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

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Research Objective

There is significant motivation to provide robotic systems with improved autonomy as a means to significantly accelerate deactivation and decommissioning (D&D) operations while also reducing the associated costs, removing human operators from hazardous environments, and reducing the required burden and skill of human operators. To achieve improved autonomy, this project focused on the basic science challenges leading to the development of visual servo controllers. The challenge in developing these controllers is that a camera provides 2-dimensional image information about the 3-dimensional Euclidean-space through a perspective (range dependent) projection that can be corrupted by uncertainty in the camera calibration matrix and by disturbances such as nonlinear radial distortion. Disturbances in this relationship (i.e., corruption in the sensor information) propagate erroneous information to the feedback controller of the robot, leading to potentially unpredictable task execution. This research project focused on the development of a visual servo control methodology that targets compensating for disturbances in the camera model (i.e., camera calibration and the recovery of range information) as a means to achieve predictable response by the robotic system operating in unstructured environments. The fundamental idea is to use nonlinear Lyapunov-based techniques along with photogrammetry methods to overcome the complex control issues and alleviate many of the restrictive assumptions that impact current robotic applications. The outcome of this control methodology is a plug-and-play visual servoing control module that can be utilized in conjunction with current technology such as feature recognition and extraction to enable robotic systems with the capabilities of increased accuracy, autonomy, and robustness, with a larger field of view (and hence a larger workspace). The developed methodology has been reported in numerous peer-reviewed publications and the performance and enabling capabilities of the resulting visual servo control modules have been demonstrated on mobile robot and robot manipulator platforms.

Research Progress and Implications

The efforts of this project have resulted in fundamental advancements that have been verified through proof-of-concept demonstrations. At the end of the first year of the project, a new method for utilizing uncalibrated (out-of-the-box) cameras to expand the FOV for a robotic system was developed in [1, 2] to enable the robot end-effector to track the unknown trajectory of a target moving in the workspace. The target tracking result in [1, 2] is achieved with no prior knowledge of the target path, or human guidance. The experimental test bed illustrated in Figure 1 was completed and a software control module was developed and implemented. The demonstration verified the 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) 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.

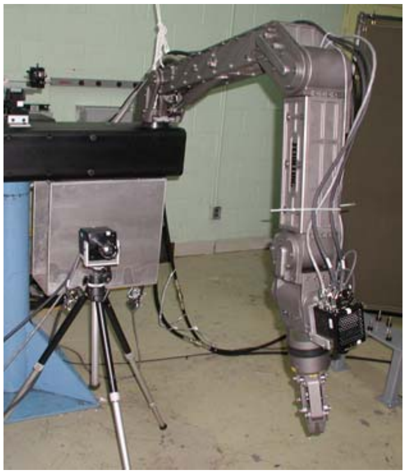

Figure 1: Experimental test bed including a Schilling Titan II hydraulic manipulator with a fixed camera and an in-hand camera.

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. Based on this restriction, the remainder of the project aimed at developing visual servo controllers for general applications where the unknown distance from the target to the camera varied in time. To this end, Lyapunov-based control design/analysis methods were incorporated with analytical techniques derived from photogrammetry.

By combining these methodologies, unique 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 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.

Lyapunov-based techniques were used in [3] to construct an observer that could be used to identify unknown range information using a single camera, and adaptive techniques are developed in [4] that identify the unknown depth information. In [5], an observer is also constructed to identify the velocity of a moving target based on image-based feedback. In [6], a controller was developed to enable regulation of a kinematically redundant robot manipulator while adapting for unknown range information. The research in [6] was extended in [7] 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 [8], 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. Strategies to actively adapt for the uncertain intrinsic camera calibration parameters are developed in [9] and [10], and a robust controller is developed in [11] to reject uncertainty in the extrinsic calibration parameters. In [12], 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 [13] and [14], 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. The control algorithms developed in [13] and [14] were implemented on the mobile robot depicted in Figure 2 with a monocular vision system. The results from the proof-of-concept demonstrations illustrate the capability of the controllers to enable the position and orientation of a mobile robot to either be autonomously regulated to a desired setpoint or track a desired time-varying trajectory despite the lack of depth information or an object model. Recent efforts in [15] describe how a sensorless mobile robot can be used to achieve task execution under visual servo control via an off-board camera that views the workspace.


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

Motivated by the successful development of visual servo tracking controllers, the final efforts in the project focused on the dual use of the camera as a feedback sensor and as a sensor for path planning. Specifically, an optimization-based, on-line trajectory generator for the image features is fused with a position-based controller to move the kinematic system to a desired setpoint in [16]. A planar example based on a fixed camera configuration is used to illustrate the approach, and simulation results were provided to demonstrate the control performance for this example. The approach was also extended to the 6 degree-of-freedom case for the camera-in-hand configuration in [16].

Planned Activities

In the final three months of this project, activities will focus on issues critical for transitioning the developed methodologies from laboratory proof-of-principle experiments to future field implementations. Specific issues include robust and flexible software interfaces/integration, guidance for gain selection and troubleshooting, and overall applicability needs and requirements. Specific DOE D&D field-related applications where there appears to be significant potential needs for visual servoing include smart tooling, shared controls, and sensor-based robotics operations. In addition, there are emerging applications in the areas of medical robotics and offroad automated guided vehicles that could benefit from this technology.

Information Access

This research has resulted in the submission of 11 journal papers (8 have been accepted for publication or have been published) and the publication or acceptance for publication of over 20 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 merits from this project have also resulted in the completion of the Ph.D. dissertation by Y. Fang [17], 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.

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