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Robust Visual Servo of the Robot Manipulators — A Strict Lyapunov Function Approach —

Saitou Aki

School of Information Science,
Japan Advanced Institute of Science and Technology

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In recent years, manipulator control schemes that utilize the visual information in the feedback, called *visual servo*, have attracted much attention because of development of computer and improvement of camera's performance. A purpose of manipulator control with visual servo is that we can autonomous control for manipulators using some visual sensors in case that work space and disposition of objects is unknowned. Visual servo can be divide broadly into two categories. The classification of the system distinguishes the position-based method from the image-based method. In position-based method, the visual information is used in conjunction with a geometric of the object and the known camera model to estimate the position of the object with respect to camera. Then, feedback is computed by the estimated position. While, the image-based method uses image feature parameters directly to compute the control input from camera. Therefore, the image-based method may reduce computational delay, eliminate the necessity for the object position estimation and eliminate errors due to camera calibration.

Although there are various approaches in the visual servo, the manipulator dynamics is often neglected. Since the manipulator dynamics is naturally nonlinear, it is essential to compensate the manipulator dynamics.

In joint space control, the manipulator control scheme based on the principle of energy conservation, such as the Lyapunov based method, has attracted much attention. This technique compensates asymptotic stability using manipulator's total energy as Lyapunov function. By Arimoto, a Lyapunov function was proposed as the total energy plus a cross-term bilinear in position and velocity in order to prove the exponential stability. Kelly *et al.* also applied the Lyapunov function with the cross-term to design of adaptive control. The proposed Lyapunov functions are able to conclude to exponential stability in stead of only asymptotic stability of the manipulator system. Hence, it is called a "strict Lyapunov function, " i.e. a function with a time derivative strictly negative definite.

Lyapunov based method require exact manipulator model. However, it is impossible to obtain exact manipulator dynamics model that idealized the real physical system for reason of its uncertainty. Further, it is difficult to obtain asymptotic convergence when uncertainty is taken into account in the model. The problem in this case is thus mainly prove boundedness, i.e., at least no signal grows unbounded in the closed-loop system, and if possible to evaluate the domain within which the state asymptotically lies. This is called the uniformly ultimate boundedness. Spong expressed uncertainty of manipulator by parameter based on the regresser expression, and propose a control law including the regresser expression. Then, additional input with switching function attenuate uncertainty of the manipulator model and compensates uniformly ultimate boundedness.

In recent year, Kelly *et al.* and Maruyama *et al.* proposed control laws that directly compensate the effect of manipulator dynamics based on Lyapunov based method in visual servo approaches. However, LaSlle's theorem was required to perform the stability analysis, still more these approaches have only shown asymptotic stability. Furthermore, uncertainty of manipulator model was not considered.

In this thesis, we deal with the visual servo control problems in compliance with the image-based method for two links planar manipulator with eye-in-hand configuration using the Lyapunov based method. The objections are as follows.

- We show directly asymptotic stability of system by Lyapunov direct method without LaSalle's theory. Hence, we use a "strict Lyapunov function, " then show exponential stability.
- We express the parametric uncertainty of manipulator model, especially gravity term, by physical parameter vector based on regresser expression, and propose the control law that compensates the uniformly ultimate boundedness for the uncertainty. We also use a "strict Lyapunov function"

The control objective is to move the manipulator in such a way that its end-effector position, that is camera position, coincides with the static object position. By restricting the control problem to set-point control of planar manipulator, we are able to design a simple controller supported by rigorous stability analysis taking account the full nonlinear manipulator dynamics. Further, we use as few camera calibration parameters as possible and never employ the inverse kinematics. Consequently, this problems result in the convergence issue for the position of the object in the image plane and joint velocity.

Firstly, it is important to model the system in order to design the control system for manipulator. It is assumed that the end-effector evolves entirely in the plane of the world coordinate frame. A static objective lies in the plane which is parallel to the motion plan of manipulator. The manipulator dynamics base on the Lagrange dynamics equations. The properties of dynamics perform some important part when we prove the stability. The kinematics is expressed using the exponential expression proposed by Brockett. The exponential expression base on Lie theory, then we can geometrically consider visual servo problems using its properties. We use manipulator kinematics to derive the camera model. We model the projective geometry of the camera in order to understand the geometric aspects of the imaging process, The camera model are formulated using the perspective transformation, and included the exponential expression in model formula. On these system models, we formulate the visual servo problem, and propose a control law based on the Lyapunov method. The proposed control law is PD control with gravity compensation. We expect that this control law has robustness for the calibration error of the camera's internal parameters. This control law has some interesting features. The first feature is that the image error is defined in a natural way as the visual distance between the end-effector and the object. The second is that only the camera orientation is required among the extrinsic parameters The third is that no intrinsic parameters are assumed to be known. The rest is that the manipulator's inverse kinematics as well as the inverse Jacobian are not used. Further, since this control law is not performed computation the inverse jacobian, we can easily realize it. We prove the stability of system for our proposed control law by "strict Lyapunov function" without LaSalle's theorem, then show exponential stability finally, but it is locally. Since the exponential stability guarantee the exponential convergence, the exponential stability is better than the asymptotic stability.

Finally, we consider the system with uncertainty of model. In this thesis, the PD controller with gravity compensation is considered, hence it is especially important to uncertainty in gravity term. Although, there are a few kind of model uncertainty, we pay attention the parametric uncertainty (e.g., length of link, math of link and inertia moment) of manipulator model, especially that of gravity term, and we propose the robust control law to achieve the uniformly ultimately boundedness. In case that uncertainty exist, asymptotic convergence can not be guaranteed. We represent the gravity term by linear expression consisting of regressors and physical parameter vector in order to deal with uncertainty easily. Indeed, computing vector is more easy than compute matrix. Hence, we can regard the magnitude of uncertainty as that of physical parameter. The physical parameter vector has upper bound as a result of the boundedness of gravity term. The input that restrain the effect of uncertainty take the shape of saturation function and perform the switching function. The switching function prevent feedback gain from growing higher. Similarly, we prove the uniformly ultimately bounded using "strict Lyapunov function". The uniformly ultimate boundedness is achieved against the model uncertainty due to "strict Lyapunov function".