Proceedings of the Third International WLT-Conference on Lasers in Manufacturing 2005, Munich, June 2005

Robot-sensor synchronization for real-time seam-tracking in robotic laser welding

M.W. de Graaf, R.G.K.M. Aarts, J. Meijer and J.B. Jonker

University of Twente - Laboratory of Mechanical Automation
P.O. Box 217 - 7500 AE Enschede - The Netherlands

m.w.degraaf@utwente.nl

Abstract

The accuracy requirements of laser welding put high demands on the manipulator that is used. To use industrial six-axis robots for manipulating the laser welding optics, sensors measuring the seam trajectory close to the focal spot are required to meet the accuracy demands. When the measurements are taken while the robot is moving, it is essential that they are synchronized with the robot motion. This paper presents a synchronization mechanism between a seam-tracking sensor and an industrial 6-axis robot, which uses Ethernet-based UDP communication. Experimental validation is carried out to determine the accuracy of the proposed synchronization mechanism. Furthermore, a new control architecture, called trajectory-based control is presented, which embeds the synchronization method and allows various sensor-based applications like teaching of a seam trajectory with a moving robot and real-time seam-tracking during laser welding.

Keywords: laser welding, seam sensors, robotics, real-time, seam-tracking, synchronization

1 Introduction

Programming the robot for laser welding is a time-consuming task, especially if complex 3D seams have to be welded. Because laser welding puts high accuracy requirements on the final position of the laser beam with respect to the seam trajectory, seam-tracking sensors are required for complex welding tasks [1].

In general two strategies can be distinguished for sensor-guided robotic laser welding:

- Teaching of seam locations with the sensor in a first step (seam teaching), laser welding in a second step.
- Real-time seam tracking during laser welding. Provided the sensor is mounted some distance in front of the laser beam it can be used to correct the welding trajectory during welding.

Seam teaching has the advantage that the velocity is not prescribed by the welding process. Therefore it can be done using point-to-point movements, where the robot stops moving and stabilizes after every step. This increases the accuracy as dynamic robot behaviour and synchronization errors between robot joint measurement and sensor image acquisition can be avoided. In a production environment the second method would probably be preferred as it makes the separate step of teaching the seam locations in a product obsolete, and thus saves time and money.

However, because the seam-tracking sensor is attached to the end-effector of the robot arm its measurements can not directly be used during a robot movement. The sensor measurements will only be useful if the location of the sensor in the robot workspace (found from the robot joints) is known at the same time. This can be accomplished in two ways:

- Let the robot make a movement and wait until it stabilizes. Because the robot is stabilized the location of the sensor in the robot workspace does not change in time. If a sensor measurement is done the corresponding robot position can therefore easily be found.
- If a sensor measurement is obtained during the robot motion, the time axis of the robot and the sensor need to be synchronized, such that the time a sensor measurement is made is known from the robot time perspective. If these are synchronized the robot joints can be interpolated to match the sensor measurement with the robot joints or vice versa.

This paper starts with an overview of the coordinate frames that exist in a sensor-guided robotic laser welding unit, because these are of great importance for a good understanding of such a system. A description of the used equipment is given in section 3. This section also proposes a new control structure for sensor-guided robotic laser welding, called trajectory-based control. Section 4

[1] This research is partly supported by the European Commission within the Fifth Framework Programme under project number CRAF-1999-71322 and acronym SenseLasBot.

[2] The practical help of H. During with the experiments is greatly appreciated

describes the synchronization mechanism that is used to synchronize the robot joint measurements with the image acquisition of the seam-tracking sensor. Experiments have been carried out to determine the time delay of the synchronization procedure. Furthermore, an analysis of the synchronization accuracy is made. Finally, conclusions will be drawn and recommendations will be given.

2 Coordinate frames

To describe the position and orientation of points or bodies with respect to each other a coordinate system or frame is usually attached to each body. A transformation describes the location (position and orientation) of a frame with respect to a reference frame. Many ways exist to mathematically describe the orientation between two coordinate frames, like yaw-pitch-roll, Euler angles, Euler parameters, direction cosines, or rotation matrices [2]. In this work position and orientation are combined by using a homogeneous transformation matrix as described by Craig [3]. An overview of the different frames and transformations that are used in this work is given in figure 1. A more general overview can be found in De Graaf et al [4].

