1. Introduction

Visual servoing is a very promising and attractive technique for the control of robot manipulators using the information provided by visual sensors. For servoing, desired visual features are extracted using a single camera mounted on the end-effector of a robot manipulator. This configuration is commonly known as *eye-in-hand* scheme [1], which allows for direct control of the motion of an object. With this approach, the desired image is captured and features are extracted in the start by placing camera at the desired location w.r.t the observed object. Then, feature errors will possibly converge to zero from any initial location in the available workspace. It is required that those locations must be selected from where the desired objects can be observed by the camera. Furthermore, it is assumed that during any robot motion, camera has image features always in sight, otherwise servoing will fail. This is usually the case, where initial and desired positions are distant. For this case, stability is not ensured and the object can get out of the camera field of view (fov) [2]. Sometimes, it is also desired to produce the bounded input signal to the controller, otherwise system can get unstable. For this purpose, kinematic constraint is introduced in the form of limit
on joint angles velocities, which will consequently input the saturated signal to the controller. The robust stability of the system is also ensured by adding the uncertainty to the system. The proposed methodology is meant for determining the stability of vision based uncertain nonlinear system in the presence of parametric uncertainties using the Lyapunov function and LMI framework by transforming the original system into differential-algebraic nonlinear system.

Most of the classical visual servoing techniques necessitate a strong prior knowledge of 3D model of the observed object, kinematic parameters of robot manipulator and camera parameters [3]-[6]. The robot kinematic parameters must be known, in order to compute manipulator Jacobian, as well as, camera needs to be calibrated or recalibrated due to sensitivity of the system to disturbance; so that, the image Jacobian matrix can be computed. These activities can both be difficult and time consuming, or perhaps unfeasible in an unstructured or dynamic environment. Contrarily, in model-free or uncalibrated visual servoing there is no requirement of any prior information of the system as composite Jacobian, i.e. product of robot and image Jacobian is estimated dynamically. Since, uncalibrated visual servoing is independent to camera and object model; it provides more flexibility in the dynamic environment. Motivated by the desire to incorporate robustness to the control scheme, a unified approach to vision-based control that does not require camera calibration is proposed in this thesis. It also has its effectiveness where model of the object is unknown.

By adopting a model-free approach, control algorithm eliminates the necessity of extensive camera recalibration and system modeling. Even though much work has
been done on camera calibration, it is still a time consuming process, requires some level of expertise and has inherent inaccuracies. Earlier visual servoing schemes require that the system parameters must be known in advance or they can be determined off-line. A control scheme with off-line parameter identification is not usually recommended, where the environment is dynamic. To overcome such inadequacies, a versatile visual servoing control scheme is proposed as the prime objective with an on-line LMI optimization to compute composite Jacobian matrix. It has the following features:

1. The proposed scheme does not require any prior knowledge of camera intrinsic or extrinsic parameters. So the exhausting calibration process is eliminated.

2. The LMI optimization scheme is not based upon any initial guess for the computation of composite Jacobian. This means that the system will be able to converge in the feasible workspace without any initial condition.

3. The scheme is designed to work with monocular vision-based system and there are no restrictions on the robot manipulator's degree of freedom (dof), SISO or MIMO. The proposed method is applicable to all cases.

4. The aim of the proposed scheme is not to search for true parameters of composite Jacobian matrix, rather to ensure asymptotic convergence of image-features to the desired values.

In the last decade or so, robots have impacted heavily the industrial applications. Industries such as food processing, microsystem applications, space and hazardous material removal is proved to have dynamic environment. Therefore, the developed
methods which involve the computation of composite Jacobian dynamically will be the most appropriate choice in an unstructured environment.

Specifically, the contributions of this thesis are:

1. LMI based optimization method is proposed that does not require any initial guess for the computation of composite Jacobian matrix.
2. A theoretical basis for uncalibrated vision-guided robotic control is developed based upon the minimization of error norm.
3. The visibility and kinematic constraints are introduced to improve the robustness and efficiency of the proposed scheme.
4. Robustness analysis of vision-based control loop in the presence of parametric uncertainties is also presented.
5. The asymptotic stability of the system is ensured using Lyapunov's direct method.

1.1. Organization of the Thesis

The thesis is organized in the following manner:

Chapter 1 discusses the motivation of the research, contribution of the work and outlines the thesis.

Chapter 2 discusses the visual servoing architecture and highlights the main contribution of the researchers in this field. Surprisingly, only a few researchers tend their efforts towards model-independent visual servo control. They employ a Jacobian estimation scheme which is based on recursive least-square minimization technique.
Chapter 3 provides a mathematical background for the model-independent vision-guided control schemes developed in Chapter 4 and 5. The work of several researchers with closely related control strategies is discussed. It is observed that a rigorous development for an uncalibrated visual servoing without requiring the initial estimate for Jacobian or any memory requirement has never been addressed before. The theoretical development leads to the development of vision-based control scheme for an uncalibrated environment.

Chapter 4 develops a model-free vision-based control scheme for an uncalibrated environment. An inner loop design for the overall vision based control scheme is discussed in detail. Two types of controllers i.e., PD and CTC are compared based upon their accuracy and efficacy. Furthermore, an uncalibrated visual servo control scheme based upon LMI optimization is developed. The proposed visual servo control scheme includes transpose Jacobian control; thus, inverse of the Jacobian is no longer required. By invoking Lyapunov’s direct method, closed-loop system stability is ensured.

Chapter 5 presents more advanced vision-based control schemes for an uncalibrated environment. The schemes proposed here find their basis in the previous chapter. The first scheme proposed here guarantees that the features would not get out of the camera fov, and kinematic constraints remain effective throughout. To ensure visibility of the features and bound the input control signal, visibility and kinematic constraints are introduced in the form of LMIs. It is concluded that this scheme yields better results as compared to the former one. The last method described in this thesis is based upon determining the robust stability of a vision-based control
loop in the presence of parametric uncertainties. The stability and convergence of these schemes is ensured using Lyapunov's direct method.

Chapter 6 simulates the proposed schemes developed in Chapter 4 and 5. Based upon simulation results, it is argued that the CTC produces better results as compared to PD. Using proposed uncalibrated visual servo control; error norm very well exhibits the exponential decrease. More importantly, the system attains asymptotic stability using convex characterization. With the inclusion of visibility and kinematic constraints, the performance of the system is significantly improved. The robustness of the vision-based system is ensured by evaluating the system trajectories from different initial estimates within the polytope. The convergence of the states to the origin assures that the system remains stable within the region $\mathcal{R}$ in the presence of uncertainties $\delta$.

Chapter 7 summarizes the results and suggests areas of further research.

1.2. Contributions

The results presented in this thesis have been published or submitted for publication elsewhere. Contents of Chapter 4 and 5 are majorly based upon the adapted version of one or more such publications. Chapter 4 is composed of two sections, and each section is closely linked with one another. Chapter 5 is also based upon two proposed schemes. Reference to the previous contents is given where desired to avoid unnecessary repetition. An attempt is made to keep the notations consistent throughout the thesis; still for the ease of readers, a list of all important variables is mentioned in the Nomenclature. All references are provided at the end of the thesis.
Short summary is presented at the end of every chapter. Below are the details of the contributions and their relevance with the chapters in this thesis.

**Chapter 4** This chapter develops the convex characterization for the control of robot manipulator in an uncalibrated environment. The work presented in this chapter is based upon these publications:


**Chapter 5** This chapter develops more advanced schemes for the control of robot manipulator in an uncalibrated environment. The contents of this chapter are mainly based upon the following publications:


In addition, the following publications were also written during my PhD as an author or co-author:

