# Uncalibrated Visual Servoing: an LMI based approach

**Muhammad Umer Khan**

Submitted in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy in Electrical Engineering**

Department of Electrical Engineering

Pakistan Institute of Engineering and Applied Sciences

Nilore, Islamabad, Pakistan

(June 2011)

# Abstract

Vision is an effective robotic sensor, since it imitates the human perception of vision and allows for non-contact measurement of the environment. The camera as a vision sensor can be employed to manipulate the robotic arm in 3D world. This means that the camera is a tool by which the robot manipulator positions itself—this is referred to as *visual servoing*. The visual servo systems considered in this thesis are known to have dynamic environment. Hence, uncalibrated visual servoing, convergence, saturation and robust stability are the main issues that provide basis for the methods proposed in this thesis. The research undertaken is divided into four phases.

In the first phase, an independent joint Proportional-Derivative (PD) control scheme for *n*-link serial manipulator is developed. The sole purpose of the PD type controller is to track the reference trajectory in joint space and compare its performance with the Computed Torque Controller (CTC). These controllers work independent of vision solely to evaluate the performance of the manipulator in terms of its accuracy and precision.

The second method presents a model-independent vision-guided robotic control method based upon Linear Matrix Inequality (LMI) optimization. The proposed scheme is considered the first rigorously developed scheme that employs LMI for Image-based paradigm in an uncalibrated environment. The aim lies in developing such a method that neither involves camera calibration parameters nor inverse kinematics. The proposed Proportional based visual servo control scheme includes transpose Jacobian control; thus, inverse of the Jacobian matrix is no longer required. LMI based optimization scheme is utilized, which estimates the composite Jacobian at each step. The composite Jacobian, that relates differential changes in the robot joint angles to differential changes in the image plane, is an amalgamation of image and robot Jacobian.

The third method proposed in this thesis computes the composite Jacobian by considering the kinematic and visibility constraints, which are incorporated to the system by means of input and output saturation. The proposed controller stabilizes the camera despite the unknown value of the target point depth. To make sure that the features remain in the camera field of view, and to restrict the controller's input using some bounds, visibility and kinematic constraints are introduced in the form of LMIs. Closed-loop stability of the system is ensured using Lyapunov's direct method. Sector boundedness condition is also added to Lyapunov. Inclusion of these constraints helps to avoid any real damage to the robot. Moreover, features remain visible throughout and the servoing would not fail.

The last method developed in this thesis presents the methodology to the robust stability of a vision-based control loop in an unknown environment. The type of uncertainty included is the parametric uncertainty. The proposed method allows the analysis of uncertain nonlinear system by representing it in differential-algebraic form. By invoking suitable system representation and Lyapunov analysis, the stability conditions are described in term of LMIs to ensure the stability of uncertain nonlinear system.

These methods have their applications in an uncalibrated environment, where monocular vision is rigidly attached to the manipulator's end-effector. In order to steer the camera, desired visual features are extracted by placing the camera at the desired location. The visual servo control directly inputs the feature error vector, which is the difference between the initial and desired features. Various simulation results are shown for validating these schemes by applying them to different serial links robot manipulators. These methods proved to be dynamic, robust, accurate and efficient in the presence of large errors.

**Keywords:** eye-in-hand, image-based visual servoing, nonlinear, uncalibrated, linear matrix inequality, multi-constraint, robustness analysis, uncertainty, differential-algebraic equation, convex optimization.