Force-Contouring Process Using Uncalibrated Vision and Impedance Control

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Abstract: This paper presents an interaction control strategy for industrial robot manipulators which consists of the combination of a calibration-free, vision-based control method with an impedance control approach. The vision-based, robot control method known as camera-space manipulation is used to map a given, previously-defined trajectory over an arbitrary surface. Then, a kinematic posture-based impedance controller is implemented in order to regulate the interaction forces and torques generated by the contact between the robot end-effector and the work surface where the trajectory is defined. The paper presents experimental evidence on how the vision-force sensory fusion is useful to implement a force contouring task in a machining process, by using a Fanuc M16-iB industrial robot equipped with a wrist force/torque sensor.

Keywords: Impedance control, Industrial robots, Vision.

Several industrial processes automated by robotic technology, require contact or interaction between the robot manipulator and its environment. The control of this interaction is crucial for the successful execution of many practical tasks where the robot's end-effector has to manipulate an object or perform some operation on a surface (Siciliano et al., 1999). Typical industrial examples include drilling, polishing, deburring, machining or assembly.

Interaction control of a manipulator has been treated using several strategies. An important approach, referred to as *impedance control* (Hogan, 1985), is based on the control of the relationship between the interaction force and the position errors, resulting from this force. The dynamic interaction between the manipulator and its environment can be regulated by changing its mechanical impedance. Then, by means of an artificially-created end-effector compliance, the manipulator is able to maneuver in constrained environments, maintaining adequate contact forces.

Extending the control of dynamic interaction, Hogan (1985) presents a general and unified approach to implement, in a robot manipulator, an impedance controller and generate a linear mass-spring-damper, closed-loop system. Based on this approach, several control schemes have been developed for interaction control (Anderson et al., 1988). Recent contributions propose the fusion of visual and force information in interaction tasks to recognize and detect the contact surface (Pomares et al., 2005)-(Pomares et al., 2008). Lippiello et al. (2007), propose a position-based visual impedance control derived from a typical position-based visual servoing scheme. They consider the environment as a rigid object of known geometry but of unknown position and orientation. In their experimental test, calibrated cameras and a robot manipulator with an open-control architecture are used.

Current research involving the development of systems for intuitive industrial-robot programming benefits from the use of calibration-free, vision-based techniques (Loredo et al., 2008). Among them, a method known as camera-space manipulation (CSM) (Skaar et al., 1987), (González et al., 2008) has demonstrated its effectiveness, especially in the cases where the cameras used to control the maneuver remain fixed in the interval between workpiece detection and task culmination. This method makes use of a simple, non-linear camera model; determining the parameters associated to this model enables an algebraic, non-linear relationship between the configuration of a manipulator and the appearance, in a two-dimensional image, of a number of visual features located at the robot end-effector. Such a relationship is referred to as camera-space kinematics.

In this paper, a combination of both calibration-free, vision-based control and a kinematic impedance controller (Fig. 1), whose objective is to control the interaction of an industrial robot manipulator with its environment, is proposed. The environment consists of an arbitrary surface with unknown geometry and location; CSM is used in order to generate a trajectory over such a surface. Consequently, an uncalibrated vision system is fused with a wrist force/torque sensor, with the purpose of improving robot performance on interaction tasks in unknown environments. The kinematic, posture-based impedance controller takes advantage of the planned trajectory obtained from the vision system, enabling a fusion of all available sensory information, i.e. visual, force and robot-joint position measurements.

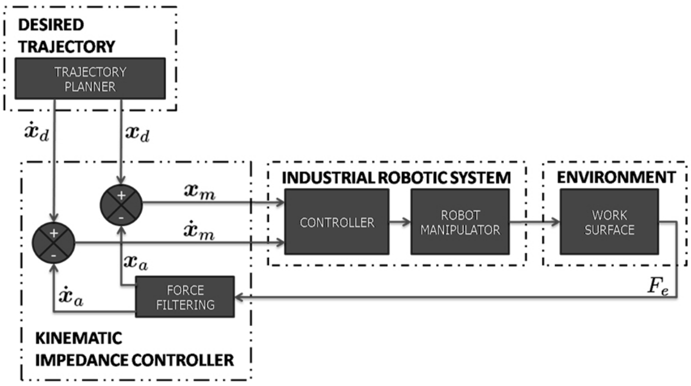

Fig. 1. Visual-based kinematic impedance control scheme.

