Proceedings of the 2000 IEEE
International Conference on Robotics & Automation
San Francisco, CA • April 2000

Real-Time Vision, Tracking and Control

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Abstract

This paper, which serves as an introduction to the mini-symposium on Real-Time Vision, Tracking and Control, provides a broad sketch of visual servoing, the application of real-time vision, tracking and control for robot guidance. It outlines the basic theoretical approaches to the problem, describes a typical architecture, and discusses major milestones, applications and the significant vision sub-problems that must be solved.

1 Introduction

Visual servoing is a maturing approach to the control of robots in which tasks are defined visually, rather than in terms of previously taught Cartesian coordinates. Information obtained from the vision system is used to control the motion of the robot in real-time, as opposed to older systems in which the vision system derives an initial representation of the world that is then used to plan robot motions that are executed without any use of online vision. The advantages of visual servoing are that part position tolerance can be relaxed, as can the open-loop accuracy specification of the robot. The ability to deal with parts that are moving comes almost for free.

The disadvantages of the approach are few, but the perceptions are mistakenly negative. Cost of cameras, image processing chips and computers is being driven downward at a high rate by the global demand for multi-media technology. Camera calibration as required by 'classical' robot vision systems has been shown to be not needed for many visually defined tasks.

A visual servo system utilizes elemental techniques and technologies from real-time computer vision, visual tracking and control. Computer vision and robotics each have a long history of research and a considerable literature. Visual servoing can be considered the fusion of computer vision, robotics and control and has been a distinct field for over 10 years, though the earliest work dates back close to 20 years. Over this period several major, and well understood, approaches have evolved and been demonstrated in many laboratories around the world. Fairly comprehensive overviews of the basic approaches, current applications, and open research issues can be found in a number of recent sources, including [1–4].

The next section, Section 2, describes three basic approaches to visual servoing. Section 3 provides a 'walk around' the main functional blocks in a typical visual servoing system. Some major milestones and proposed applications are discussed in Section 4. Section 5 then expands on the various vision sub-problems that must be solved for the different approaches to visual servoing. Finally Section 6 gives an outline of the accompanying technical papers in this mini-symposium.

2 Basic Approaches

There are two basic approaches to visual servo control: Image-Based Visual Servo (IBVS), in which an error signal measured directly in the image is mapped to actuator commands; and, Position-Based Visual Servo (PBVS), in which computer vision techniques are used to reconstruct a representation of the 3D workspace of the robot, and actuator commands are computed with respect to the 3D workspace. We give here a very brief description of these two, as well as hybrid approaches that combine the two. Later, in Section 5 we will describe a few of the computer vision problems that are relevant to these approaches.

2.1 Position-Based Visual Servo:

In PBVS systems, features are extracted from an image, and subsequently used to compute a (partial) 3D reconstruction of the Euclidean environment or of the motion of a target object in the environment [5–9]. An error is then computed in the Euclidean task space,

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and it is this error that is used by the control system. Thus, the actual control problem confronted by a PBVS system is the classical robotics problem of tracking a Cartesian trajectory.

2.2 Image-Based Visual Servo:

In an IBVS system the pose estimation is solved implicitly — if the current view of the object matches the desired view then the object must be in the desired relative pose. More formally let $\mathbf{r}$ represent coordinates of the end-effector in some parameterization of the task space, and $\dot{\mathbf{r}}$ represent the corresponding end-effector velocity. Let $\mathbf{f}$ represent a vector of image feature parameters and $\dot{\mathbf{f}}$ the corresponding vector of image feature parameter rates of change. If the image feature parameters are point coordinates these rates are image-plane point velocities. The image Jacobian, $\mathbf{J}_v$, is a linear transformation that maps end-effector velocity to image feature velocities,

$$\dot{\mathbf{f}} = \mathbf{J}_v(\mathbf{r})\dot{\mathbf{r}}. \tag{1}$$

The image Jacobian was first introduced by Weiss *et al.* [10], who referred to it as the *feature sensitivity matrix*. It is also referred to as the *interaction matrix* [11] and the **B** matrix [12, 13]. Other applications of the image Jacobian include [14–17].

