ISSN 2229-5518

Visual Servoing of a Switched System with Supervisory Control

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Abstract—Sensory information provided by the camera mounted on robotic end effector can be used for visual guidance and feedback. Interaction of more than one camera in a large workspace can ensure that image based visual servoing (IBVS) does not fail. A master camera monitors the scene and helps the system overcome the chances of failure of IBVS. Asymtotic stability of is assured by identifying a region around the target where IBVS will not fail is identified and a robot end effector with an eye in hand camera is guided to this region. Simulation studies are carried out and the efficiency of the system is ensured. The supervisory control scheme proposed in this paper works satisfactorily for targets which are initially not visible for the robot in a large workspace.

Index Terms— Visual Servoing; switching control; supervisory control; asymptotic stability; Jacobian condition number.

1 Introduction

Visual data provided by camera can be used to control and feedback the robotic end effector in industrial applications like gripping, sorting and cutting. A camera observing a workspace for the guidance, control and feedback (eye-to-hand) of a robot has a global sight of the scene compared with a camera mounted on the robotic end effector (eye-in-hand) which has a partial sight of the scene. Basically the sensory information provided by the camera can be utilized either for image based visual servoing (IBVS) wherein the two dimensional features available from the image are utilized along with depth information, or for position based visual servoing (PBVS) where a set of three dimensional parameters from image measurements are used. The basic approaches in visual servoing are available in [1]. PBVS offers globally stable and feasible trajectories but servoing can fail for the object tracked leaving the field of view of the camera [2]. Full reconstruction of the 3D environment is required with the help of geometric model is also required. The trajectory of the image is regulated by commands directly mapped from error signal measured in image which prevent the features from leaving the field of view of the camera. Although IBVS is a fairly robust approach for visual servoing it suffers from certain drawbacks like local minima where singularities invoked in image Jacobian by certain targets result in system failure and camera retreat for which complicated and unnecessary motions are performed since direct control of Cartesian velocities are rendered. The translation along the z axis for rotations around optical axis for certain configurations theoretically approaches infinity as the rotation about the optical axis approaches 180°. For physically limited workspace this will be troublesome and hazardous. Since magnitude of image error is large for far away feature points initial velocity will be high. Also the knowledge of depth is required for the calculation of image Jacobian.

A number of solutions were formulated and proposed for the solution of problems associated with IBVS and PBVS. The control law is used in 2 ½ D visual servoing [3] combined the 3D information retrieved either by a pose estimation algorithm or a model of the environment with the image data acquired by the camera. X and Y axes are grouped together and Z axes as different one in XY/Z partitioned IBVS [4] to eliminate camera retreat problem by a partitioned controller approach. The translational and rotational components were separated and depth was treated as gain factor to the translational component in [5] while [6] presents a separated IBVS scheme where rotation about the z axis is performed first so that image direction is in accordance with the desired image direction. A PBVS like controller based on fundamental matrix relating camera views and asymptotically stable for large calibration errors [7], an IBVS path planner keeping the features in the field of view with a minimal pose error [8] and a PBVS controller following minimum distance path and maintaining target visibility by allowing freedom in orientation [9] were hybrid approaches to be listed a few utilizing the advantages of IBVS and PBVS. Visual servoing methods based on navigation function was presented in [10]. Switched methods were another solution. The control was partitioned along the time axis and by switching between pose and image control, asymptotic stability wss ensured in [11]. A threshold region for both IBVS and PBVS was defined and the control is switched between pose and image controllers in [12]. PBVS is globally asymptotically stable and IBVS is locally asymptotically stable, even though the region of convergence is very difficult to obtain. The switching surfaces have been redefined and local stability through switching approach is established in [13]. For avoiding image singularities and image local minima, two hybrid switching strategies have been proposed in [14] with the help of a local switching controller. For large camera displacements, switching to a different PBVS controller that keeps features in the field of view while servoing is given in [15] and strategies for avoiding joint limits and joint space singularities by switched schemes for an eye-in-hand system are available in [16]. Many of the switching schemes compute the epipolar geometry that relates a pair of images. The camera configurations corresponding to the initial and desired images are related by homography matrices. These can be decomposed into translational and rotational components of motion between the two configurations of the camera. A separated

IBVS scheme illustrated in [17] carries out the z-axis rotation first if the image is not in accord with the desired image in direction. The hybrid controllers have their Cartesian space and image space trajectories smooth with the advantage of global stability [18].