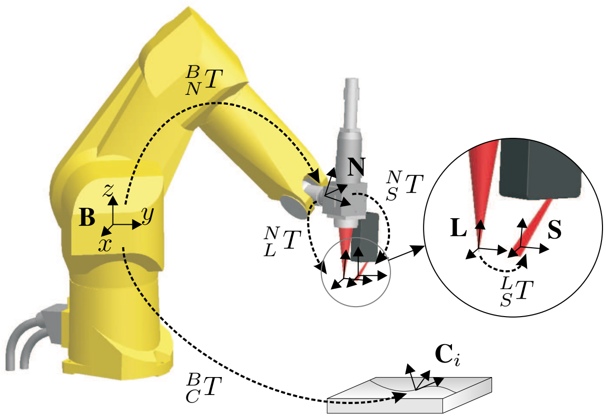

Fig. 1: *Frames for sensor-guided robotic laser welding*

Frames are indicated by a capital. Transformations are indicated by the symbol T with a leading superscript, that defines the reference frame they refer to. The leading subscript defines the frame they describe. The following frames can be distinguished:

- Base frame **B**. This frame is attached to the robot base. It is used as a reference frame and does not move with respect to the environment.
- Null frame **N**. The Null tool is located at the end of the robot flange. The Null frame is described with respect to the Base frame by coordinate transformation ^B_NT, which is a function of the values of the joint angles of the robot arm (forward kinematics).
- Laser tool frame **L**. The Laser tool is located at the Tool Center Point of the laser beam, where the z-axis coincides with the laser beam axis. Because the laser beam is axi-symmetric, the direction of the x-axis is arbitrary. It will be chosen in the direction of the Sensor tool. The transformation ^N_LT describes the laser tool frame with respect to the Null tool frame. This is a fixed transformation determined by the geometry of the welding head.
- Sensor tool frame **S**. The seam tracking sensor is fixed to the welding head and therefore indirectly to the robot flange. The transformation ^N_ST describes the sensor tool frame with respect to the Null frame, where the x-axis of **S** is chosen in the welding direction. Note that, because both transformations are fixed, this transformation can also be described with respect to the laser tool frame instead of the null tool by transformation ^L_ST.
- Seam frames $\mathbf{C}_i$. Every discrete point on a seam can be described with a different coordinate frame, which is the reason the index i is used. The transformation $^B_CT_i$ describes seam frame i with respect to the base frame.

The seam-tracking sensor can measure a location ^S_CT on the seam trajectory with respect to its own coordinate frame **S**. To store a seam location with respect to a fixed coordinate frame in the robot work cell (e.g. base frame **B**) the transformation ^B_ST needs to be known at the same time as the transformation ^S_CT. The transformation ^S_CT is derived from the sensor image by image processing, whereas the transformation ^B_ST can be calculated from the robot joint angles and the known sensor tool transformation ^N_ST. Therefore to accurately calculate a single seam location ^S_CT, the robot joint measurements need to be synchronized with the sensor image acquisition.

3 System description

The important pieces of equipment that can be distinguished in the system are the following:

- 6-axis robot arm from the Stäubli RX series, which is an accurate industrial robot with a specified repeatability of 25 μm.
- Stäubli CS8 robot controller with Low-Level-Interface (LLI) software. The LLI is a C/C++ software Application Program Interface (API), used to program the robot on a very low-level inside the controller. The robot must be provided with joint angle and joint velocity setpoints every 4 ms and in order to move it smoothly, the programmer must take care of correctly calculating these setpoints. The measured joint angles are also available at a rate of 4 ms. The LLI can be programmed using the real-time operating system VxWorks. It provides the programmer with means to access the robot on the basic level that is required for the synchronization method that is presented in this work. More information on the LLI can be found in Pertin and Bonnet-des-Tuves [5].
- Falldorf Sensor GmbH seam-tracking sensor. The working principle of this sensor is based on optical triangulation using structured light. The sensor can extract the 3D-position and 1 orientation angle of a seam location. Several other features can be extracted from a 2D CMOS image at a full frame rate (512 x 256 pixels) of 200 Hz or faster if a smaller region of interest is chosen. The pixel resolution is about 25 μm and it has a 3D field of view of 13 x 10 x 6 mm.