The most common image Jacobian is based on the motion of points in the image. This Jacobian method has been used by many researchers, including [11–14, 16, 18–21]. Suppose that the end-effector is moving with angular velocity $\Omega_e = [\omega_x, \omega_y, \omega_z]$ and translational velocity $\mathbf{T}_e = [T_x, T_y, T_z]$, both with respect to the camera frame in a fixed camera system. Let P be the coordinates of a point rigidly attached to the end-effector, expressed with respect to the camera frame. If λ is the focal length for the camera, and $(u, v)^T$ are the image-plane coordinates of the point P, then the velocity of the point P, again expressed relative to the camera frame, is given by

$$\dot{P} = \Omega_e \times P + \mathbf{T}_e \tag{2}$$

If $P = [x, y, z]^T$, then the image Jacobian is given by

$$\begin{aligned} \mathbf{J}_v &= \begin{bmatrix} \frac{\lambda}{z} & 0 & \frac{-u}{z} & \frac{-uv}{\lambda} & \frac{\lambda^2 + u^2}{\lambda} & -v \\ 0 & \frac{\lambda}{z} & \frac{-v}{z} & \frac{-\lambda^2 - v^2}{\lambda} & \frac{uv}{\lambda} & u \end{bmatrix} && (3) \\ \dot{\mathbf{r}} &= [T_x, T_y, T_z, \omega_x, \omega_y, \omega_z]^T && (4) \\ \dot{\mathbf{f}} &= [\dot{u}, \dot{v}]^T && (5) \end{aligned}$$

which relates image-plane velocity of a point to the relative velocity of the point with respect to the camera. Derivations of this can be found in a number of references including [2, 22, 23].

The simplest approach to IBVS is to merely use this Jacobian relationship in the simple control law

$$\mathbf{u} = \mathbf{J}_v^{-1}(\mathbf{r})\dot{\mathbf{f}}, \tag{6}$$

where $\dot{\mathbf{f}}$ is the desired feature motion on the image plane, and $\mathbf{u} = \dot{\mathbf{r}}$ is the control input, an end-effector velocity. Of course this approach assumes that the image Jacobian is square and nonsingular. More sophisticated approaches can be found in a variety of sources, including [24] where state space design techniques are used, and [11] where the task function approach is used.

2.3 Hybrid Methods

Hybrid methods use IBVS to control certain degrees of freedom while using other techniques to control the remaining degrees of freedom. Visual compliance [14] is a method in which IBVS is used to control translation parallel to the image-plane, while the Cartesian position control is used to control depth. Such an approach is useful, for example, for performing insertion tasks, in which lateral degrees of freedom have tight uncertainty constraints [25].

In [26], 2.5D visual servo is introduced. In this approach, IBVS is used to control translational degrees of freedom, while the epipolar geometry of the current/desired images is used to estimate the desired rotational motion. However such rotational motion may cause feature points to leave the image-plane, and Morel et al. [27] propose visual servoing on the spatial bound of the points to prevent this. Another hybrid approach in this spirit is [28].

3 The grand tour

Figure 1 shows a generalized block diagram of visual servo system that represents the two basic approaches to visual servo control. We now discuss each of the elements in turn to highlight the similarities and differences in the two methods.

3.1 Robot

The robot is considered to be a velocity controlled device, with a command input $\dot{r}$, a velocity screw, and output x which is the Cartesian pose. It is easiest to consider the case where the robot has 6DOF but the more general case is covered in [2]. It is generally assumed that the robot's joints are fitted with encoders, which allows for high-quality motion control at the axis level.

