Volume 12, Issue 3
June 2023

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Extending the Scope of Robot Visual Feedback with Regulatory Control

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ABSTRACT

Autonomous platforms for the operation of robots sharing workspace with other robots and operators demand effective feedback control. Visual servoing allows the adoption of the camera in the feedback control loop, exchanging tactile information between the controller and the surroundings. Interaction of more than one camera allows efficient utilisation of the workspace. This paper aims at studying a switching scheme in visual servo control with two cameras in a robotic application. The transition from control scheme and configuration help the system in overcoming regions of ambiguity posed by system constraints, ensuring convergence even with targets initially not visible for the robot. Division of the control scheme into coarse and fine approaches saves computation time. Condition Number, representing the interaction and wellness of the system matrix determines the switching in control. This paper presents at least three methods to smoothen the velocity curve during transformation between control schemes. Simulation studies show the feasibility of the methods and experimentation on a 6-DoF industrial manipulator validates the results.

Keywords: *Visual Servoing, IBVS, Supervisory Control, Interaction Matrix, Condition Number*

1. INTRODUCTION

Visual servoing is a well-studied and established component of robot automation control where the sensory information provided by the camera or other vision sensor governs the feedback control. Inherent shortcomings of conventional approaches and ever-increasing variability and complexity of workspaces led to switched and hybrid control strategies in visual feedback. A two camera robotic system guided towards the target with region based control laws ensure convergence. This paper details three approaches for improving the velocity profile of the switching scheme ensuring stable operation.

Computer vision systems play a vital role in industrial automation by collecting information from surrounding as images and processing them for object identification and control, reducing the human intervention in control systems and technologies aiming at a superior performance. Complex environments, the levity of the processes and cost efficient use of the technology demand customised solutions for industrial vision applications in manufacturing technology, product finishing, nuclear and chemical industries and robotics [1]. Visual feedback loop uses a camera appended to a robot end effector (eye-in-hand) or a fixed one (eye-to-hand) for collecting information. Image-based visual servoing (IBVS) generates signals for the robot movement by comparing current and desired sets of selected image features while position based visual servoing (PBVS) estimates the error between poses [2] offering viable, globally stable trajectories. However, a three dimensional model of the working system is required, and the tracked object may leave the camera's view. IBVS, on the other hand, is locally asymptotically stable and robust barring the singularities in image Jacobian evoked by certain targets and local minima resulting in failure [3]. The rendering of Cartesian velocity control may lead to unnecessary and complicated camera motion due to the pairing of rotational and translational components.

Combining or partitioning the control law between translational and rotational components, along the coordinate axes and time-frame or between image and pose controllers, hybrid and partitioned approaches solved the demerits of primary visual servoing [4-8]. Servoing utilises 3D information retrieved from a model of the environment or through pose estimation algorithm along with 2D data from the vision sensor. The hybrid controllers also included IBVS path planner with minimal pose error trying to keep the features in view and PBVS like controller based on homography matrices depicting initial and final camera views. Decoupling these views into translational and rotational components of the required motion defines the camera motion.

Partitioning the system into rotational and translational components to address the undefined motions like retreat of camera treats the depth as a controller gain. Rotation along the z-axis alone brings camera and desired image in the same direction. Switching between controllers not only avoids local minima, but also excludes singularities and limit constraints in joint space resulting in smooth trajectories and continuous tracking of the target. Selection of control strategy depends on value of threshold in respective regions of PBVS and IBVS.

Working in unstructured and physically limited work areas and sharing the workspaces with operators and other robots demand reliable operations. Considering the issues of limits and singularities in joint space, shifting the control strategy between IBVS and PBVS is one way of ensuring stability and convergence [9-13]. The partial but explicit sight of an eye-in-hand camera and global vision range of the eye-to-hand camera combines to give solutions in large and complicated environments where the global camera does not manoeuvre the whole scene and a local camera does not interact with the whole space [14-17]. Switching between different configurations overcomes comprehensive and local visibility constraints.

