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Dismantling Interior Facilities in Buildings by Human Robot Collaboration

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Abstract— **New robotic systems will be playing an essential role in the future dismantling service for renewing office interiors facilities in buildings. In our study, the dismantling task would be achieved by proper collaboration between human workers and robots utilizing mobile arms, interface devices and software. This paper describes an overview of the proposed dismantling system as well as its requirements. The real experiments presented are focused on the disassembling task of a ceiling lamp panel (LP). In the disassembling task, a robot arm collaborates with the human worker holding the LP, accomplishing an assisting function. At first, in order to approach the robot to the holding position, the worker controls the robot using interface devices which are also evaluated in their usability aspect. Then, a laser pointer fixed at the robot's tip is used both as a guidance in the teleoperation process and as a first indicator of the holding position. As a second step toward the target, the control program applies model-based 3D object recognition techniques to calculate the final position. At this stage the information of an stereo camera, configured as an eye-in-hand system, is necessary. On the last part of the task, the robot reaches the estimated position automatically by using the results of its kinematic analysis. The experimental results show the effectiveness of the proposed methodology.**

Index Terms — dismantling, human robot collaboration, lamp panel, user interface, vision

I. Introduction

A large business market is expected in renewing building construction. In 1998 it was estimated that the service for dismantling office interiors for renovation would represent a business of around ¥5.5 trillion. In the current dismantling service most works are done by human manual operations, typically so-called "3K" works (*kitsui*, *kitanai*, *kiken*), that is, "tough", "dirty", and "dangerous". This kind of job demands a great physical effort and the worker's load carrying capacity decreases with age [1]. In addition, the number of workers will be decreasing drastically in Japan, so the construction industry will suffer serious shortage of labor power. The automation applying RT (robotics technology) is a requisite for solving the problem.

The Ministry of Economy, Trade, and Industry (METI) started a NEDO strategic project on robotics key technology development in 2006. Our group is studying and developing a dismantling robotic system applied to the renewal building office interiors as one of the above mentioned project themes. The final goal is to systematize disassembly, to segregate disposal tasks, and to reduce total wastes in dismantling service. As a result, the system contributes to improve efficiency, productivity, and safety for both workers and environment in the coming aging society. Our short term goal is to develop collaboration between robots and human workers on disassembling ceiling materials including air conditioners and lighting appliances (See Fig. 1).

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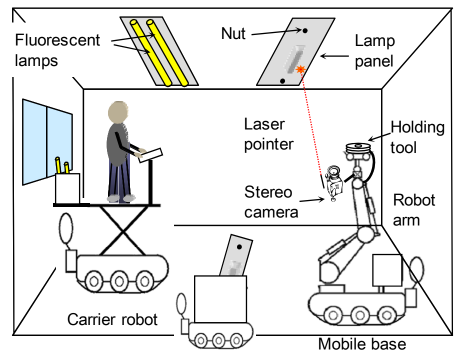


Fig. 1. Concept for the lamp panel disassembling task. The robot is configured in an assisting mode.

Many robots have been applied in building and construction automation [2], [3], as well as intelligent systems to detect defects during the construction [4]. The number of robotic applications on dismantling and disassembling tasks are rather limited as just seen in hazardous nuclear decommissioning tasks [5], software for the generation of disassembly sequences [6], and disassembly stations for used cars [7]. The dismantling of office interiors is a challenging trial for RT application. The office interiors mainly consist of wall, ceiling, floor, lighting and air conditioning appliances.

Currently all facilities are dismantled by workers manually. For example, let us look at ceiling dismantling. First, all appliances are removed carefully. Then workers break and remove ceiling panels by using a simple tool, a long rod with sharp hook on its end. Pieces of broken panel are scattered on floor, and workers must collect all of them. The dismantling process takes only a small time, however, the collection of pieces wastes so much time. Thus the segregation is not a simple task. Fig. 2 shows an example of the mentioned dismantling task.

Fig. 2. Current conditions in the works for dismantling offices.

The objects in the ceiling side are the toughest to be dismantled because workers have to do those tasks repeatedly and against the influence of gravity. In our project, it is planned to engage elderly people, citizens who have physical handicap, and women in the dismantling service. Thus, we have to avoid the repetitive tasks for them and ensure their safety. Both points can be achieved by using remote operations instead of systems where the human worker and the robot operate a shared workpiece.

