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学 位 論 文 名	VISION-BASED ROBOT SYSTEM FOR UNSTRUCTURED ENVIRONMENTS （非構造化環境のための視覚に基づくロボットシステム）
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論文内容の要旨

SYNOPSIS OF THESIS

This thesis addresses the introduction of a vision-based robot system for unstructured environments which can be applied in the dismantling service for interior renewal of buildings. The objective is to remove ceiling materials by human workers and robots. The robotic system consists of a stereo vision sensor mounted on the tip of a robot arm, illumination devices, and a human interface. The purposes of including vision are both detecting the objects to be removed and measuring their 3D pose (position-orientation).

Working in unstructured environments such as construction sites, vision-based object recognition is difficult since the pose of the object is variable into the environment. Furthermore, the lighting conditions are neither stable nor controllable. Moreover, there is need of recognizing very small objects. These are very critical issues for vision systems in practical applications. In building dismantling tasks, these problems have not been solved yet. Thus, the goals addressed in this thesis are to recognize the objects, including very small ones, robustly and precisely when working in unstructured environments. The proposed methodologies to achieve the goals are based on the combination of several computer vision techniques. Such methodologies are described next.

Regarding object recognition in unstructured environments. First by using the interface, human teaches a rough position on the object to the robot in order to lead it to the target. Next, the robot computes automatically the object pose by using multiple recognition results from multiple view-points of the robot and artificial lighting changes (the proposal is needed since conventional recognition methods often fail in this type of environments). The lighting is actively changed by LED arrays mounted around the vision sensor, the view-points are generated by robot kinematics, and the multiple recognition results are integrated by using the weighted average of all recognitions. Feasible parameters for robot pose and active lighting are derived from experimental analysis. The assumption in this methodology is the use of a 3D model-based object recognition method as a recognition module –single recognition–, it means that the proposed methodology can be applied using any other model-based object recognition. As a target application, the methodology is tested in an actual dismantling environment where human and robot collaborate for removing several ceiling appliances. In the collaboration, the robot arm achieves the assisting function of holding and collecting the appliances, and human only removes nuts/screws easily. The appliances are recognized in the fashion aforementioned. And after an appliance is recognized, the robot is able to manipulate it. Experimental results show a robust recognition with enough accuracy for the application.

Concerning recognition of small objects in unstructured environments. The proposed methodology consists in the application of

hierarchical recognition where large objects are recognized at first, and the small objects attached to these are recognized next. The methodology for recognizing the small objects in the input images consists in the use of multi-template matching to detect candidates of the small objects. Followed by, the Support Vector Machine, a kernel-based learning machine, which classifies the candidates with a better performance. In order to increase the robustness in the recognition, the detected small objects are tracked by using a temporal multi-image integration. Those small objects detected out of a region of interest of the large object, are not considered by the next processes. The 3D position of the targets is computed by detecting the same pattern in both images from the stereo camera (right and left). The use of an LED lighting array, mounted on the robot, contributes to a better recognition. As a target application, the methodology is tested in the recognition –for removing– of the screws (small objects) that once held the ceiling boards to the ceiling structure (large object), with the purpose of reusing it. The human only gives the starting position to the robot. Afterwards, the 3D pose of the ceiling structure is computed. Subsequently, the robot can approach to this structure and look for the screws. The detection of the large structure is based on a process of straight segments detection and the screws are recognized in the fashion mentioned above. In the experiments, the actual screws are successfully recognized with the minimum of false recognitions. All the methods together are capable of recognizing –robustly and precisely– the small objects at different lighting conditions, which makes feasible the application of the proposed methodology in an actual dismantling site.

Finally for the implementation of the proposed methodologies, the analysis of all the components –vision sensor, robot arm, interface, etc.– is required in order to have a suitable integration as whole prototype system. Calibration methods for vision sensor and robot arm are conducted. Robot kinematics is analyzed as well as path planning. The end-effector for holding and carrying different types of appliances is designed and built. And all the algorithms required by the proposed methodologies are grouped in a computer program with a friendly interface which requires only brief and simple commands.

SYNOPSIS OF EVALUATION RESULTS

Some parts of the thesis have been improved in base of evaluation results. These are described next together with an explanation of what changes were made:

1. Dismantling Scenario (Chapter 2, section 2.2). Since the research presented in the thesis is part of a whole project, clarification of the tasks conducted by our research team is needed.
   Answer: the tasks conducted by every research team have been clarified through section 2.2. More references to the work of the other research teams were included in the text and figures as well. A special labeling for listing all the tasks was used for a better understanding. Figure 2.1 also includes this labeling in order to see the distribution of the tasks. Moreover the phrases containing the terms *we* and *our* were rewritten to avoid confusion in understanding the tasks conducted for each research group.
2. Human-robot collaboration (Chapter 2, section 2.3). Two modes of collaboration are described in the thesis, but the level of human-robot interaction in collaboration is unclear.
   Answer: the section dedicated to the human-robot collaboration has been rewritten in its entirely. First, the methods of control of robots are described. Next, some types of human-robot collaboration are explained. In base of both, the level of human-robot interaction is analyzed for the two modes of collaboration described in the thesis. In the so-called assisting mode, since the workspaces of human and robot overlap, the interaction is considered of middle level. And in the semi-autonomous mode, the workspaces of human and robot are different, thus the human-robot interaction level is low.
3. Object recognition (Chapter 3, section 3.3). For the first challenge cited in the thesis, a 3D model-based object recognition was adopted to estimate a 3D pose of the appliances. It is claimed that the recognition by using the mentioned method has been improved, however, it is unclear which parts of the recognition method were modified.
   Answer: the vision-based recognition aforementioned often fails depending on both the illumination conditions and the pose between the camera and the object to be recognized. The proposal for improving the recognition is to integrate multiple recognition results from multiple view-points of the robot and artificial lighting changes –external factors–. In brief, the recognition method is used as an object recognition module –single recognition–. It means, there is not modification of the algorithms of the 3D model-based object recognition method.
4. Suggestion of using Least Squares instead of Principal Component Analysis –PCA– (Chapter 4, section 4.3). In the thesis, PCA method is just applied for computing the direction where the data vary the most, thus the line of best fit can be calculated (line that the robot will follow for recognizing the small objects). Since the use of PCA implies more analysis of data, the term PCA has been changed by the term Least Squares.

5. Others
   a. In Figure 4.8 –Block diagram of the processes for screw recognition– (Chapter 4, section 4.4), the arrow from the block *Projection in Left image* was changed to the block *3D position* instead of the previous block *Results left*.
   b. There was a question about the creation of templates for finding the small objects. However, this information had been already included in Chapter 4, section 4.4.1.
   c. In Chapter 4 –small object recognition–, two extra Tables were included for a better understanding of the results. Table 4.4 summarizes the improvements by using the proposed hierarchical recognition method. And Table 4.5 includes the variations of the vision algorithm performance.

The reviewers' suggestions have been helpful for improving both the content and the presentation of the thesis.

論文審査の結果の要旨

対象物の配置や寸法などに関する知識が事前に十分得られない，いわゆる整備されていない非構造的な環境内でロボットが作業を行うために必要なロボットビジョンの構成法とロボットの制御手法，さらにその応用例としてビルの内装解体作業における器具や天井ボード取り付けネジなどの取り外し作業を扱っている．解体作業など，特に環境の条件がロボットにとって極めて不利な状況を想定し，２つの方法論を提案している．

第１の方法論では，人とロボットの協調を想定したシステムの構築法とビジョンの適用法，並びに制御手法について議論を行っている．協調作業ではロボットは人間の作業を支援する立場を取っており，ボルトの取り外しなどロボットには達成が困難な軽作業は人間が行うシステムを提案している．ロボットは取り外しのための器具把持位置を特定するが，作業を効率的に行うため，器具の初期位置を人間が指示デバイスを用いて短時間で大まかに教示する．このための，指示操作方法を３種類提案しており，操作性と作業性の視点から多数の被験者実験を行い評価している．正確な把持位置はアーム先端に搭載された視覚センサにより認識を行う．能動照明によるロバストな把持位置認識を実現し，ロボットアームが安全に動作して把持動作と取り外し動作を実行する制御系を提案している．

第２の方法論では，大量の小対象物を対象とする作業を想定し，ビジョンの効果的な適用法について議論を行っている．具体的には，天井ボートを取り外した後の軽量鉄骨に残るボード取り付けネジの認識を扱っている．ここでは，広い動作レンジの中から極めて認識が困難な小対象物を認識する手法として，対象物の位置や包含関係に着目した階層型認識手法を提案している．ターゲットの対象物がその上に存在する，あるいはそれを含む上位対象物を定め，この上位対象物を始めに探索する．次に，この上位対象物を特定し，視覚センサを適切な位置に近づけ，この上に存在するターゲット対象物を改めて探索する方法がポイントである．解体作業への応用では，初めに軽量鉄骨を探索し，その位置方向を特定した後，軽量鉄骨表面に視覚センサを近づけ，ターゲットである多数のネジを探索し特定する．実際の応用では，照明条件の変化にも対応できるよう，能動照明による画像取得環境の設定や，サポートベクタマシンによる判別アルゴリズムの導入により，ビジョンの信頼性とロバスト性の向上を図っている．

解体環境を忠実に再現した模擬解体実験施設においてロボットシステムを稼働させ，作業時間や認識・作業達成率などを評価し，提案した手法の有効性を実証している．

以上の研究により，非構造的な環境下でビジョンを用いてロボットが適切に作業を行う方法論を示し，実環境下で有効に適用できることを実証し，ロボット工学における学術的かつ技術的貢献をもたらしており，博士（工学）の学位論文として価値のあるものと認める．