Overall stability of PBVS, robustness of IBVS, master view of eye-to-hand systems and the specific sight of eye-in-hand systems motivate the design of hybrid and switched controllers. The proven convergence of IBVS from a neighbourhood of the target puts this strategy in the

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Information Technology & Electrical Engineering

ISSN: - 2306-708X

finishing line even though the dimensions of this region are unclear. The wellness of the image Jacobian formed from the features of interest improve for this part, and the system acts as a multi-input multi-output system.

Cooperation of more than one sensor can be more appreciable in visual servoing problems liable to fail for the lack of visibility or complexity of workspaces. This paper addresses a switched scheme comprising of two cameras with global and local views ensuring convergence. The eye-to-hand camera steers the robot to a vicinity of the target from where the eye-in-hand camera carries on for partially visible or invisible initial positions. Differentially decoupling the elements of rotation and translation, in a prioritised manner would direct the robot towards the target. The criterion selected for switching depend on the value of condition number representing the wellness of the incoming control strategy. The change in control makes it a discrete event process. This paper presents three strategies for improving the velocity profile during switching. The simulations in MATLAB [18-19] and the experimentation on an ABB make IRB 1200 industrial robot [20-22] validate the proposal. The following sections would explain supervisory control, switching schemes, simulation and testing, results and conclusions.

2. REGULATORY CONTROL

Conventional approaches in visual servoing may fail under certain constraints invited by the visibility and availability of image features. Regions in workspaces can be identified where one strategy is superior over other in terms of convergence, stability or robustness, suggesting the validity of interactive configurations and switched or hybrid controls. Multiplicity and dynamics of targets, lack of visibility, indistinct features and intricate or parallel workspaces demand the fusion of data from more than one sensor for successful task accomplishment in vision-based systems.

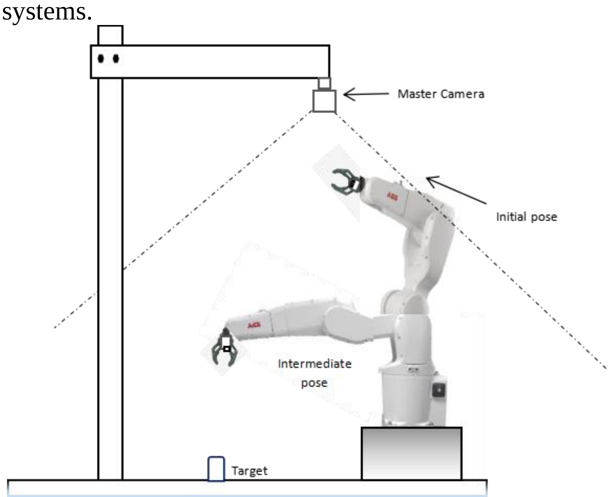

Figure 1. A two-camera robotic system

If a visual servoing task for pick and place application from an unknown environment has coarse and fine movements, the regulation by an eye-in-hand camera handles the latter better, with a closer view of the target. An eye-to-hand camera having an extensive view of the scene for identifying the target, monitoring its mobility and understanding the workspace achieves the former task easily. In terms of nature of control, local asymptotic stability of IBVS in a sufficient vicinity of the target renders it a good choice for convergence. The robotic manipulator, fitted with an eye-in-hand camera has to identify the target and pose itself to grab it using the gripper. As seen from the figure1, the robot is unable to see the target initially and needs a guidance, rather than searching for the object. The presence of a master camera ensures that an initial control strategy drives the robot to an intermediate pose suitable for switching to IBVS. Although computationally efficient, local minima, uneven camera motions and depth estimation can affect the performance of IBVS in larger workspaces and distant or similar targets, where hybrid control laws are more agile. This paper studies the effectiveness of a switch in both control and configuration with a two-camera robotic system for pick and place applications in unstructured environments. The eye-to-hand master camera is responsible for ascertaining the target and guide the robot towards it with a hybrid control law. The eye-in-hand camera of the six DOF robot then takes over for finer movements with IBVS. The control may fall back to master camera in case of uncertainties.