The proposed system for the disassembling process of the ceiling LPs includes a robot arm which assists the human worker holding them (See Fig. 1). Thus, he/she will do effortless work such as remove nuts. Our goal is to teach the robot arm the holding position easily, because these workers are new to controlling a robotic system, and remotely in order to keep them safe. To achieve the goal, the worker can control the robot using an interface device; to choose the proper one for our dismantling system, a fundamental evaluation is carried out considering the teleoperation of the robot by human workers of various ages. Additionally, a vision sensor calculates the 3D position of a laser spot which is considered a target in the first approach for the holding task, both the vision sensor and the laser pointer are attached on the robot arm. After this stage, the control system applies model-based 3D object recognition functions to detect some characteristics of the central part of the LP. The recognition process fails in some occasions due to illumination conditions. For the solution of this problem, the system changes several times the view point of the robot. Moreover, a lighting system contributes to extract more characteristics of the LP.

In the final phase, the robot arm reaches automatically the final holding position decided by the control system which applies the results of the related kinematic analysis.

In this paper, the objectives to be discussed are the system concept, its requirements, the current integration, and the disassembling task of a LP. Thus, Section II presents the general idea of the proposed system. The analysis of the dismantling system integration is explained in section III. The LP disassembling task is detailed in Section IV. Section V describes the related experiment and its results. The conclusion and future work are summarized in section VI.

II. The Proposed System: An Overview

A. Items to Be Dismantled

In this project, the items to be dismantled are assumed to be: the ceiling boards and both lighting and air conditioning appliances. Each disassembly method is roughly as follows:

1) Lamp panel (LP): After the operator removes the fluorescent lamps by hand, the panel is held by the robot arm and when the operator removes the nuts manually, the arm transports the LP to a carrier robot.

2) Air conditioning device: it is removed following a procedure similar to the one required for removing the LP.

3) Ceiling boards and their related screws: After an operation plan by remote instruction, at first the ceiling boards dismantling task is accomplished by cutting and then pulling the remains by the arm. The cutting rubbish is vacuumed as much as possible and the arm transports the pieces of broken panel to a robot carrier. Concerning the screws that hold the ceiling boards to the metal ceiling structure, their position could be detected with a sensor and aiming to detach them by the arm. In the renewal process, the ceiling structure will be reused, so that we need to remove the screws carefully without damaging the structure.

B. Procedure of the Cooperative Task.

Since the dismantling task with collaboration between human and robots may bring some risks to human workers, a full automated robot is a safer alternative. Even though it is possible to achieve both effectiveness and operability in the case where a human worker and a robot share the workpiece [8] this way of assistance demands a high level of safety [9]. By using the remote operation of the robot the dismantling task becomes more secure. Thus, elderly people, citizens who have physical handicap, and women can be engaged in this kind of job.

The following two modes are examined about the ideal method of cooperation between man and robot in a dismantling task.

1) Assisting mode

The dismantling of the equipment is the target and the person's work is supported by the robot (holding and collection). Since it is difficult for the worker to detach the LP and air conditioning facilities alone because of their large size and weight, it would be desirable that the robot holds the equipment while the worker does only effortless work such as removing nuts.

2) Semi-autonomous mode

In the ceiling dismantling process, once the starting position is given, the robot can work automatically. This means that the operator gives the robot a rough instruction (instruction of the initial position and instruction of the dismantling operation). Afterwards the robot generates automatically the dismantling operation according to a task plan.

C. Task Development

In order to cooperate effectively and accurately, the operations are designed for both the person's advanced judgments and the robot's power. An efficient dismantling system and the procedure for executing such a task based on a dismantling work plan are being developed as follows:

1) Control of the arm for the dismantling work

A 4-dof micro-shovel machine is being remodeled and it will be utilized to do the dismantling work. The control of the robot arm is being developed using visual feedback information; thus, the movements to a target position for holding, cutting, etc. can be achieved.

2) Human interface

An interface designed to work remotely and safely while watching a monitor outside of the dismantling site, is being developed. By using the interface the human operator will be able, among others, to select and follow the dismantling task in an intuitively way [10]. Furthermore, it is required to examine the remote control method of the system that is appropriate for the dismantling work with operations that combine devices such as keyboard, track ball, and PDA, etc. and evaluate its usability.

3) Construction of a data base for the dismantling tasks

A data base is under development. It provides the robot with the required operating instructions and information for the dismantling task, based on the worker's judgment and the information provided by the sensors. For instance, before the ceiling board is dismantled, information on the board-cutting position, cutting shape and cutting path must be prepared. These data are inserted in the robot's operation plan.