Visual servoing is the research area that considers the use of cameras and image-based sensors inside the control-loop of robots and other manipulators. In general two control architectures can be distinguished: position-based control and image-based control [6]. Both of these use the sensor measurements from a camera directly within the time-based control-loop of the robot controller. This paper presents a new control architecture, which is called trajectory-based control (figure 2).

To start a cartesian movement with the sensor, at least one location has to be added to the Motion Location Buffer. This initiates a cartesian movement from the current location to the locations in the Motion Location Buffer from the first to the last location, until the last location has been reached. The Setpoint Generator calculates location setpoints ${}^{B}_{S}T(k)$ for the robot every time 4 ms. The movement should be smooth as defined by the acceleration, velocity and deceleration profile in the Motion descriptor. The Setpoint Generator is a real-time setpoint generator that only calculates the next setpoint at the moment it is required. During the robot motion it is possible to add new locations to the Motion Location Buffer. From the cartesian location setpoints ${}^{B}_{S}T(k)$, robot joint angle setpoints $\mathbf{q}_d(k)$ are calculated using the Inverse Kinematic model of the robot. These robot joint setpoints are the reference input for a joint motion controller, proprietary to Stäubli as a part of the LLI, which tracks the specified path such that the measured joint angles $\mathbf{q}_m(k)$ are equal to reference $\mathbf{q}_d(k)$.

If properly synchronized, the measurements from the seam-tracking sensor ${}^{S}_{C}T(i)$ can be combined with the measurements of the robot joints $\mathbf{q}_m(k)$ to a seam location ${}^{B}_{C}T$. After the robot joints and sensor image are synchronized, the time the locations were measured is not relevant anymore, only the order in which they are obtained. By moving the sensor tool frame along the seam and storing the obtained seam locations into the Seam Location Buffer, a complete geometric seam description is obtained.

The trajectory-based control approach can be used for the following procedures:

- Teaching of an approximately known seam trajectory
- Teaching of an unknown seam trajectory
- Real-time tracking of an approximately known seam trajectory
- Real-time tracking of an unknown seam trajectory

The trajectory-based control structure only differs slightly for the mentioned seam teaching and tracking procedures. In the case of teaching of an approximately known seam trajectory, the Predict Seam Trajectory block is not needed, because the motion locations are known beforehand and the seam locations only have to be recorded. For the other three procedures, the control loop has to be closed by on-line calculation and addition of locations to the Motion Location Buffer. A proper filtering must be taken care of to prevent unstable motion behaviour. In the case of teaching of an unknown seam trajectory, the Motion Location Buffer needs to be filled with estimated seam locations, somewhere ahead of the current sensor location, calculated from the measured seam locations. For real-time tracking of an approximately known seam trajectory, the main difference is that the sensor is used for recording the seam locations, but that the laser spot needs to be kept on the just recorded seam trajectory. In addition, real-time tracking of an unknown seam trajectory also needs to make sure the sensors field-of-view will stay on the seam trajectory, e.g. by rotating slightly around the laser tool.

An illustration of the used approach for teaching of an approximately known seam trajectory can be found in figure 3. Initially, it is assumed that the seam is a straight line between locations L_1 and L_2. The seam trajectory will be more accurately measured using a seam-tracking sensor by moving the sensor along the straight line from location L_1 to location L_2. These two locations are added to the Motion Location Buffer and the sensor can start moving. Using the acceleration and deceleration profile from the Motion descriptor, the Setpoint Generator calculates Cartesian setpoints ${}^{B}_{S}T_d(k)$ (the black dots) for the robot every 4 ms, which are converted to robot joint setpoints $\mathbf{q}_d(k)$ using the inverse kinematics. These joint setpoints are used as a reference for the Joint Controller. Note that because of the acceleration and deceleration, the setpoints are closer to each other in the beginning and end of the trajectory. An advanced feature of the Setpoint Generator is that the setpoints are calculated in real-time during the motion, so if a new location is added in time to the Motion Location Buffer before reaching L_2 the movement continues beyond L_2 at the specified speed.