For a given target and robot initial pose, the master camera observes the scene and guides the manipulator such that target is visible for the end effector camera. The homogeneous transformation matrix to represent the pose of the tool attached to the robot end effector is $T_e = \begin{bmatrix} R(\theta)e & d_e \\ 0 & 1 \end{bmatrix}$; $R(\theta)$ is the rotational matrix for the rotation along the three Cartesian axes and d_e carries the position information. The target pose is $T_g = \begin{bmatrix} R(\theta)g & d_g \\ 0 & 1 \end{bmatrix}$. The control law for the initial portion uses the error between these poses $e_T = T_e \sim T_g$. Unlike conventional PBVS, in order to calculate the pose error three dimensional model of the working environment is not required. The translational and rotational components of pose of end effector forms a 6x1 vector. As the robot moves and aligns towards the target, the error decrease. The time variation of error e_T can thus be represented as

$$\dot{d} = \dot{e_T}. \quad (1)$$

This is equivalent to the spatial velocity of the end effector. The relative movement of the target V_g with respect to the end effector velocity V_e is given by,

$$V_g = J_T V_e \quad (2)$$

The Jacobian matrix J_T relates its positional Jacobian at the pose T_e using the transformation $\begin{bmatrix} R(\theta)e^T & [S(d_e)R(\theta)e]^T \\ 0_{3x3} & R(\theta)e^T \end{bmatrix}$; $S(d_e)$ represents the skew-symmetric matrix for the translational vector d^T. Both the above equations represent same motion

$$\dot{e_T} = J_T V_e. \quad (3)$$

Selecting a linear controller with a gain λ' to allow an exponential decay in the pose error,

$$\dot{e_T} = \lambda' e_T\ . \quad (4)$$

Hence the velocity of the end effector can be calculated as

$$V_e = -\lambda' {J_T}^{-1} e_T \quad (5)$$

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Information Technology & Electrical Engineering
ISSN: - 2306-708X

The control law (5) does not ensure convergence owing to the nature of vector d, rather it directs the robot towards the target. Identification of objects and its features is the prime requirement of any visual servoing system with a calibrated camera. Hence orienting the eye-in-hand camera in the direction of target has more priority than translating it. This goes by differentially decoupling the velocity components to operate two controllers in parallel. The homogenous transformation matrix of effective pose is due to high gain orientation controller and a low gain translation controller. This prevents the system from doing large computations with joint limit constraints.

With the intermediate pose, robot is in a position to see the features on the target distinctly and end effector camera can take over the control. For an observable point $p(x,y)$ in the image plane, the time variation of the point is a function of the camera velocity $V_c = (\vartheta_c,\ \omega_c)$ and J_s, the image Jacobian matrix

$$\dot{p} = J_s V_c \tag{6}$$

ϑ_c and ω_c are the translational and angular components of the velocity along three axes. As $p(x,y) = p(\frac{x}{z},\frac{y}{z})$, the projection of world points transformed by its depth z, the components of J_s are

$$J_s = \begin{bmatrix} -\frac{1}{z} & 0 & \frac{x}{z} & xy & -(1+x^2) & y \\ 0 & -\frac{1}{z} & \frac{y}{z} & 1+y^2 & -xy & -x \end{bmatrix} \tag{7}$$

The error in current $(s(p))$ and desired $(s*)$ values of target image will give the feature error as

$$e_p = s(p) - s* \tag{8}$$

The control law will try to change the image error as $\dot{e}_p = -\lambda e_p$, the controller gain being λ . The camera velocity will be

$$V_c = -\lambda {J_s}^{+} e_p \tag{9}$$

${J_s}^{+}$ is the Moore-Penrose pseudo-inverse of the interaction matrix or Image Jacobian. When the degrees of freedom equals the number of features selected, the matrix inverse solves the equation.

When the manipulator motion is small, IBVS works adequately. Hence, on sufficient proximity to the target, assuring visibility of features, the manipulator camera acquires the control of velocity. The visual servo system is hence a MIMO system having interrelated variables. The controllability of the system is dependent on the interaction of its components also. The wellness of the Jacobian matrix thus can be treated as a criterion for switching to convergent IBVS to complete the task. The change in point feature in image plane is the manipulated variable and the six element vector comprising of the linear angular components of velocity along the three axes. On examining the interaction matrix of the point features, it is clear that the first three elements (translational) alone depend on the depth and the last three bare rotational components. The interaction matrix representation as $J_s = [J(x,y,z)|J(x,y)] = J_{trans}|J_{rot}$ suggests the multivariable nature of the system (figure 2). The condition for switching is derived by analyzing the condition of the system.

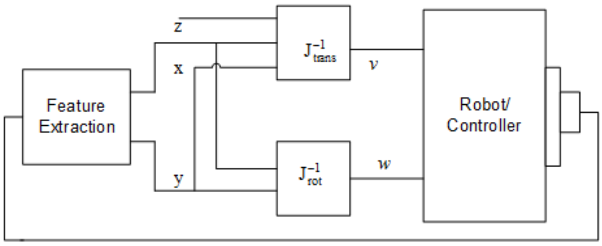

Figure 2. Multivariable nature of the visual servo

3. CONDITION NUMBER

Singular value analysis provides a powerful tool to extricate a matrix representing a system into its fundamental subspaces. SVA finds use in multivariable control problems in identifying the suiting multi-loop configurations, assessing the robustness and selecting the variables. Condition number (CN) is merely a ratio of the maximal and minimal values of the singular values of the system, which are greater than zero. It can give information about the behavior of the system with variation of its elements.

CN indicates the system performance in terms of its wellness. When the maximum and minimum singular values do not have much difference in magnitude, it will suggest wellness of the system. As the ratio increases, wellness also decreases. The multivariable nature of the system explains why IBVS is prone to failure in many occasions. The norm of the interaction matrix estimates the feature variation per unit change of camera's pose and vice versa for its inverse. CN evaluates the product of norms of the image Jacobian and its inverse, representing a way to show the easiness of inverting the matrix. The matrix needs to be non-singular for solving the equations. Lowest singular value being close to zero or highest singular value being very high can result in large value of CN, indicating interaction. The former condition shows proximity to singularity. Selection of collinear image features along the z-axis can result in singularity. The condition number has a multiplier effect and norm of the inverse affects the system most.

In the regulatory control, one has to make sure that the features are distinctly clear and visible for the eye-in-hand camera. The wellness of the matrix given by the image Jacobian ensures that IBVS will not fail. A look at the condition number of the Jacobian matrix during the coarse movement of manipulator end effector provides a benchmark for switching to IBVS. This approach is particularly beneficial for large changes and partially visible targets. Figure shows the control structure with CN as the criterion for switching. Multiple switching results when the end effector camera loses the features during IBVS which can be due to features at the image boundary or the selection of control gain. A high value of gain may result in large movements in the initial phase of servoing. A low value will slow down the system. Hence a criterion regarding the state of the system matrix will be more suitable for transferring the control

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ISSN: - 2306-708X

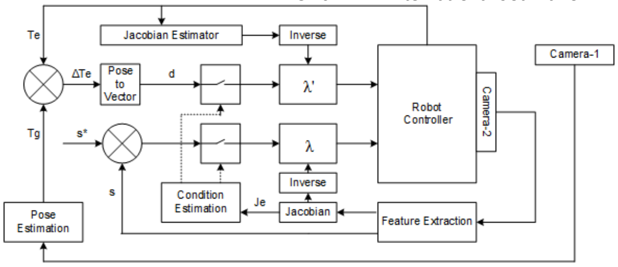
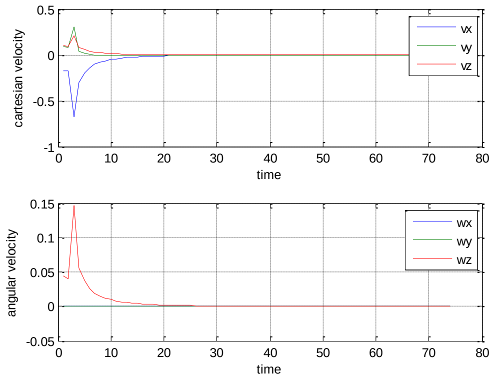
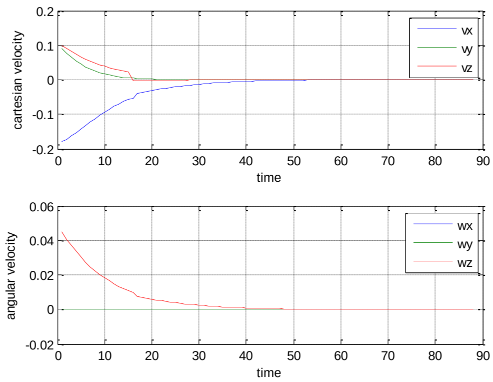