III. Dismantling System Integration

The architecture of the dismantling system is illustrated in Fig. 3. It is composed of a robot arm, a vision sensor, a laser pointer, and interface devices. These are connected to the PC which controls the dismantling task including the user interface.

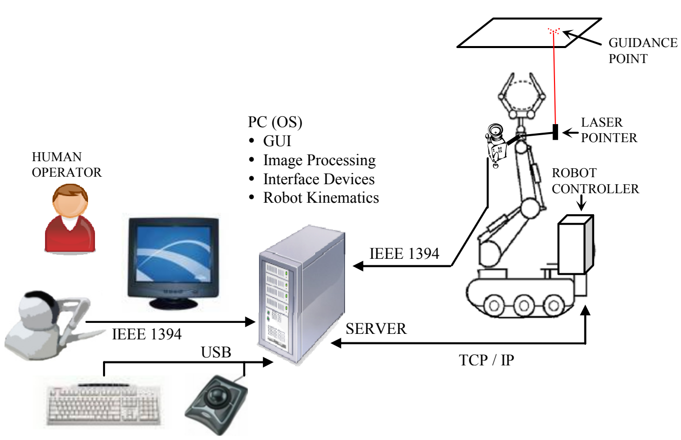


Fig. 3. System architecture.

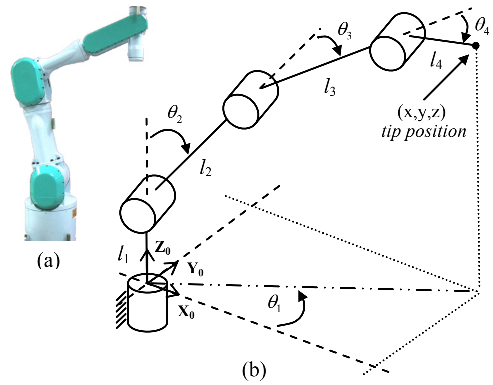


Fig. 4. a) An industrial robot PA-10 (Mitsubishi Heavy Industries, Ltd.) is used in the experiments. b) Scheme to analyze the kinematics of the robot arm.

A. Analysis of the Robot Arm

An experimental robot arm simulates a 4-dof micro-shovel with revolute joints. The well known configuration of a typical shovel machine is composed of a first joint with rotational motion around the Z_0 axis, in the base frame, and the other joints form a planar manipulator perpendicular to the $X_0 Y_0$ plane. With reference to Fig. 4, the basic equations of the forward kinematics are given as follows:

$$\begin{aligned} x &= c_1\left(l_2 s_2 + l_3 s_{2+3} + l_4 s_{2+3+4}\right) \\ y &= s_1\left(l_2 s_2 + l_3 s_{2+3} + l_4 s_{2+3+4}\right) \\ z &= l_1 + l_2 c_2 + l_3 c_{2+3} + l_4 c_{2+3+4} \ , \end{aligned} \qquad (1)$$

where $c_i = \cos\theta_i$, $s_i = \sin\theta_i$, l_j is the longitude of the *j*-th related link, and $(\theta_2 + \theta_3 + \theta_4)$ is the orientation angle of the robot's tip frame with reference to Z_0 axis. Besides, (1) can be solved for each θ_k; $k = 1 \ldots 4$, for an analytical solution of the inverse kinematics problem.

B. Evaluation of Interface Devices

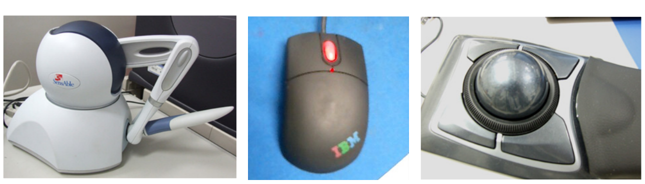
Usability of robot arm has been evaluated in previous works [11], [12], [13]. The usability evaluation of human interface devices is important especially for the development of robot systems which will be used and operated by various people, in some cases, with different physical limitations.

In this section, usability of human interface devices is evaluated considering the teleoperation of robot for human workers of various ages. The devices are different in the mechanisms and input methods. Human interface is expected to be simple and easy to use for various aged people.

A questionnaire for the participants whose age is distributed between 18 and 74 years old (average age of 52 years) is used to evaluate the usability of the devices. The questionnaire is prepared as subjective evaluation. On the other hand, accuracy of operation is measured as objective evaluation of usability.