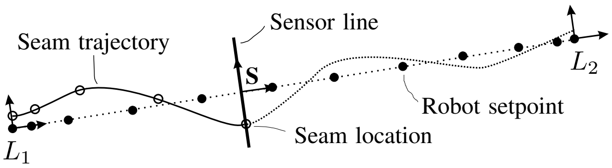

Fig. 3: *Illustration of trajectory generation*

The trajectory-based control approach yields some major advantages:

- It is possible to remove some of the measured seam locations if the sensor measurements are not reliable. This may be the case when using an optical sensor, in combination with dust, spatter from the process, a high power laser beam, etc.
- The measured locations in the Seam Location Buffer, can be filtered in the position-domain instead of in the time-domain, which makes the filtering independent of the velocity. This is more logical as seam trajectories are normally described by their radius of curvature. Curvature is meaningful in the position-domain, not in the time or frequency domain.
- Some packets on the network may not arrive because of heavy network load or network errors. As long as the Motion Location Buffer is not empty, the movement will continue, only the amount of measured locations on the seam trajectory will be less, which means that trajectories with a small radius of curvature will be less accurately measured.
- It is independent of a varying delay after processing of the sensor image which may be caused by the image processing algorithm.

However, to use the proposed trajectory-based control, a real-time Setpoint Generator is needed. Many robot controllers do not have such a Setpoint Generator at the moment, but with the trend of increased processing power

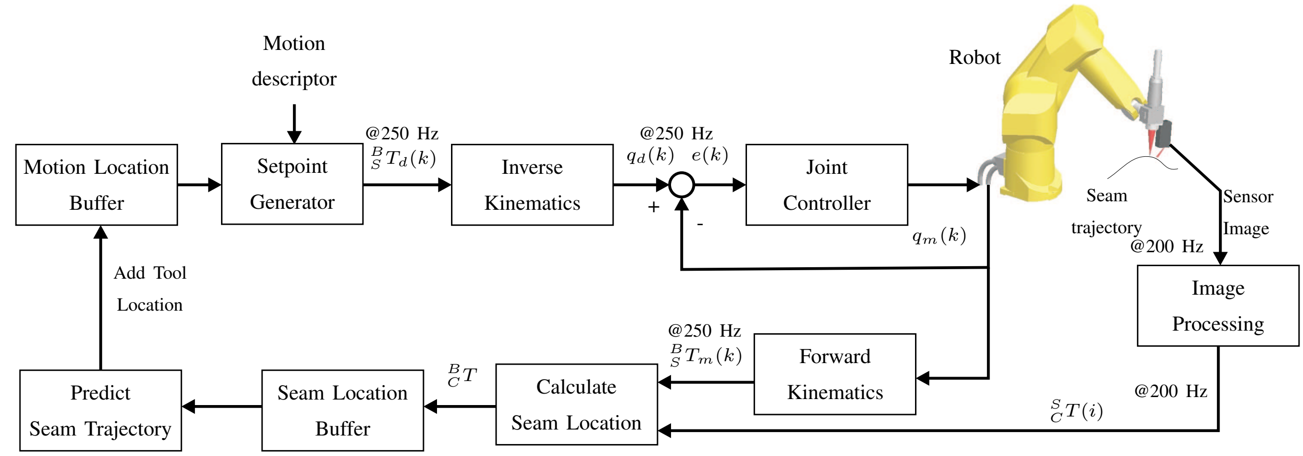

Fig. 2: Control Architecture

inside the controller and the need for such a Setpoint Generator, this will hopefully change in the future.

4 Synchronization

In figure 4 the used synchronization method is shown. The robot controller and the seam-tracking sensor both have their dedicated hardware and thus also their own different time-lines. The robot controller needs to be provided with joint position and velocity setpoints at a rate of 250 Hz. Internally, it interpolates these to a much higher frequency of 2000 Hz to smoothly control the robot motion. The measured joint position is also available to the user at a sample rate of T_r=4 ms.