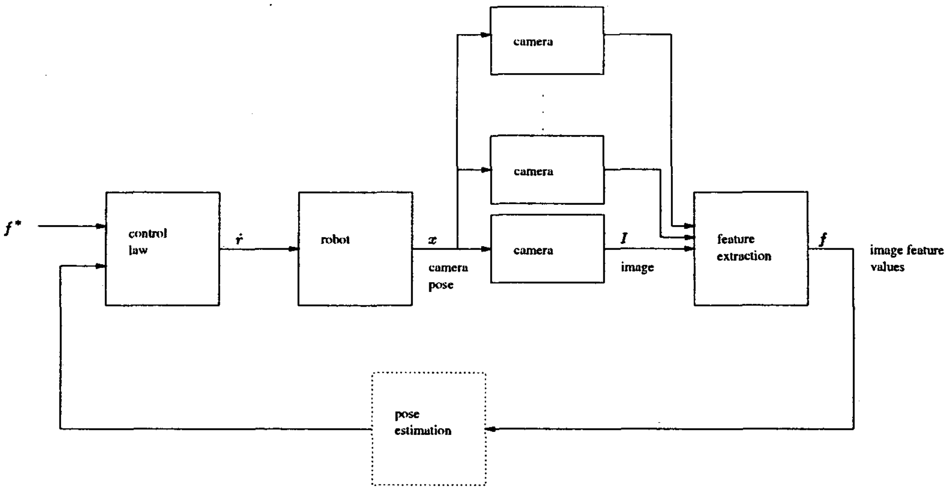

Figure 1: Generalized schematic of a modern visual servo system.

3.2 Camera

The output of a camera is an image, a 2D intensity function which is a perspective projection of the scene and which generally depends on the robot as well as the targets in the scene. In general it is possible to have multiple cameras which may be mounted on the robot ('eye in hand') or fixed in the world observing just the target ('end point open loop') or observing the target *and* the robot ('end point closed loop'). The latter configuration has the particular advantage that motion accuracy is independent of camera calibration.

A camera is much more than just a black box with a focus adjustment. Downstream computer vision tasks are simplified if the image is of high quality and this requires knowledge of the tradeoffs involved with lighting, exposure time, depth of field, signal to noise ratio and so on (see [3] for more details). Cameras are also dynamical systems and introduce a pure time delay into the control structure.

Most researchers make use of commodity cameras that conform to RS170 or PAL video standards with sample rates of 30 Hz or 25 Hz respectively. More recently digital output cameras are available with a wide variety of frame rates and pixel array sizes. Commonly the analog signal from the camera is digitized and stored in a block of memory on the "framegrabber" card. Recently the move has been toward PCIbus interfaces which have no on-board memory but stream the video by DMA into host processor memory. Digital cameras have the digitizer and memory built into the camera, and allow retrieval of arbitrary pixel regions.

3.3 Feature extraction and tracking

Feature extraction is the computer vision task of finding numerical values of measures associated with visual features corresponding to the target or robot in the scene. Point features, described above, are perhaps the most popular, but are certainly not the only features that have been used in visual servo control research. Other features that have been used include the distance between two points in the image plane and the orientation of the line connecting those two points [15, 29], perceived edge length [30], the area of a projected surface and the relative areas of two projected surfaces [30], the centroid and higher order moments of a projected surface [17, 30–32], the parameters of lines in the image plane [11, 33] and the parameters of an ellipse in the image plane [11]. Of course, each different image feature requires its own specific image Jacobian, and these can be found in the references listed above.

Locating features in an image involves sifting through a significant amount of data, for example at 30 Hz with 512×512 pixels, this is nearly 8Mbyte/s. In the 1980s and early 1990s this problem was tackled with specialized hardware [34] or expensive pixel-rate processing systems from companies such as from Datacube or ITI.

In general the features occupy a very small number of pixels in the scene and their position can be predicted based on past history, thus enabling a general purpose computer to extract features at video rates by restricting its attention to just these regions. Figure 2 shows the general form of a feature tracker. The

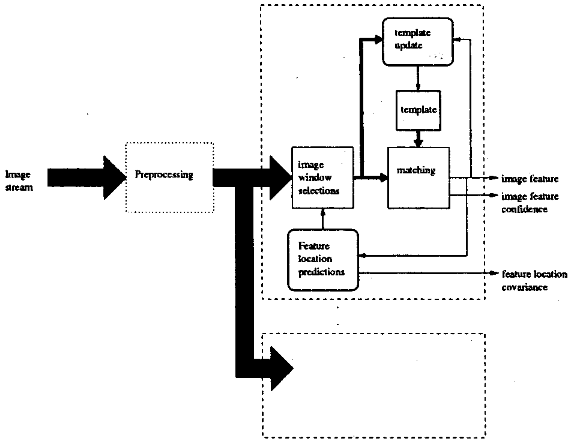

Figure 2: Generalized feature tracker.

matching operation can be performed by a number of classic computer vision techniques such as SAD, SSD or NCC in software or using special purpose matching chips. Output from the tracker also includes the quality of the match and the covariance of its location estimation. Changes in lighting or partial occlusion may reduce match quality, and high velocity or occlusion may decrease confidence in the location estimate.