Switching between controllers is an effective way of solving the drawbacks associated with visual servoing. Even switching between eye-in-hand and eye-to-hand configurations or an interaction of both are possible. This will bridge the gap where the global camera may not be able to maneuver the whole scene and the local camera cannot interact with the whole workspace. This is true for complex tasks and environments where excellent results can be obtained by the interaction of both eye in hand camera and eye to hand camera [19]. Switching can be made between these camera configurations depending on the working conditions and environment. Switching between eye to hand and eye in hand configurations is employed in [20] with a hybrid visual servoing control for a space robot based on global and local visibility of the target.

In order to make servoing smooth while employing switching schemes number of switching has to be minimal to reduce the effect of switching on the robotic manipulator. We present a new supervisory hybrid switching scheme with one time switching in control and configuration for a larger workspace and for targets which are initially not visible for the eye-in hand camera. By switching from eye-to-hand configuration to eye-in hand configuration while taking advantage of the local asymptotic stability of the classical IBVS, the system performs well in the workspace.

The remainder of the paper is organized as follows. In section II the need for IBVS for switched schemes and the task to be accomplished is briefed. Section III describes the development of the proposed control strategy and stability of the system. In section IV Simulation case studies are given and section V contains the results and analysis.

2 Problem Description

Even though there are a few drawbacks associated with classical IBVS approach like camera retreat problem, local minima and need to estimate the target depth, it has been proved to be locally asymptotically stable. Most of the switched controllers have been designed on the fact that IBVS is locally asymptotically stable in a region sufficiently neighboring the target, even though the size and shape of the region of convergence has not been established. To confirm the stability and convergence of IBVS, a simple switching scheme to place the robot in a region near or in the aforesaid neighborhood is presented in this paper.

All the visual servoing tasks in the literature are validated with targets initially visible for the camera. But in a sufficiently large workspace, there can be configurations where the camera in hand may not be seeing the target initially or it may not be able to see the target image features distinctively for the far away targets. In such a case the global sight of a master camera observing the workspace can direct and drive the eye-in-hand camera to the neighborhood of the target from where the IBVS would be essentially converging. Additionally the depth of the target can be updated by the master camera. Such a generalized workspace for a supervisory guidance scheme with the initial robot end effector pose and intermediate pose from where it follows IBVS are shown in fig.1

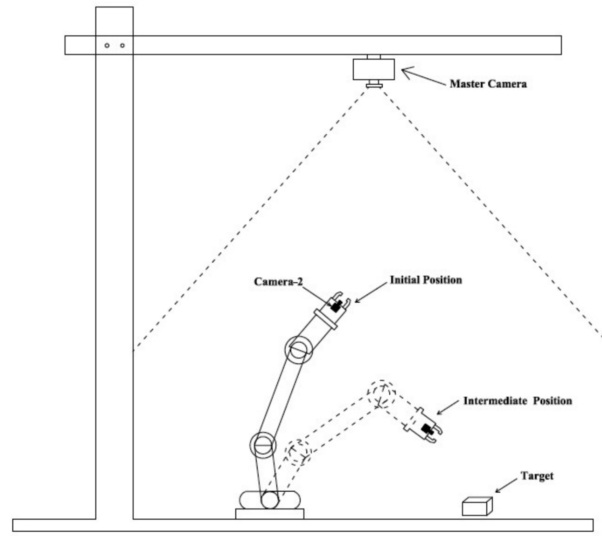


Fig. 1 The workspace with two cameras

3 A New Hybrid Switched Scheme

Conventional IBVS works satisfactorily for small motion, but with large motions like those with rotation about z-axis problems may arise. The control strategy proposed is divided into three regions of control with one switching. If the eye-in-hand camera attached to the robotic end effector is not aligned in the direction of the target, the master camera aligns it accordingly in the first region of control where a normalized velocity vector is chosen. In the second region, the robot is guided in such a direction that the distance between the eye in hand camera and the target decreases. For this no prior information of the scene is required.