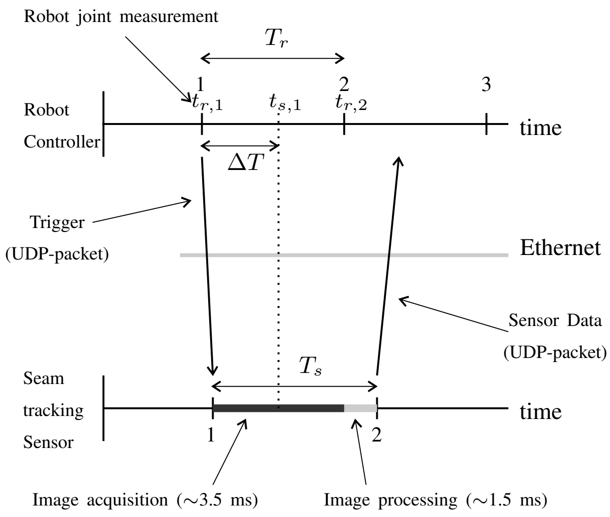

Fig. 4: Synchronization method

The Falldorf seam-tracking sensor operates at a nominal rate of 200 frames per second (T_s=5 ms). It is equipped with a secondary network card that is dedicated for synchronization purposes. If a special trigger UDP packet is received by the sensor computer, a single image acquisition is started. The sensor computer checks at a rate of 4 kHz wether a synchronization packet has arrived and there is a jitter (variation in time delay) of 0.25 ms before the start of the image acquisition. Therefore the total jitter between receiving the trigger packet and the start of the image acquisition should be 0.5 ms. The image acquisition takes (depending on the field-of-view) a fixed amount of time, which is about 3.5 ms for a full frame of 512 x 256 pixels. Within this time, the CMOS chip is read out column-wise from one side to the other, which means it will take about 1.75 ms from the start of the read-out to the measurement of a seam located in the middle of the image. After the image acquisition is completed, image processing will be carried out on the sensor computer. The image acquisition time depends strongly on the chosen feature detection algorithm and used CPU.

Although the use of the UDP-protocol on a switched network does not guarantee a fixed time delivery of packets on the network, packet delivery time is low (∼0.1 ms) compared to the image acquisition time for a moderate network load. Therefore the total time ΔT it takes between a trigger packet being sent from the robot controller and the acquisition in the middle of the camera image at the sensor computer is fixed, but yet to be determined. In section 5 experiments have been carried out to determine the delay.

After the image processing has been completed at the sensor computer, the sensor data is transmitted back to the robot controller. On arrival of the sensor data at the robot controller, the time $t_{s,i}$ at which the image acquisition took place is calculated as the sum of the time at which the trigger packet was send and ΔT. The two surrounding robot measurements $t_{r,k}$ and $t_{r,k+1}$, are linearly interpolated to find the robot joint position

$$\mathbf{q}(t_{s_i}) = \frac{(t_{s_i} - t_{r_k})\mathbf{q}(t_{r_k}) + (t_{r_{k+1}} - t_{s_i})\mathbf{q}(t_{r_{k+1}})}{t_{r_{k+1}} - t_{r_k}}. \tag{1}$$

More accurate higher order interpolation methods are not needed as the robot cycle time is small (T_r=4 ms) and the errors that are introduced because of the used interpolation method are small. Since the synchronization has now been carried out, a seam location can be found with respect to the robot base frame as:

$$^B_CT_i = ^B_S T(t_{s,i}) ^S_CT(t_{s,i}) \tag{2}$$

Please note that it is not necessary to store the synchronization time $t_{s,i}$ anymore. Only the order of incoming seam locations (denoted by index i) needs to be known to construct the seam trajectory.

5 Results

To measure the time delay ΔT the following experiment has been carried out. An object with a straight seam has been put in the middle of the field-of-view of the sensor. The sensor tool frame is moved perpendicular to the seam direction using a sine-motion at a frequency of 1 Hertz. The sensor-measurements and the measurements of the robot joints are both plotted with respect to the time recorded at the robot controller. The result of this measurement is shown in figure 5. The robot and sensor measurements are both scaled and an offset is applied to be able to plot them in the same figure. The time delay between the two sine-measurements should correspond with the time delay ΔT.

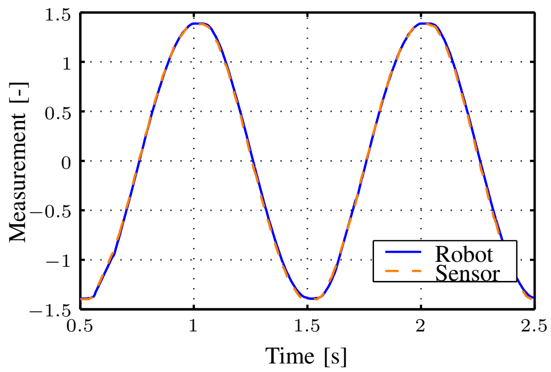

Fig. 5: *Sine motion*

As expected both measurements closely fit. To see the time delay figure 6 is zoomed in around 1.26 s.