We evaluate the usability of the three devices depicted in Fig. 5. Twelve people including young, elderly, male, female people used the devices in an experimental system for this evaluation. Particularly for this evaluation, the purpose of the task was to lead the light of a laser pointer, fixed at the robot arm, on a visual mark, cross pattern as a target. The mark is attached to a model ceiling in order to evaluate the positioning accuracy of the end effector of the arm. The light beam direction of the laser pointer is identical to the optical axis of an stereo camera also mounted on the robot. A target position is indicated by the laser pointer. We develop a system where a target object of disassembling tasks is indicated by the laser pointer. A human worker operates the laser pointer only in a two dimensional space because ceilings are assumed to be parallel to the floor. For the interface devices, magnification ratio of the motion range is changed by software program. We use two speed levels, fast and slow, in the experiments. Vibration by human hand motion is filtered and suppressed using a software process, in order to move the robot arm smoothly.

The subjects operate the interface devices while watching the ceiling directly by their eyes to utilize the merits of the three dimensional input device. The laser pointer is moved by the robot arm. When the target is in the field of view of the eye-in-hand camera, the subject follows the spot motion in the input image from the camera displayed on a monitor. Once this spot comes to the target position, the subject pushes a key. Then, the three dimensional position of the target position is measured by the stereo camera and the end effector is moved to the indicated target position automatically using the inverse kinematics of the robot arm. With the mouse device (Fig. 5 (b)), contrasting with the others cases, the participants select directly the target on the monitor image by clicking a mouse button. The operation devices are randomly experienced by each subject. Usage of devices is explained before experiments. One minute of preliminary practice experiment is given to each subject for each device in order to get accustomed to its use. In the questionnaire, there are four items to evaluate (Table I): simple, boring, familiar, and intuitive. On the other hand, the operation time required to place the end effector and the positioning accuracy are measured, for the objective evaluation (Table II). The initial position of the robot arm is the same for each operation device.



(a) (b) (c)

Fig. 5. Some commercial interface devices. (a) Left: a phantom-omni. (b) Center: a mouse. (c) Right: a track ball.

TABLE I
AVERAGE OF THE SUBJECTIVE RESULTS

Device	Simple	Boring	Familiar	Intuitive
phantom-omni	6.3	4.1	6.5	5.4
mouse	2.9	3.8	3.1	3.6
track ball	3.1	3.3	5.1	3.9

Evaluation by questionnaire, where: (high) 1 • 2 … 9 • 10 (low)

TABLE II
AVERAGE OF THE OBJECTIVE RESULTS

Device	Time [sec]	SD	‖Error‖[a] [mm]	SD
phantom-omni	82.4	38.40	5.8	2.87
mouse	66.1	38.69	3.3	2.77
track ball	50.0	16.73	3.0	1.74

[a] The actual position of the target was measured beforehand with reference to the robot's base frame.

Table I shows the subjective evaluation results. It shows that a mouse and a trackball are easier for positioning a target, and their usage is easy to understand for subjects. An opinion was given by a subject that the operation of omni-device is more interesting than the other devices. Subject's interest in device usage may improve the total operation time and positioning accuracy after practicing.

Table II shows the objective evaluation results. The total operation time required for positioning the end effector with the trackball is shorter than the one required for the mouse and the omni device. The average error and the standard deviation with trackball are the minimum of the three. Thus, a trackball is the most suitable device for subjects of various ages and genders, to operate the robot arm.

C. Vision Sensor and Unstructured Laser Light

1) Camera

With an eye-in-hand configuration, an stereo vision camera is attached to the robot arm in its fourth link (See Fig. 6). In an interface monitor, the visual information is provided to the human operator, thus he/she can select the appropriated dismantling task. Additionally, the vision sensor calculates the 3D position of the spot irradiated by a laser pointer; this is carried out in the rough-positioning stage of the robot arm to hold the LP for its disassembling task.

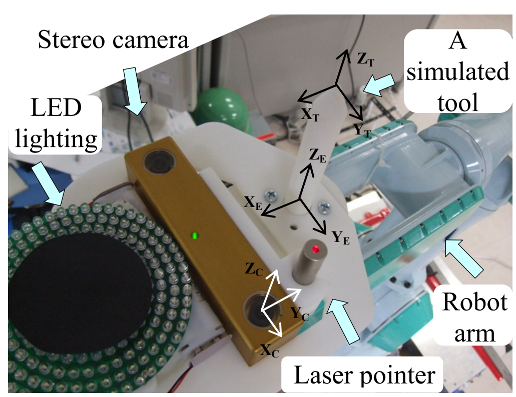


Fig. 6. Coordinate frames in the robot arm and devices attached to its tip.

