the graphics guidance.

There are several issues that can be developed to improve the system performance and usability. Since the graphics texts information does not get much attention, the augmented guidance information should be graphic symbols instead of texts. The operating time of human-robot cooperation can be reduced by speeding up the robot's movement. However, the change of robot's speed should be considered along with the human's safety. For more natural communication, the interaction between human and robot can be improved by using gesture or speech recognition.

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