The velocity of the of the robot end effector V_T, its change in pose $\dot{T}$ and Jacobian matrix J(T) are related by

$$V_T = J(T)\dot{T} \tag{1}$$

The error in position of the end effector and camera can be calculated as $e_T = d - d^*$ where d is the difference in coordinates and angular position and d* is the desired difference in coordinates and angular position. Here d* is be set to zero since during the phase of the control region 2, the system will switch to IBVS.

$$\dot{e}_T = -\beta e \tag{2}$$

The error is allowed to decrease exponentially with a gain β so that

$$V_T = -\beta J(T)^{-1} e \quad (3)$$

In the third region of control image based visual servoing is carried out. The switching is done by keeping an eye on the value of Jacobian number of the interaction matrix. The velocity of the camera V_C is given by

$$Vc = -\lambda Je^{+} e \quad (4)$$

Where $e = s(m(t), a) - s^{*}$ is the image feature error [1]. The vector m(t) is a set of image measurements which are used to compute a vector of k visual features $s(m(t), a)$. The part a is additional information about the system. The vector s* contains the desired values of the features and λ is the control gain. Je + ∈ ℝnxk is the Moore-Penrose pseudo inverse of Je where n is the number of degrees of freedom (DOF) of the robot and $Je^{+} = \left(Je^{T} Je\right)^{-1} Je^{T}$ when Je is of full rank n. If Je is invertible when k= n, $Vc = -\lambda Je^{-1} e$. An approximation or estimation of Je + is essential for visual servo systems.

Manipulability and Stability

The condition number of a matrix is the ratio of its largest singular value to smallest singular value. A higher condition number indicates a poor or ill conditioned matrix. During the convergence of visual servoing the feature points will move apart and the image Jacobian will become better conditioned. This will also be a measure of the manipulability of the robot.

The Lyapunav function defined by the squared error norm $L = \frac{1}{2}\|e(t)\|^2$ is considered. The derivative is given by

$$\dot{L} = -\lambda e^{T} J_e J_e^{+} e$$

Global asymptotic stability of the system is obtained for the sufficient condition $J_e J_e^{+} > 0$.When number of features k equals the camera DOF and if Je and J_e^{+} are of full rank this condition can be ensured. But in IBVS this is not ensured since k may be greater than DOF and $J_e J_e^{+}$ belongs to ℝkxk is atmost of rank k. $J_e J_e^{+}$ has a nontrivial null space. If $e \in Ker J_e^{+}$ correspond to local minima, where error is not exactly zero but the camera velocity falls to zero, local asymptotic stability can be obtained. It has been proved that [18] IBVS is locally asymptotically stable in a small neighborhood of the target but global asymptotic stability cannot be ensured in outside this neighborhood due to the presence of local minima. A lower condition number of Je ensures that the camera is in the specified neighborhood and system stability is ensured.

4 Simulation Results

Simulation studies were carried out for the proposed control strategy with different initial conditions using Robotics and Machine Vision Toolbox in MATLAB®. Results presented include those which were to fail with IBVS alone as the camera on the end effector was not in a direction as to see the target.

After aligning in the direction of the target the camera on the end effecter was guided towards the target by the master camera. As the visibility increased and the depth decreased the interaction matrix became well-conditioned. The system switches to classical IBVS once a favorable condition number is reached. Fig. 2 shows the image plane motion with the suggested control strategy. An initial position from where the feature points are visible are chosen. But for the switching, the velocity characteristics of both IBVS and the proposed strategy were almost same. The time taken by both the strategies are same with same value of control gain chosen. On simulating with an initial position from where the feature points are not visible, IBVS failed whereas the proposed strategy showed clear results.