It is interesting to observe that while the vision sensor provides input to the robot's control system, the vision task may in turn contain control tasks, for example to track visual features in the scene. A more complete exploration of the interrelationship between vision and control can be found in [1].

Feature values are always obtained some time after the camera 'sees' the scene, and thus lag behind the current state of the world. Prediction can be used to compensate for this, typically based on a first-order feature motion model which requires an estimate of feature velocity.

3.4 Pose estimation

For PBVS the pose estimation function uses a geometric object model and observed image features to estimate the Cartesian pose of the object. There is a large literature on this topic, and many real-time solutions have been demonstrated. Classical IBVS systems do not require this step, but hybrid approaches have various levels of pose estimation.

3.5 Control

The final block in the loop is that marked control which must generate appropriate robot velocity commands so that the image features, or the object pose, asymptotically approach the demand.

For the IBVS case the control problem is non-linear and requires an accurate local linearization, the image Jacobian, to achieve stability. The main difficulty in achieving this is accurately determining feature depth, as mentioned in Section 5.2.

The visual servo system is generally a discrete-time dynamic system, often containing multiple sample rates. The controller must therefore account for the dynamics of the various blocks which are often pure time delay. Since the open-loop system contains an integrator, the robot has velocity input and position output, it is of Type 1 and should therefore have zero steady-state error with respect to a static target. However for a uniformly moving target, the tracking problem, there will be a constant offset. Corke [3] evaluates different controllers for this tracking problem and introduces a performance measure to facilitate quantitative comparison.

4 History and applications

4.1 Some milestones in visual servoing

The earliest work is generally considered to be that of Shirai and Inoue [35] in 1973 who describe how a visual feedback loop can be used to correct the position of a robot to increase task accuracy. The term visual servoing was coined later, in 1979 by Hill and Park [36] at SRI.

In 1980 Weiss made the distinction between position-based and image-based visual servoing[1] and went on to investigate image-based techniques. In 1984 at Bell Labs Ganapathy demonstrated 6-axis position-based control of a robot based on an analytic pose recovery technique [7].

Feddema [15, 29, 37] demonstrated the first IBVS system, but used an explicit feature-space trajectory generator and closed-loop joint control to overcome problems due to low visual sampling rate. Rives et al. [38] formalized the IBVS approach and investigated various features such as points, lines, and ellipses. They also applied the task function method of Samson [39] to the problem.

Wilson and colleagues [5, 6, 40] have progressed the PBVS approach, and use extended Kalman filtering for pose estimation and feature prediction.

In 1993 Corke [41] introduced feature prediction and feed-forward control techniques to achieve stable high-performance feature tracking.

In 1998 Malis and Chaumette [26, 42] introduced the first hybrid PBVS and IBVS system, the "2.5D approach" which uses partial pose estimation (rotation

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[1] Though his terminology is no longer in current usage.

only).

4.2 What has it been used for?

Although we know of no current production application, visual servoing has been proposed for a great variety of applications over many years. A more comprehensive list of applications is given in [3].

At SRI International during the late 1970s visual feedback was demonstrated for picking moving parts from a conveyor [43], and tracking a swinging part [44]. More recent work on part grasping includes Zhang et al. [45] who describe visually servoing a robot to pick items from a fast moving conveyor belt (300 mm/s) and Allen et al. [46] who describe grasping a toy train moving on a circular track. In a non-manufacturing context visual guidance has been used for fruit picking [47] where the the target may be moving in an unpredictable manner due to wind disturbances. Skofteland et al. [48] describe the applications to grasping free-floating objects in space.

Part mating applications of visual servoing date back to Geschke [49] who described a bolt-insertion task using stereo vision. Ahluwalia and Fogwell [50] describe a system for mating two parts, each held by a robot and observed by a fixed camera. On a larger scale, visually servoed robots have been proposed for aircraft refueling [51] and demonstrated for mating an umbilical connector to the US Space Shuttle from its service gantry [52].

In other manufacturing applications simple hand-held light stripe sensors have been used for planar applications such as connector acquisition [53], weld seam tracking [54], and sealant application [55]. Weber and Hollis [56] developed a high-bandwidth planar-position controlled micro-manipulator to counter room and robot motor vibration effects with respect to the workpiece in a precision manufacturing task.