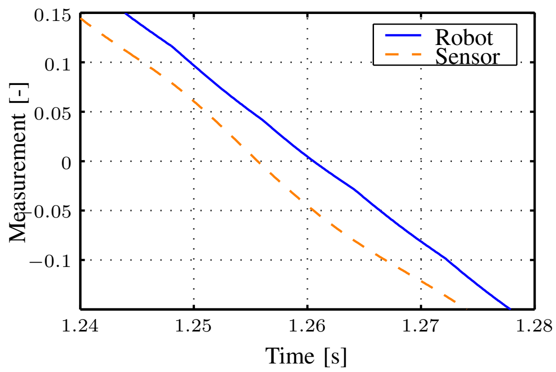

Fig. 6: *Sine motion (zoomed)*

Using a cross-correlation method, the time delay ΔT is found to be 3.4 ms. It should be noted that this measurement method can only be used if the robot measurements at the joint level correspond with the sensor measurement at the robot tip. This is the case when the robot is rigid, but does not apply when the robot starts to show flexible behaviour. Therefore the sine-motion is carried out at a frequency well below the first eigen-frequency of the robot, which is around 20 Hz.

To give an idea of the accuracy of the synchronization method, the following worst-case scenario is considered. The total jitter in the system was calculated as 0.5 ms in section 4. At full welding speed of 250 mm/s this means the error in the welding direction (which is not very critical) is 0.125 mm. The error perpendicular to the seam trajectory is much more critical and needs to be small (< 0.1 mm). This error depends on the radius of curvature of the seam trajectory. In our case it means that seam trajectories with a radius of curvature down to about 1 mm can still be measured accurately using the synchronization method.

6 Conclusions and recommendations

In this paper, a synchronization method is presented between an industrial robot controller and a seam-tracking sensor. It uses Ethernet UDP-communication which makes it fast and cheap. Experiments have been carried out to determine the time-delay between the robot joint measurements and the sensor measurements, which is found to be 3.4 ms. The jitter in the system is about 0.5 ms, which allows accurate measurements at full welding speed (250 mm/s) up to seam curvatures of 1 mm. The accuracy makes this method very suitable for laser welding.

Furthermore a new control architecture for sensor-guided robotic laser welding, called trajectory-based control is proposed. It can be used for various seam-teaching and seam-tracking procedures. The measurements of a sensor that measures at some distance ahead of the laser spot are used for on-line generation of the seam trajectory. The geometry of the seam trajectory is generated independent of time instead of using the sensor measurements directly in the time-based feedback loop. The proposed control architecture fits seamlessly with the synchronization method.

Trajectory-based control has several advantages over the time-based methods that are frequently used in industry. Using this approach, sensor measurements can easily be removed if they are expected to be unreliable, which can be the case using optical sensors. Furthermore the filtering of seam locations can now be carried out in the position-domain instead of in the time-domain.

The practical use of the trajectory-based control will be investigated in further research. The seam locations of an approximately known seam-trajectory should be accurately known after a single movement. Furthermore research will be carried out to close the control loop by on-line addition of new locations to the motion location buffer from the seam location buffer. Using this approach real-time seam-tracking during laser welding can be carried out, where the laser spot accurately stays on the seam trajectory with the use of the seam-tracking sensor.

Bibliography

[1] J.P. Huissoon. Robotic laser welding: seam sensor and laser focal frame registration. *Robotica*, 20:261–268, 2002.

[2] W. Khalil and E. Dombre. *Modeling, Identification & Control of Robots*. Hermes Penton Ltd, 2002.

[3] J.J. Craig. *Introduction to robotics: Mechanics & Control*. Addison-Wesley publishing company, Inc., 1986.

[4] M.W. de Graaf, R.G.K.M. Aarts, J. Meijer, and J.B. Jonker. Modeling the seam teaching process for robotic laser welding. In Paul Drews, editor, *Proceedings of the Mechatronics & Robotics 2004 conference*. APS - European Centre for Mechatronics, September 2004.

[5] F. Pertin and J.M. Bonnet-des-Tuves. Real time robot controller abstraction layer. In *Proceedings of the International Symposium on Robotics 2004*, 2004.

[6] Peter I. Corke. Visual control of robot manipulators - a review. In K. Hashimoto, editor, *Visual Servoing*. World Scientific, 1993.