Figure 3. System model with Condition Number as the criterion for switching

For any target, if the eye-in-hand (camera-2) camera has enough visibility, it follows IBVS to reach the target. In other cases, the camera-1 estimates the target pose and the end effector pose and error is used in deriving the commands for the robot motion. Simulation studies in MATLAB shows that system performance improves with the choice of Condition Number. Two values of condition number, 100 and 40 are considered for the discussion. The velocity profile and image plane motion have smooth variation for a lower value of CN (Figures 4 and 5). The difference in magnitudes of error in the two control regions affects the velocity.



(a)

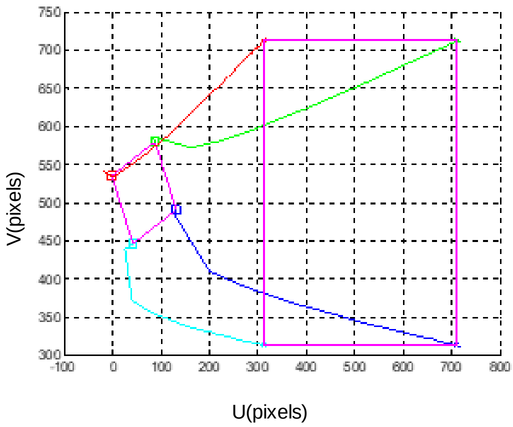


(b)

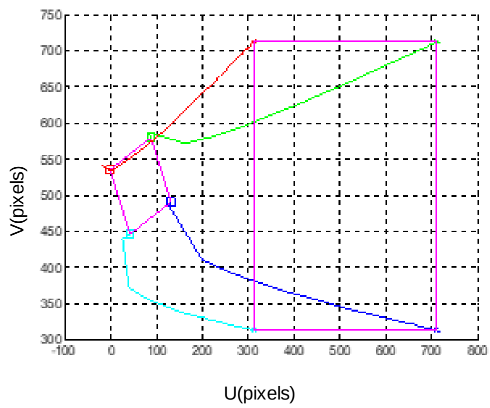
Figure 4 Velocity profile during servoing
(a) CN=100 and (b) CN=40

Observations regarding the performance of the system with CN as a criterion for switching are as follows

1. Number of control states: With the introduction of CN as the basis of adoption of the control strategy, the system has a maximum of only two states. If the object is out of the manipulator camera's field of view, camera-1 directs the end effector towards the final pose and transfers control only when manipulator camera has a clear sight of the object. Its condition number expresses the wellness of the image Jacobian.
2. Smooth velocity curve: The pose error computed by the master camera is of few meters compared with the pixel error calculated by the end effector camera. Unless the controller gain is very small, initial movement by IBVS would be high. The high change in velocity is not preferable for delicate applications. By selecting a lower value of CN, the velocity curve is smoothened.
3. Servoing time: When the value of CN is lowered and the controller gain is low, it takes more time for servoing. When implemented on the hardware, additional time will be required for image processing applications.
4. Optimal value of Condition Number: The programmer does not know the optimum value of CN, which is best, suited for convergence in terms of servoing time and tolerable jerk in velocity during switching. For example, a visible target with translation along Z-axis alone will have different condition numbers depending on their depth. In such cases, RGA (Relative Gain Array) also can be considered along with CN to determine the event of switching.