Visually guided machines have been built to emulate a wide variety of human skills including ping-pong [34, 57], juggling [9], inverted pendulum balancing [58,59], catching [60,61], and controlling a labyrinth game [59]. Skaar et al. [20] use as an example a 1-DOF robot to catch a ball.

Visual servoing has also been applied to the control of different sorts of vehicles. Dickmanns, for example, has described road vehicle guidance [58] and aircraft landing [62]. Control of underwater robots using visual reference points has been proposed [63].

The use of visual servoing in a telerobotic environment has been discussed by Yuan et al. [8], Papanikolopoulos et al. [24] and Tendick et al. [64]. Visual servoing can allow the task to be *specified* by the human operator in terms of selected visual features and their desired configuration and *executed* by the visual servo system.

5 Vision Problems

Each of the approaches described in Section 2 brings its own set of vision-related problems. Here we give a brief overview.

5.1 PBVS

The obvious vision problem confronted by a PBVS system is the task of 3D scene reconstruction. While there are many methods aimed at this general problem [65], these are not generally applicable to PBVS due to its real-time constraints and their reliance on precise calibration of the vision system. Furthermore, there are often aspects of the task that can be used to constrain the solution to the reconstruction problem. For example, Kalman filtering techniques that incorporate some knowledge about object dynamics can improve the accuracy and speed of the reconstruction algorithm. Finally, full 3D reconstruction of the environment is rarely necessary, since it is generally necessary to reconstruct only those features that directly determine an object's motion.

5.2 IBVS

As can be seen in equation (3), the image Jacobian is a function of the unknown depth, z. A number of researchers have proposed methods for dealing with this problem. The classical solution is to use standard computer vision techniques to estimate the value for z [15]; however, this approach amounts to performing a 3D reconstruction of the scene, and brings with it the same drawbacks faced by position-based visual servo schemes.

A second approach is to estimate the value of z online, as demonstrated by Papanikolopoulos et al. [24] using adaptive control techniques. Hosoda [66], Jägersand [67] and Piepmeier [68] have shown how the Jacobian matrix itself can be estimated online from measurements of robot and image motion. Finally, one can merely assume a constant value for the depth [11], an approach that is reasonable if the motion of the object remains approximately in a plane parallel to the image plane.

A second problem with IBVS is the use of the inverse or pseudo-inverse of the image Jacobian. Clearly, if the Jacobian is not full rank, such methods fail. Thus the existence of singularities in the image Jacobian is a problem confronted by IBVS systems. From the computer vision point of view, these singularities correspond to configurations at which specific motions cannot be observed by the vision system [69]. These problems manifest themselves in a variety of ways, some of which are described in [42]. Even if the Jacobian is of full rank features can be dynamically selected so as to maximize the condition of the matrix [29], or redundant features can be used [16].

Finally, because the control law is effected in the image plane, the path of the end-effector can be erratic, even causing the target features to leave the camera's field of view [27].

5.3 Hybrid Methods

The hybrid methods reported to date [26–28] have used epipolar geometry to determine the rotational component of camera motion while using a traditional IBVS approach to determine the translational component of the velocity. These methods rely on the online computation of the epipolar geometry of the camera [70], which amounts to computing a homography between two images. This homography is encapsulated in the fundamental matrix (for uncalibrated cameras) or essential matrix (for cameras with internal parameters calibrated). The homography must then be decomposed to extract the rotational component and the problem of non-unique solutions must be dealt with.

6 The Mini-Symposium at a Glance

The papers in this mini-symposium address many of the problems outlined above. A brief overview is as follows. The paper by Chaumette and Malis addresses the problems of IBVS. Specifically, this paper describes how 2-1/2-D visual servoing (a hybrid method) can be used to solve the problem of erratic end-effector trajectory. The paper also addresses the problem of determining the depth parameter used in the image Jacobian matrix. The paper by Hager and Dodds discusses how complex tasks can specified in terms of primitive actions on visual features. The paper by Vincze addresses the issues of visual servo dynamics, control system design, and the effect of different processor architectures on closed-loop performance. Finally, the paper by Nakabo, Ishikawa, Toyoda and Mizuno addresses issues related to high-speed target tracking.

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