Several images are also required when the control program applies techniques of model-based 3D object recognition, to find a final holding position. For the camera calibration process, the extrinsic parameters are calculated by firmly fixing the camera to the robot. The intrinsic ones are assumed to be constant.

2) Laser pointer

Laser pointers have been used in several robotic applications. In [14], a manually driven laser pointer is used by a human operator in order to lead a mobile robot to an object. Concerning to underwater vehicles, the use of laser pointers has shown better results in sensing and navigation processes rather than using acoustic measurements systems [15]. For positioning tasks of industrial robots, laser spots are projected over a workpiece in order to gather information about the workpiece geometry using a multi-camera system [16].

In our system for dismantling, a laser pointer is fixed parallel to the optical axis of the camera, at the tip of the robot arm. Since the camera's field of view is limited and it can change drastically in an eye-in-hand configuration, for the human operator is difficult to find a desired target by only watching the interface monitor in a teleoperation process. Thus the laser pointer is useful as a visual guidance at the time of looking for the LP. Once the LP is in the camera's field of view, the operator can follow the laser-spot motion in the monitor interface and place it approximately at the central area of the panel. The position of the irradiated spot is measured using the stereo camera and is assumed to be the target in the first approach of the robot arm for a holding positioning in the LP disassembling task.

D. Model-Based 3D Object Recognition

The 3D vision system called *Versatile Volumetric Vision (VVV)* Tomita *et al*. [17], and its integration in Sumi *et al*. [18], has been adopted in our application in order to find particular areas in the objects to be dismantled, in this case the central part of a LP.

A brief explanation of the object recognition method mentioned above could be as follows: it identifies a desired object, with a CAD model in a database, and determines its position-orientation related to the camera's frame. The method recovers 3D boundaries and vertices from an stereo image, selects candidates for the object position according to the alignment of the boundary features, and verifies and improves each candidate by iterative closest point registration.

The recognition method can deal with any shape objects, partially occluded by other objects and in cluttered environments. Also, the application provides a confidence value in the matching process. This value is calculated as

$$C_m = \widetilde{N}_m / N_m \;, \tag{2}$$

where $\widetilde{N}_m$ is the number of model points with correspondences, and N_m is the total of model points. Defining a threshold, the confidence value indicates if the system fails to identify an object. For further information about this application please refer [17], [18].

Concerning our application, the real dismantling sites are only illuminated by the day lighting. As a result of illumination changes, the features extraction process sometimes is poor and consequently the recognition method fails. For the solution of this problem, the control system changes the view point of the robot arm several times. Moreover, a lighting system near of the vision camera contributes to extract more characteristics of the LP. With this method, a set of confidence values can be generated and then calculate the final holding position considering only the best results.

IV. Ceiling Lamp Panel Disassembling Task

A. Assembling Sequence

Before starting with the explanation of the disassembling task, let us check briefly the assembling sequence of a typical LP. In a collaborative work, two electricians start installing the LP doing the necessary power line connections. After that, they use a few nuts to fix the LP to the ceiling. In the final stage, the fluorescent lamps are installed together with a metallic layer along the central part of the LP. In some other situations, more items are installed just for decorative purposes.

B. Disassembling Strategy

The disassembling strategy requires that the robot holds the equipment while the worker performs only reduced effort work such as removing nuts.

In this project, the disassembling sequence is the inverse of the assembling one. According to Fig. 1, the disassembling sequence starts when the operator manually removes the fluorescent lamps, the metallic layer, and possibly the decorative items. Then, using interface devices and the laser guidance, the operator can control easily the position and orientation of the robot arm. Thus, the operator can find the LP and ensure that it is in the camera's field of view.

The method used by the operator in order to teach the holding position to the robot consists of directing the laser beam to an approximate location near the central area of the LP using a GUI, then he/she commands the robot to approach to this temporary target. An advantage of this strategy is that the robot can be initially a few meters of the target because this first approach means that the solution is *around there*. A fixed distance from the current target is applied to avoid the robot reaching it completely, since the robot's position is essential in the second part of the automatic positioning. After this stage, the control program changes the position-orientation of the robot arm to take images in several view points and applies techniques of pattern matching recognition in each case. In the matched geometry, a second and final target is assigned and it is where the robot takes its end-effector automatically. While the robot is holding the LP, the operator removes the nuts that hold the panel to the ceiling and also he/she cuts some of the power cables. In the final stage, the operator commands the robot to put the dismounted panel in the carrier robot.