(a)



(b)

Figure 5 Image plane motion for figures

(a) 4.a and (b) 4.b

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Information Technology & Electrical Engineering

ISSN: - 2306-708X

A greater condition number indicates sensitivity to uncertainty but not necessarily shows the level of interaction in the system. This implies that system control is not easy, as it is ill conditioned. Large CN can result from the minimum singular value nearing the zero or the maximum value being very high, the former condition being undesirable for a control system. If both larger and smaller singular values are high enough, the condition number would be reasonable. A large CN caused by significant value of RGA elements is indicative of a strong interaction in the variables. This does not generalise that large RGA components in all cases do not imply this ambiguity.

4. STRATEGIES TO REFINE THE VELOCITY PROFILE

As stated earlier, when the optimum value of CN is not known, a moderate value (10-40) may be chosen

Three methods are suggested for improving the velocity profile.

4.1 Choice of controller

Controllers are designed to decrement the steady state error by comparing the controlled and desired values of a variable. They are intended to improve the stability, reduce the offsets and overshoots and respond to the error in a logical manner. Basically there are three modes in which controllers act in a loop; proportional (P), integral (I), and derivative (D). As the name suggests, a proportional controller acts according to the current value of error which is useful in reducing the steady state error and has a fast response. But they may set offsets in the system and cause overshoots to the response. Integral controllers act according to the integral value of error representing a cumulative action.

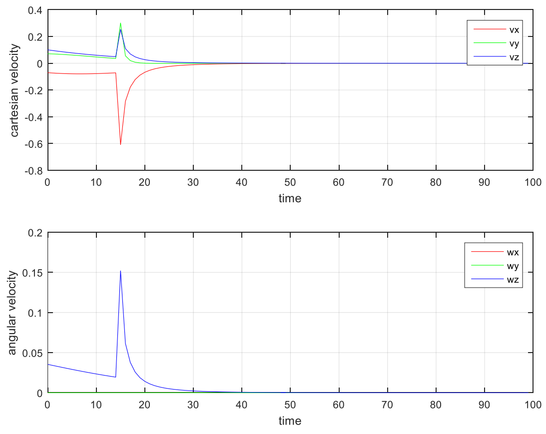
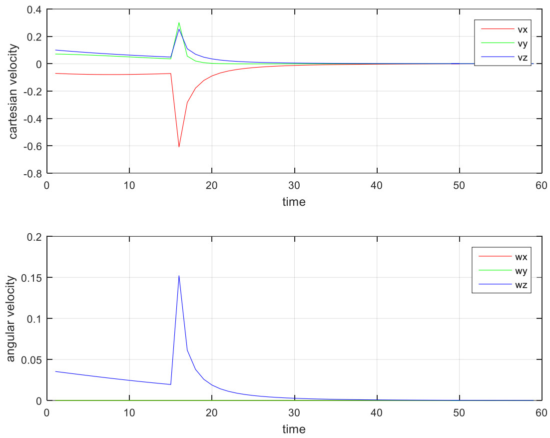


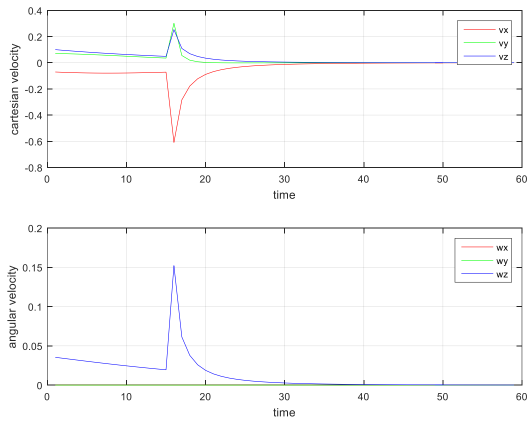
Figure. 6 Camera velocity with proportional controller

They are able to return the set point value following a disturbance in the system, but the response may be slower. The combinations of these controllers are selected for different applications.

Majority of industrial controllers are proportional or integral as the former responds to an immediate error while the latter eliminates the error when longer terms are considered. Derivative controllers react to the derivative of error in the system to improve the transient response. Unlike proportional and integral controllers, derivative controllers are known for their ability to deal with sudden changes in the system occurring from external sources. Derivative controller can act like an extrapolating function pointing to the future state based on the current values. The present state is able to draw some inference regarding the slope of the system. The derivative controller allows one to cope with the scenario when error changes consistently. From the above discussion, even though they add a proportion of complexity in the control loops, they can be useful in dealing with discrete time events. Figure.6 shows the simulation results of supervisory control with a proportional controller.



