Visual servoing in medical robotics

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Abstract

The paper achieves a review of visual servoing approaches and their use in medical robotics.

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1 Introduction

Visual servoing, also known as vision-based control, relies on techniques from robotics, imaging, image processing, vision and control theory (figure 1). It refers to the use of informations measured in an image flow to control the motion of a robot.

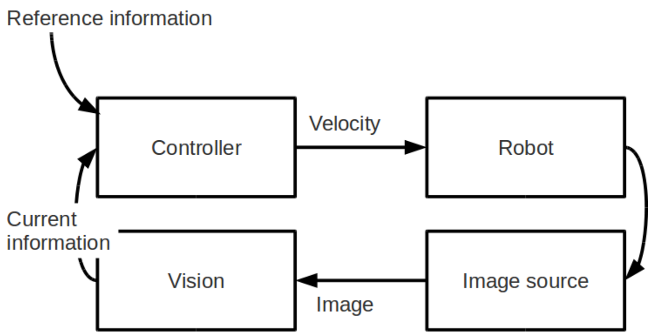

Figure 1: Modelling of visual servoing.

The latter may be a manipulator, a mobile robot or a micro-nano-robot. The informations reflect the relative spatial position between the image source and the robot, and may be 2D data as well as 3D data. In the former case the image source may be a camera, a microscope, an ultrasound, a fluoroscope,

... In the latter case it may be a stereo-camera, a CT scanner, a MRI, a 3D ultrasound, ...

Visual servoing is fundamentally a nonlinear control problem because of the nonlinear behavior of the couple (robot, image source). It also may include a delay in the loop because of the time required to perform image acquisition and processing and information tracking (Chaumette and Hutchinson, 2006),(Chaumette and Hutchinson, 2007), (Chaumette and Hutchinson, 2008), (Gangloff et al., 2012).

Visual servoin have been used for the automation of many robotic applications like:

- industrial applications like welding, assembly, painting, material transfer (Hägele et al., 2008),
- underwater and space applications like exploration and manipulation (Yoshida and Wilcox, 2008),(Antonelli et al., 2008),
- medical applications like surgery (Taylor et al., 2008), (Troccaz, 2012).

2 Taxonomy

According to the link between image source and robot, two configurations may considered:

- the source is mounted on the robot and then the motion of the robot induces that of the source, this corresponds to the *eye-in-hand* configuration,
- the source is fixed in the workspace and then observes the motion of the robot, this defines th *eye-to-hand* configuration.

The latter case is mandatory if the imaging system is too heavy to be carried by the robot, typically for a microscope, a CT scanner, a MRI. Actually, in medical robotics, this configuration is often used even if image source is not heavy, notably endoscope. However, the mathematical developments of both cases are similar to the minus sign near.

The control signal delivered by visual servoing is the velocity of the camera (image source) in the robot frame: visual servoing is a kinematic control. However two cases may be considered according to the mode of operation.

- If the robot has a joint position controller, which is the case of most commercial robots, the velocity has just to be integrated during the sampling period to obtain the joint position that is applied to that joint controller. The advantage of this *kinematic* mode is the benefit of a pure integrator in the loop. But its drawbacks are: the slowness and no taking account of any sampling effect, digital to analog conversion errors and dynamic effects. This approach has been used to control conventional industrial robots (Chaumette and Hutchinson, 2008) as well as micr-robots for manipulation and assembly (Tamadazte et al., 2010).

- On the other hand, if the robot has no joint position controller, a dynamic modelling of the robot is required in order to establish the link between velocity, position, torque and control voltage. The advantage are the rapidity and the tacking into account of sampling, conversion and dynamic effects. This approach has been used in a cardiac surgery experiment to track the beating motion of the heart. The loop is clocked at 500 Hz using an eye-to-hand camera viewing both the end-effector of the robot and the myocardium of the beating heart (Ginhoux et al., 2005). Also it has been used to control a parallel robot whoses acceleration reaches 16 m/s^2 (Dahmouche et al., 2012).

According to the type of information involved three cases may considered.

- In 2D visual servoing or Image-based visual servoing (*IBVS*), reference and current informations are of the type 2D computed directly in images. They may be coordiantes of interest points, equations of lines, intensity of pixels, entropy of images, ... This visual servoing approach gives very precise results but suffers from the non control of the trajectory in the space which can gives indesirable trajectories. It has been used to perform handling of 400 μm $\times$ 400 μm $\times$ 100 μm $\pm$ 1.5 μm silicon parts with a final precision of 2 μm and $7{\times}10^{-3}$ radian for position and orientation respectively (Tamadazte et al., 2009).

- In 3D visual servoing or Position-based visual servoing (*PBVS*), informations are of the type 3D and computed from 2D informations of images. They are the position and orientation of the target. This approach enables accurate trajectories of the robot in the space but is less precise because of the errors of calibration and computation. It has been used to perform assemby of 400 μm $\times$ 400 μm $\times$ 100 μm $\pm$ 1.5 μm silicon parts by their grooves of 100 μm $\times$ 100 μm $\times$ 100 μm $\pm$ 1.5 μm with a final precision of 4 μm and $0.4{\times}10^{-3}$ radian for position and orientation respectively (Tamadazte et al., 2010).

In both cases the challenge is the accurate tracking of informations in images (Chaumette and Hutchinson, 2008).

Both 2D and 3D informations also can be combined to perform visual servoing (Malis and Chaumette, 2000).

3 Discussion

A review of visual servoing is achieved in the paper, with particular attention to medical robotics experiments. Visual servoing is classified with respect to many point of views:
- configuration, this leads to eye-in-hand and eye-to-hand visual servoings,
- mode of operation which leads to kinematic and dynamic visual servoings,
- type of information which leads to 2D and 3D visual servoings.

Each class has some advantages and some disadvantages.

Visual servoing has been used in a lot of robotic surgery experiments excepts phonosurgery. But it has many interesting properties that can benefit to this surgery, particularly to its *micro* version.
- Eye-to-hand configuration will be the appropriate solution. Indeed, it is more practical to uncouple imaging and laser steering device.
- The mode of operation will be clearly the dynamic one because of its ability to perform very fast control as required by laser. A low laser steering can induce serious damages to tissues and should be avoided.
- For the informations, each type described above can be used. But if the constraints allow, the ideal solution will be 3D position of laser spot on tissue that includes lateral and depth position. A stereo imaging system can be used to derive that 3D position.

Any way visual servoing in laser phonomicrosurgery faces many challenges, notably:

1. design of tiny endoscope system that can bring imaging, laser and other tools close to the vocal folds,

2. monofocal and stereofocal calibration of image source in the containment of the larynx,

3. accurate fast tracking and steering of laser spot.

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