With this scenario, the human worker teaches the robot the holding position easily, only an initial position is required and the control system completes the next processes.

V. Experimental results

An industrial robot PA-10 (Mitsubishi Heavy Industries, Ltd.) simulates the real robot for the dismantling tasks. In the operation control system, four of its seven available axes are used to obtain the configuration of a typical shovel machine (s1= θ_1 , s2= θ_2 , s3=0, e1= θ_3 , e2=0, w1= θ_4 , w2=0. Where s: shoulder, e: elbow, w: wrist.) A trackball interface device controls the robot's motion in order to locate the LP in the camera's field of view. In the teleoperation process, a laser pointer (1 [mW] and 650 [nm] length wave) generates a visual guidance for the human operator. After that, the laser spot can be followed in a monitor interface and can be directed around the central area of the LP. Thus, the operator commands the robot to an approximate holding position. In the experiments presented herein, the initial position of the robot is around 1[m] from the LP, because robot's workspace limitations and a mobile base is not considered this time.

To achieve the temporary phase, the control program takes several images using the vision sensor (Point Grey Research, Inc. BumbleBee2 camera with a resolution of 640x480 pixels RGB). Then, through image processing, the centroid of the bright red spot in camera-space can be calculated. The techniques for image-analysis consist of red color and brightness segmentation. At first, the RGB data of the images are encoded into YUV space (Y brightness, U and V color information). Thus, some of the information can be discarded easier than in a RGB space. Defining threshold values in the YUV space, the bright and red area can be located; the thresholds values were defined experimentally by projecting the laser spot over several surfaces in the ceiling side. Additionally, edge detection and searching the center of an elliptical region are carried out.

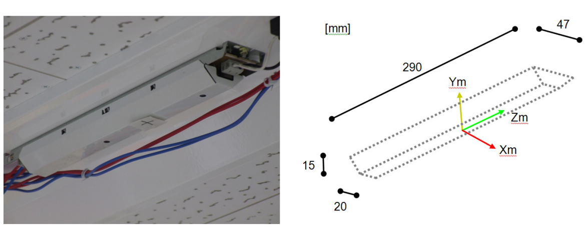


Fig. 7. Central part of the lamp panel and its CAD model.

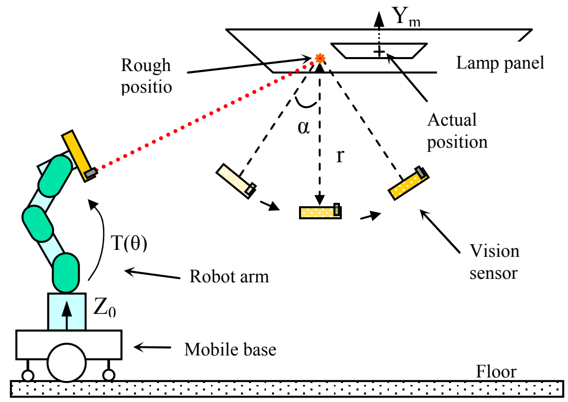
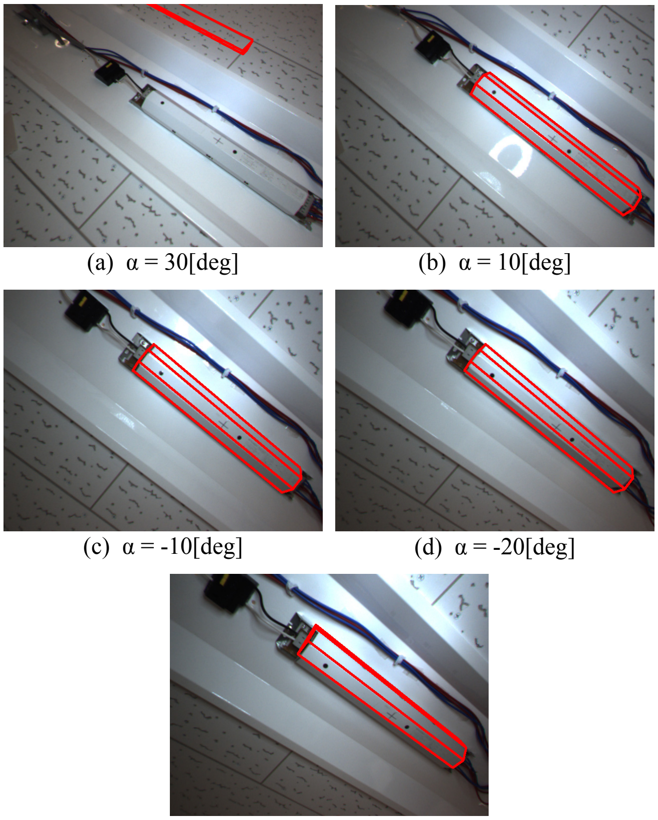