(a)



(b)

Figure. 7 Camera velocity with (a) PD and (b) PID controller

The velocity curve and image plane motion for PD (Proportional plus Derivative) and PID (Proportional plus Derivative plus Integral) for the same initial configurations is shown in Figure 7. Compared with the proportional control (figure 6), the velocity curves have been modified by PD control (figure 7.a) and PID control (figure 7.b). PID controller helps the system converge faster. The derivative term which is seldom used in control applications renders the PD response sluggish making servoing a time consuming event. But at the same time, the velocity curve is having less slope compared with the other two during switching. It is noteworthy that

Volume 12, Issue 3
June 2023

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

the choice of the constants in the control strategy too will affect the performance.

Simulation studies were carried out to evaluate the performance of controllers with addition of derivative and integral actions along with proportional control. The integral term causes faster convergence while the derivative term makes it sluggish. The former will induce large steps leading to loss of features from camera field of view. Hence only proportional control is followed in the study.

4.2 Gain adaptive controller

The static gain factor also affects the performance of the controller. Generally, the gain is kept constant throughout the process resulting in finite number of steps for the convergence. Too low value makes the servoing a time consuming event. A high value of gain is not desired in visual servoing as the camera may lose the features in single large steps, especially when the object is at the image boundary. For the systems which are subjected to discrete time events, the response will not be similar as the controller and forcing error vary. Hence the velocity curves have different values in adjacent zones in the case of supervisory control. Setting a dynamic value for the controller can curtail the bump in the velocity curve.

4.2 (a) Finite step variable gain

The gain of the incoming controller can be set to a low value as the error is unknown. By giving an increment in each iteration, its value can be made nominal during servoing. Figure 4.17 (a) shows the velocity characteristics with finite variable gain, starting with 0.001 and incrementing with 0.05 in each iteration till the gain is 0.1.

4.2 (b) Adaptive gain

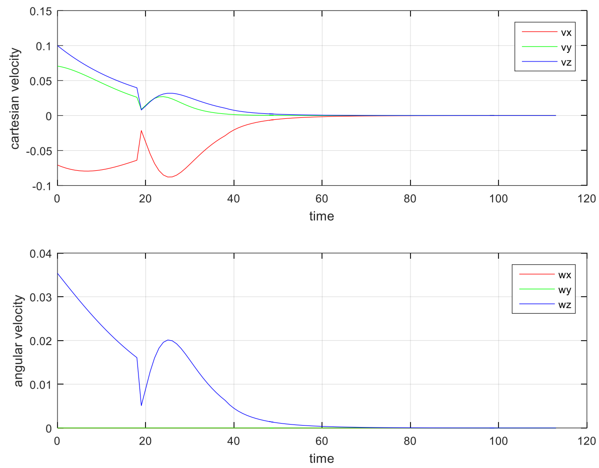
If the controller gain is set to follow the change in error norm, its value will be low if the error is maximum and vice versa. One can expect that the minimum error region experiences a higher velocity, thus reducing the settling time and thus leading to an adaptive gain control law.

For 'n' iterations to follow, the gain at each step of iteration would be

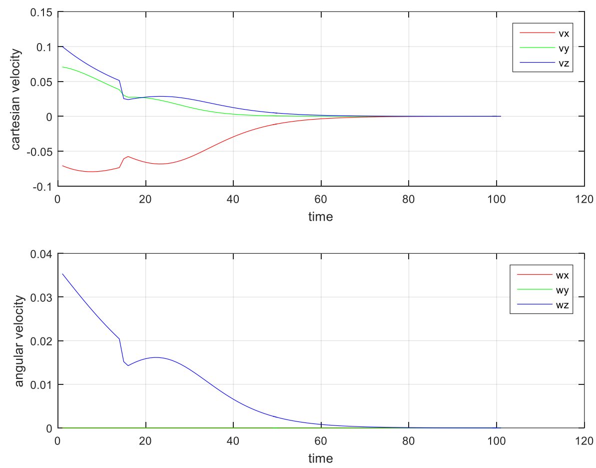
$$\lambda(n) = \lambda_{min} + \left(1 - \frac{e_n(n)}{e_{nmax}}\right)\lambda_{max}. \quad (10)$$