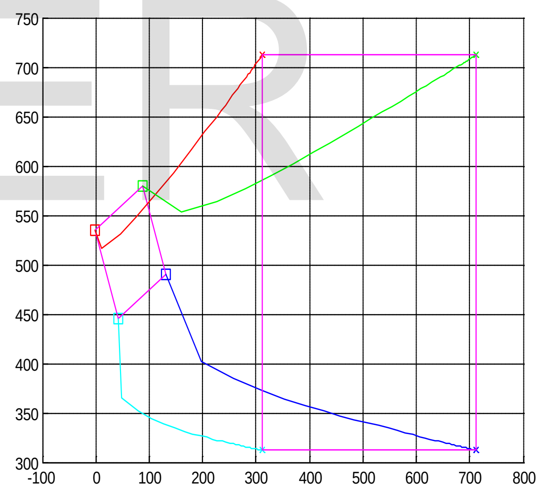
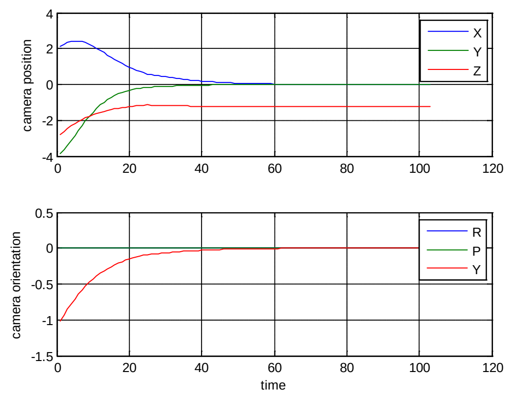
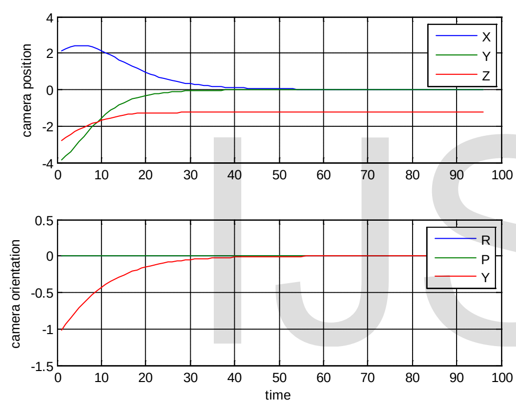


Fig. 2 Image plane motion for supervisory control

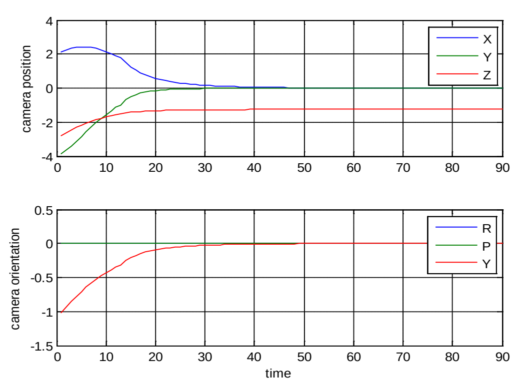
The condition number of the interaction matrix is used as the criterion for switching from the hybrid control region to the classical image based visual servoing. The camera position during visual servoing for different condition numbers are shown in figure 3.



3(a)



3(b)



3(c)

Fig. 3Camera position with different condition numbers (a) 30, (b) 50, (c) 70

Figure 4 shows the effect of selection of condition number for switching on the time to complete the task. Higher the condition number, lower is the time taken but too high values does not guarantee final convergance

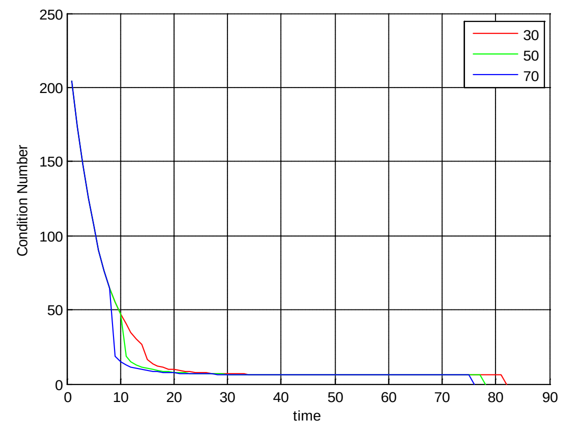


Fig. 4 Switching with different condition numbers

5 Conclusion

The control proposed in this paper switches to classical IBVS in a region near the target which is the stable neighborhood for local asymptotic stability. Visual servoing tasks were accomplished successfully by the cooperation of master camera and the eye in hand camera attached to the robot. Two controls were implemented, to align the camera in the direction of the target and then to move the camera to the neighborhood of the target prior to this switching. The selection of the gain in the control law would decide the rate at which the robot is guided. The strategy proposed in this paper is simple but stable and is well suited for large workspaces and initial configurations where the target is not initially visible. This can be further extended to coordination of more than a single manipulator.

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