Fig. 8. Modifying the view point in the recognition process.

Some of the mentioned techniques are achieved using the Open Source Computer Vision library (*OpenCV*) [22] from Intel Inc. Afterward, by applying some algorithms of the Point Grey Triclops library [23], the stereo vision system calculates the physical position of that temporary target including a fixed shift. The resultant position is reached by the robot using its inverse kinematics function. The fixed shift is to ensure that the vision system can capture some required characteristics of the LP. Thus, the control program applies functions contained on the *VVV* library [24] for the recognition of the model depicted in Fig. 7. To solve the problem of illumination changes in a real dismantling site, the process is carried out for 7 view points by changing the position-orientation of the robot arm in a semi-circular trajectory under the target, as shown in Fig. 8. The parameter r was set experimentally at 400 [mm] and the limit values of α were set at ±30[deg]. If the last value increases, the number of detected edges will be reduced, which in turn affects the possibility of successful object recognition. Sometimes the recognition process fails in the defined interval because the amount of illumination was not enough in those positions.

During the recognition process, an illumination system based in LED technology is turned on; the purpose is to improve the feature extraction and, as a consequence, the confidence value defined in (2) will increase too. Fig. 9 depicts the results using the recognition method. Fig. 9(a) shows an example when the recognition process calculates the pose of the target far from the actual solution. Nevertheless, the confidence value for those cases is always low. For instance, less than 0.2 when the point of view is 30[deg] (Fig. 10).

In each recognition process, the *VVV* application generates q candidates depending mainly of the features extraction. The position-orientation of every candidate with reference to the camera's frame can be determined using the *VVV* library [24]. The final holding position is calculated by applying a hierarchical selection using the information of every candidate in the 7 view points. The first criterion is defined by a threshold in the confidence value, this threshold was set experimentally at 0.3 and it can be adjusted. In Fig. 10 the confidence values for this experiment are shown.



(a) α = 30[deg] (b) α = 10[deg]

(c) α = -10[deg] (d) α = -20[deg]

(e) α = -30[deg]

Fig. 9. Visual results of the candidates with higher confidence in each recognition process. In the case of α = 20[deg] and α = 0[deg], the application did not generate any candidate.

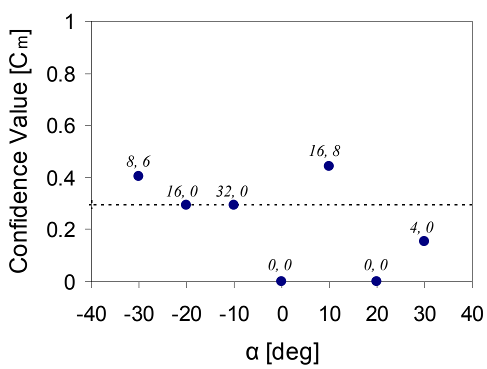


Fig. 10. Highest confidence value in each view point. The dotted line specifies the threshold. The pair *m*, *n* above of the graphed points, *m* denotes the number of candidates generated and *n* indicates those above the threshold.

Since sometimes there are results with high confidence value but their pose in the visual results is not correct, the next criterion is in function of the model orientation. With reference to Fig. 8, we can assume that the Z_0 axis in the robot's base is parallel to the Y_m axis in the model's panel. In an ideal situation the angle between these axes is 0 [deg]; hence, a second threshold is defined as the angle of those axes by $\beta = \arccos(Y_{mz})$, where Y_{mz} is the Y component of the model's panel projected on the Z_0 axis and β was decided to be less than 20[deg] for the estimated poses.

With these criteria, the information of the selected candidates is listed in the next 2 tables.