λ_{min} is the lower limit of gain, λ_{max} is the upper limit of gain, $e_n(n)$ is the norm of feature error at nth step of iteration, e_{nmax} is the maximum value of error norm obtained at the first step of iteration. The value of λ will always ranges between λ_{min} and λ_{max}. According to equation (10), when $e_n(n)$is maximum the gain is λ_{min} and as the error reduces the gain is gradually increased to the upper limit, λ_{max}.

The gain adaptive control is designed to vary the gain in accordance with the error norm. Initially when the target is farther, the error is maximum and the gain must be minimum to control the velocity. Larger steps can take the target out of camera field of view resulting in failure of servoing. The error at the first iteration is the maximum which is proportioned against current values of error. In the results shown, minimum and maximum values of gain are 0.001 and 0.1 respectively.



(a) Finite step variable gain



(b) Adaptive gain

Figure 8. Velocity characteristics of gain adaptive controllers

Figure 8 shows the velocity characteristics of end effector camera during visual servoing utilising finite step variable gain and adaptive gain during switching for the same initial conditions as in figure 6. In terms of simulation time both are similar but there is evident difference in the slope during switching. For delicate systems, the second strategy is better than the first considering that gain of the controller adapts exactly towards the error function of the system and guarantees a lower rate of change of velocity.

4.3 Hybrid control law

In the previous section, the adaptive gain was developed with pre-set limits for minimum and maximum values for the controller gain. A hybrid control law can be formulated by replacing the pose error by the image error during the transition. In a similar approach, the Jacobian matrix of initial control law can be replaced with the image interaction matrix. Only three image points can be selected with this approach to balance the dimensions of the matrices in the control law. With three image points, there is always a possibility of encountering a singularity, if they happen to be collinear.

If the controller gain after switching is limited by the equality $\lambda'\|e_p\| = \lambda\|e_T\|$, the rate of change of velocity can be controlled; $\|e_p\|$ and $\|e_T\|$ represent the norm of error in the two regions with proper scaling. λ' and λ are the controller gains in pose based control and image based control, respectively. With the above approach, the variation of camera velocity during servoing is shown in Figure 9. Even though the velocity characteristics are smooth, the time for servoing has not improved. From the above discussions, it is clear that adaptive gain control law is the best suited one for controlling the camera velocity

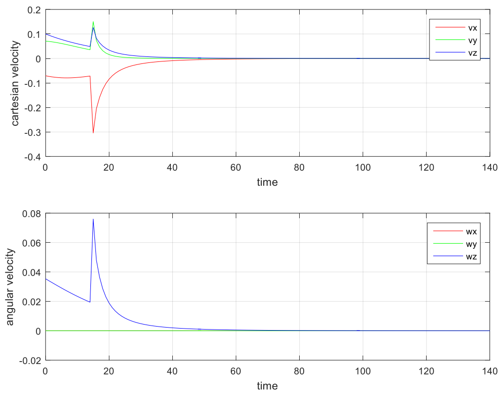


Figure 9. Camera velocity with hybrid control law

5. CONCLUSION

This work aimed at modelling a two-camera system with switching approach as a multivariable system, which is prone to loop interactions. Condition Number, being a quantitative measure of interaction is selected as the benchmark for determining the wellness of the image Jacobian to transfer the control. The neighbourhood of the target for optimum servoing is also debatable as with the selection of an optimum value of condition number. The two camera robotic system accomplished the servoing problem, through a switching approach. The control law and the gain decides the time for the robot to reach the object. The switching control scheme suffers from an uneven velocity profile. The paper presented three different approaches to smoothen the velocity curve and curtail the bump. A smooth curve is necessary especially for delicate robotic operations. The strategies are effective in checking the discrete nature of switching between strategies.

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ISSN: - 2306-708X

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