There has been a large amount of research in machine tool servomechanism control, contour control, and machining force control (Tang et al., 2006). One of the most important uses of machine tools is the cutting of complex continuous part paths, or contours. Force contouring controls the force so that the robot constantly pushes the surface along the taught trajectories. In this paper, we consider force contouring as a potential industrial application for our control approach, and some experimental tests are presented in order to show its effectiveness.

1. CAMERA-SPACE MANIPULATION

Camera-space manipulation emerged in the mid-eighties and has proven its effectiveness in tasks that involve high accuracy in robot positioning using uncalibrated vision. An important feature of this method is that the maneuver objectives are specified within the reference frame of a number of two-dimensional images obtained with cameras that remain stationary between target detection and maneuver culmination.

Typically, the camera-space samples are obtained by placing special marks on a tool held by a robot. Such marks, referred to as manipulable features, are detected in camera-space using dedicated image-analysis software. Their corresponding physical location is determined with respect to a system at the base of the robot using the nominal forward kinematic model, obtained by using the Denavit-Hartenberg convention.

1.1 Perspective Camera-Model

Based on the geometry depicted in Fig. 2, the perspective projection (x_{c_i}, y_{c_i}) of a point of coordinates (x_i, y_i, z_i) is described as follows,

$$
\begin{aligned}
x_{c_i} &= f\frac{R_{11}x_i + R_{12}y_i + R_{13}z_i + X_0}{R_{31}x_i + R_{32}y_i + R_{33}z_i + Z_0} \\
y_{c_i} &= f\frac{R_{21}x_i + R_{22}y_i + R_{23}z_i + Y_0}{R_{31}x_i + R_{32}y_i + R_{33}z_i + Z_0}
\end{aligned} \tag{1}
$$

where coordinates (X_0, Y_0, Z_0) represent the origin of an arbitrary reference frame xyz with respect to the XYZ frame attached to the camera, while f represents the focal distance. The terms R_{kl}, k,l = 1,...,3, are expressed in terms of the Euler parameters $e_1, ..., e_4$, as follows,

$$
\begin{aligned}
R_{11} &= e_1^2 + e_2^2 - e_3^2 - e_4^2 \\
R_{12} &= 2(e_2e_3 + e_1e_4) \\
R_{13} &= 2(e_2e_4 - e_1e_3) \\
R_{21} &= 2(e_2e_3 - e_1e_4) \\
R_{22} &= e_1^2 - e_2^2 + e_3^2 - e_4^2 \\
R_{23} &= 2(e_3e_4 + e_1e_2) \\
R_{31} &= 2(e_2e_4 + e_1e_3) \\
R_{32} &= 2(e_3e_4 - e_1e_2) \\
R_{33} &= e_1^2 - e_2^2 - e_3^2 + e_4^2.
\end{aligned} \tag{2}
$$

Considering the restriction $e_1^2 + e_2^2 + e_3^2 + e_4^2 = 1$, the perspective camera-model in eq. (1) depends on 7 independent parameters.

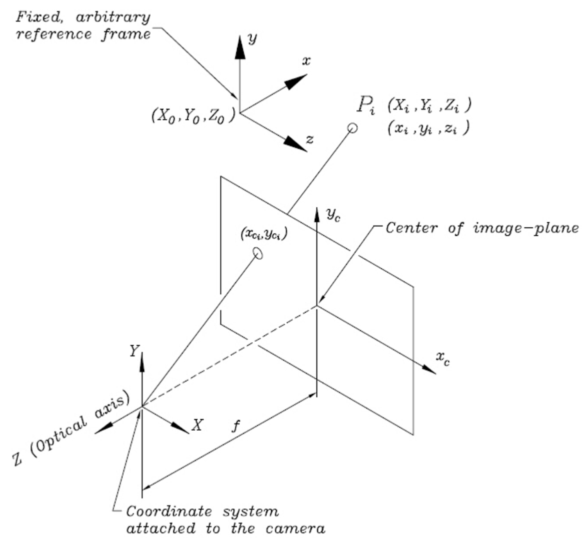

Fig. 2. Coordinate systems associated to the perspective camera-model.

The relationship between robot configuration and the appearance in camera-space of a number of manipulated visual features, is established by determining seven parameters included in the following simplified, recursive camera model,