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

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 controlled robots. 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 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 the 9th month of the 3 year project, both theoretical and experimental progress has been made. In [1], a significant breakthrough was achieved by using Lyapunov-based design tools to develop a visual servo control algorithm that enabled multiple uncalibrated cameras to be used to enable the end-effector of a robot manipulator to track an object moving in the task-space in an unknown manner. An experimental testbed has been constructed (see Figure 1) that incorporates a high-speed vision system with a Schilling Titan II hydraulic manipulator to verify the theoretical results. As stated in [2], a hardware-in-the-loop simulation has been performed using simulation models of the robot manipulator that have been experimentally proven yield very close approximations of the actual performance. Although the visual servo control result is independent of the manipulator used, the Schilling manipulator is being used for the experimental development because of feedback by the EM Robotics Crosscutting Activities ongoing at ORNL. The result in [3] was developed as a means to improve the hydraulic robotic performance. The result in [4] demonstrated how the position/orientation of a robot manipulator could be regulated to a desired position/orientation using feature-based visual servoing. One of the limitations of the results given in [1, 2, and 4] are that the manipulator is constrained to planar robotic applications. Motivated by the desire to extend the applicability of the developed algorithms a completely new visual servo control approach is being investigated. Specifically, by coupling Lyapunov-based control techniques with recently developed homography-based visual servoing techniques that exploit both image data and reconstructed task-space data, algorithms are under development that will compensate for unknown depth information without the requirement for additional sensors (e.g., laser range finders, additional cameras). These current efforts are the basis for the result in [5] and one chapter of [6]. To address mobile robot applications, the results given in [5, 6] were modified to address unknown depth information and to address the nonholonomic constraints imposed by mobile robotic vehicles. The result in [7] was developed to provide a mechanism for mobile robot controllers to be designed separately from parameter update laws to provide for increased flexibility. This result may foster advances in compensating for the uncertain camera effects in addition to uncertain effects caused by the dynamics of the mobile robot in subsequent visual servoing efforts.

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

Planned Activities

In the remaining months of FY 2002, the experimental results for the theoretical development given in [1] will be completed. In FY 2003, the recently developed homography-based visual servoing methodology developed in [5, 6] will be further explored to enable multiple cameras to be used to extend the field-of-view and enable the ability to adapt for uncertain intrinsic and extrinsic camera calibration parameters. In addition to the continuing development for robotic manipulators, research efforts will focus on modifying the control algorithms for robotic systems with constrained motion (e.g., the nonholonomic constraint for mobile robot motion). These efforts will include various camera configurations that will result in different projective properties (i.e., camera mounted in a fixed position on the mobile robot, camera mounted on a pan-and-tilt unit on the mobile robot, and a fixed camera mounted away from the robot). Theoretical and simulation results will be submitted to conference proceedings and to journal publications. An experimental testbed will be constructed to demonstrate developed mobile robot algorithms (e.g., [7, 8]). Developed visual servoing control modules will be demonstrated on a mobile platform at ORNL facilities and the theoretical development and the experimental results will be submitted to journal publications. In FY 2004, the project will focus on the integration of the various theoretical and experimental results. 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 a leading control systems and/or robotics journal.

Information Access

As of June 11, 2002 this research has resulted in a journal paper that is under review, two published conference papers, two conference papers that are to appear, and two conference papers that are under review. The lead principal investigator serves as the co-advisor for the Clemson University doctoral student Y. Fang. Two chapters of the doctoral dissertation by Y. Fang are based on upcoming journal length papers addressing research issues for this project. The following publications acknowledge support by the EMSP project (with the exception of the dissertation by Y. Fang).

1. W. E. Dixon, E. Zergeroglu, Y. Fang, and D. M. Dawson, "Object Tracking by a Robot Manipulator: A Robust Cooperative Visual Servoing Approach", *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, Washington, DC, May 2002, pp. 211-216.
2. W. E. Dixon and L. J. Love, "Lyapunov-based Visual Servo Control for Robotic Deactivation and Decommissioning", *The 9th Biennial ANS International Spectrum Conference*, to appear.
3. J. Chen, W. E. Dixon, J. R. Wagner, and D. M. Dawson, "Exponential Tracking Control of a Hydraulic Proportional Directional Valve and Cylinder via Integrator Backstepping", *Proceedings of the 2002 ASME International Mechanical Engineering Congress and Exposition*, to appear.
4. P. Setlur, A. Behal, W. E. Dixon, and D. M. Dawson, "Adaptive Position and Orientation Regulation for the Camera-in-Hand Problem", *Robotica*, in review.
5. Y. Fang, A. Behal, W. E. Dixon, and D. M. Dawson, "Adaptive 2.5D Visual Servoing of Kinematically Redundant Robot Manipulators", *Proceedings of the 2002 IEEE Conference on Decision and Control*, in review.
6. Y. Fang, *Lyapunov-Based Control for Mechanical and Vision-Based Systems*, Ph.D. Dissertation, Clemson University, under doctoral committee review.
7. Y. Fang, D. M. Dawson, W. E. Dixon, and M. S. de Queiroz, "2.5D Visual Servoing of Wheeled Mobile Robots", *Proceedings of the 2002 IEEE Conference on Decision and Control*, in review.
8. W. E. Dixon, M. S. de Queiroz, and D. M. Dawson, "Adaptive Tracking and Regulation Control of a Wheeled Mobile Robot with Controller/Update Law Modularity", *Proceedings of the 2002 IEEE International Conference on Robotics and Automation*, Washington, DC, May 2002, pp. 2620-2625.