TABLE III
ESTIMATION OF THE POSITION

Candidate [a]	*Cm* [b]	Position [mm]			‖Error‖
		x	*y*	*z*	[mm]
(10, 1)	0.44	378.15	19.24	1148.37	9.85
(10, 2)	0.44	378.15	19.24	1148.37	9.85
(10, 3)	0.41	377.30	19.16	1148.62	9.80
(10, 4)	0.41	377.30	19.16	1148.62	9.80
(-30, 3)	0.39	382.18	10.65	1154.92	4.30
(-30, 4)	0.39	382.18	10.65	1154.92	4.30
Estimated Position		379.21	16.35	1150.63	6.37

[a] (View point [deg], Candidate number)
[b] Confidence value

TABLE IV
ESTIMATION OF THE ORIENTATION

Candidate [a]	*Cm* [b]	Orientation [deg]			‖Error‖ [deg]		
		roll	*pitch*	*yaw*	*roll*	*pitch*	*yaw*
(10, 1)	0.44	90.80	-3.77	37.96	1.51	0.09	2.13
(10, 2)	0.44	89.20	-3.77	37.96	0.09	0.09	2.13
(10, 3)	0.41	90.45	-0.49	38.34	1.16	3.37	2.51
(10, 4)	0.41	89.55	-0.49	38.34	0.26	3.37	2.51
(-30, 3)	0.39	89.52	-0.25	38.61	0.23	3.61	2.78
(-30, 4)	0.39	90.48	-0.25	38.61	1.19	3.61	2.78
Estimated Orientation		90.00	-1.50	38.30	0.71	2.36	2.47

[a] (View point [deg], Candidate number)
[b] Confidence value

Both tables include the magnitude errors referred to the actual pose of the target which was measured by an off-line positioning process of the simulated tool on the robot in 4 points of the LP's geometry. Table III refers to the estimated positions, where the actual position of the target for this experiment was: x = 380.0[mm], y = 14.0[mm], and z = 1156.5[mm]. Regarding the orientation, Table IV lists the estimated *roll-pitch-yaw* angles. These angles for the actual pose were: 89.29[deg], -3.86[deg], and 35.83[deg].

Using the selected candidates, the final pose of the target was calculated considering the average of associated data. Thus applying the related inverse kinematics solution, the robot arm approaches automatically its end effector to the final target in the LP as in Fig. 11, for the cooperative task.

In the situation as described above, 30 experiments were carried out. The average error in the positioning of the tip of the simulated tool, with respect to the actual position of the target on the LP, was 21.5 [mm] with an standard deviation of 12.7 [mm].

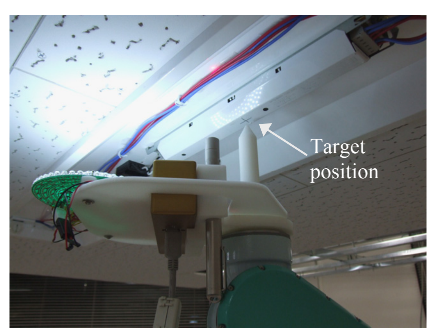


Fig. 11. The final estimated position is reached automatically by the arm.

VI. CONCLUSION AND FUTURE WORK

A robotic system has been proposed to assist the workers engaged in the area of dismantling office interiors. The outline and the research program of the dismantling robotic system were described. The kinematics analysis of the robot arm for dismantling was carried out as well as a fundamental evaluation of interface devices where the results show that the track ball is the most suitable device to operate de robot arm. The real experiments presented were about the cooperative work between the human operator and the robotic system to achieve the disassembling task of a ceiling lamp panel.

With the proposed methodology, the operator can teach the robot a holding position easily using a laser pointer, a user interface, and the interface devices. The control program applies image processing functions and matching recognition, in several view points, to achieve the task. The estimation of the final pose for holding shows satisfactory results since a high level of precision is not required in the LP disassembling application.

Additionally, in order to complete the LP disassembling task, an end-effector with suction technology is under development. One characteristic of the tool will be the flexibility, thus ensuring a good fitting in the holding task.

About the proposed disassembling sequence, in its last stage, the operator is close to the robot arm when it holds the LP. Thus, we have to consider a sophisticated system for safety.

Finally, although only one panel had been studied, the proposed method can be applied to other kind of panels since a database can be used to storage the CAD models information. Moreover, radio-frequency identification (RFID) tags can be attached to the LP at the beginning of its disassembling task. Thus, the robotic system will be able to recognize the LP type.

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