Image-Based Visual Servoing for Robotic Systems: A Nonlinear Lyapunov-Based Control Approach

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Research Objective

The objective of this project is to enable current and future EM robots with an increased ability to perceive and interact with unstructured and unknown environments through the use of camera-based visual servo controllers. The scientific goals of this research are to develop a new visual servo control methodology that: (i) adapts for the unknown camera calibration parameters (e.g., focal length, scaling factors, camera position, and orientation) and the physical parameters of the robotic system (e.g., mass, inertia, friction), (ii) compensates for unknown depth information (extract 3D information from the 2D image), and (iii) enables multi-uncalibrated cameras to be used as a means to provide a larger field-of-view. Nonlinear Lyapunov-based techniques in conjunction with results from projective geometry are being used to overcome the complex control issues and alleviate many of the restrictive assumptions that impact current visual servo controlled robotic systems. The potential relevance of this control methodology will be a plug-and-play visual servoing control module that can be utilized in conjunction with current technology such as feature extraction and recognition, to enable current EM robotic systems with the capabilities of increased accuracy, autonomy, and robustness, with a larger field of view (and hence a larger workspace). These capabilities will enable EM robots to significantly accelerate D&D operations by providing for improved robot autonomy and increased worker productivity, while also reducing the associated costs, removing the human operator from the hazardous environments, and reducing the burden and skill of the human operators.

Research Progress and Implications

As of 1 year and 8 months of the 3-year project, both theoretical and experimental progress is continuing to be made. At the end of the first year of the project, the experimental test bed illustrated in Figure 1 was completed and the algorithm developed in [1, 2] was experimentally demonstrated. The demonstration proved that the developed cooperative visual servo control module could be used in a plug-and-play manner with a generic robot manipulator (a typical EM robot, a hydraulic Schilling Titan II was utilized for the experiment) to enable the robot end effector to track a target moving in the workspace in an unpredictable manner. The target tracking result is

Figure 1: Experimental test bed including a Schilling Titan II hydraulic manipulator with a fixed camera and an in-hand camera.

achieved with no prior knowledge of the target path, or human guidance. The robot performed autonomously based on feedback from the **uncalibrated** camera system. The novel aspect of the demonstration was the generic nature of the robot manipulator (i.e., true plug-and-play capabilities) and the fact that the camera system was not calibrated.

One limitation of the algorithm developed in [1, 2] is a restriction on the robot motion to maintain a constant depth to the moving target. The recent focus of the project has been to overcome this obstacle by incorporating Lyapunov-based control design/analysis methods with analytical techniques derived from photogrammetry. By combining these methodologies, hybrid controllers were developed with feedback signals composed of both image data and reconstructed Euclidean information. This new strategy is based on the idea of comparing multiple images taken by a single camera to recover unknown range information. In effect, a geometric relationship (a Euclidean homography) is developed that mimics a stereovision technique for depth recovery by using a single camera. By further developing this idea, numerous scientific breakthroughs were obtained that can be applied to address the aforementioned project objectives.

The recently developed controllers have been submitted/published in peer-reviewed literature [3-17].

Specifically, Lyapunov-based techniques were used in [3, 4] to construct an observer that could be used to identify unknown range information using a single camera, and adaptive techniques are developed in [5] that identify the unknown depth information. In [6], an observer is also constructed to identify the velocity of a moving target based on image-based feedback. In [7], a controller was developed to enable regulation of a kinematically redundant robot manipulator while adapting for unknown range information. The research in [7] was extended in [8, 9] to enable a robot manipulator to track a desired trajectory by comparing multiple images from a ceiling-mounted stationary camera (or a camera attached to the robot end-effector) while adapting for unknown time-varying depth information and an unknown object-model. In [10, 11], a class of object-model free controllers was developed that provided 6 degrees-of-freedom exponential regulation of a robot manipulator despite unknown depth information and unknown intrinsic camera calibration parameters. A strategy to actively adapt for the uncertain intrinsic camera calibration parameters is developed in [12], and a robust controller is developed in [13] to reject uncertainty in the extrinsic calibration parameters. In [14], an alternative, multi-camera method is developed as a new method for generating the desired image for the previous controllers that is independent of the camera calibration.

In [15-17], several controllers were designed to enable a wheeled mobile robot to autonomously navigate based on feedback from a single camera while accommodating for the lack of depth information. To provide a proof-of-principle demonstration of the capabilities of the control algorithms developed in [15-17], the experimental test bed depicted in Figure 2 has been constructed. Experimental trials are under development and will be completed in the remaining months of the second fiscal year.

Figure 2: Experimental testbed including a K2A mobile robot and on-board camera.

Planned Activities

In the remaining months of FY 2003, the experimental results for the theoretical development given in [15-17] will be completed. In FY 2004, the recently developed homography-based visual servoing methodology will be further explored to incorporate the multiple camera strategy developed in [14] to generate desired trajectories via an alternate approach to the standard teach-by-showing paradigm. Future research will also target additional abilities to actively adapt for uncertain intrinsic and extrinsic camera calibration parameters. In addition, new research will focus on casting the visual servo control problems in terms of a quaternion framework to address the theoretical and practical limitations discovered by the lead investigator while using typical Newton-Euler representations. The development will target both robot manipulator and mobile robot applications. Theoretical and simulation results will be submitted to peer-reviewed conference proceedings and to journal publications. Various camera configurations and models will be further explored as a means to determine the specific advantages that each configuration yields. The generalized results may be demonstrated using a mobile manipulator platform. The results of the general image-based visual servoing control module will be submitted to leading control systems and/or robotics journals.

Information Access

As of June 9, 2003 this research has resulted in the submission of 6 journal papers (2 have been accepted for publication) and the publication or acceptance for publication of 16 peer-reviewed conference papers. The lead principal investigator serves as the co-advisor for several Clemson University graduate students. Through collaborative efforts with the lead investigator, the scientific breakthroughs from this project have also resulted in the completion of the Ph.D. dissertation by Y. Fang [23], the on-going dissertation work by the co-advised doctoral students V. Chitrakaran, J. Chen, and M. McIntyre, and the co-advised master degree student P. Chawda. The following publications acknowledge support by the EMSP project (with the exception of the dissertation by Y. Fang).

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