Robotics and Computer-Integrated Manufacturing 29 (2013) 261–270

Contents lists available at SciVerse ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Dynamic visual servo control of a 4-axis joint tool to track image trajectories during machining complex shapes

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ARTICLE INFO

Article history:
Received 7 August 2012
Received in revised form
26 November 2012
Accepted 2 January 2013
Available online 8 February 2013

Keywords:
Visual servoing
Tracking image trajectories
Direct control
Robotics

ABSTRACT

A large part of the new generation of computer numerical control systems has adopted an architecture based on robotic systems. This architecture improves the implementation of many manufacturing processes in terms of flexibility, efficiency, accuracy and velocity. This paper presents a 4-axis robot tool based on a joint structure whose primary use is to perform complex machining shapes in some non-contact processes. A new dynamic visual controller is proposed in order to control the 4-axis joint structure, where image information is used in the control loop to guide the robot tool in the machining task. In addition, this controller eliminates the chaotic joint behavior which appears during tracking of the quasi-repetitive trajectories required in machining processes. Moreover, this robot tool can be coupled to a manipulator robot in order to form a multi-robot platform for complex manufacturing tasks. Therefore, the robot tool could perform a machining task using a piece grasped from the workspace by a manipulator robot. This manipulator robot could be guided by using visual information given by the robot tool, thereby obtaining an intelligent multi-robot platform controlled by only one camera.

1. Introduction

The complexity of geometric shapes, the accuracy needed in the finished worked piece and the high speed required for the machining processes are some of the current requirements for the new generation of computer numerical control (CNC) systems. Complex CNC architectures, most of them based on robotic systems [1–4], have been developed in order to provide more flexibility, efficiency, accuracy, and velocity in the implementation of many manufacturing processes. In this context, robotics technology permits machining via different working methods (e.g., milling, polishing, cutting) thus enabling higher working efficiency. In addition, commercial manufacturing machines are expensive and their utilization in some cases is quite limited in practice due to their low versatility and flexibility. For these reasons, research about the development of reconfigurable CNC manufacturing machines has increased in the last few years [4–7]. This paper proposes a 4-axis robot tool (RT) based on a joint structure whose main use will be to perform complex machining shapes in some non-contact processes such as laser and water cutting. This RT can be coupled to a robotic system in order to perform complex manufacturing tasks. A new dynamic visual controller is proposed to control the 4-axis joint structure, where image information is used in the control loop to guide the RT in its machining task.

CNC manufacturing machines are normally controlled without vision. Only few works have dealt with the introduction of vision in CNC machining processes. In [8], it is presented an approach to improve the performance of CNC machining by utilizing on-line vision-based monitoring. A stereo camera configuration is employed to monitor the milling task, but there is no direct control of the position using the vision system. This same scheme is used before in [9], introducing vision for inspection of the CNC machining task. Thus, vision has been applied to CNC systems only for monitoring or inspection tasks. A computer vision system is applied in [10] to the generation of tool path in a previous phase of the milling task. In this paper, vision is used to directly control the CNC system.

High-speed machining processes have great dynamic requirements on the structure, which are further augmented by the acceleration of different parts of the machine or robotic platform. This may cause some alterations of the tool's position and orientation errors [3,11]. For these reasons, control of the machine's engine can be a difficult task utilizing position, orientation or velocity sensor data. Currently, there are many approaches where a new control system is proposed for machine's axes [3,12,13]. The dynamic visual controller proposed here permits

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http://dx.doi.org/10.1016/j.rcim.2013.01.008

accurate guidance of the RT's end-effector, guaranteeing the correct joint motion. The classic image-based controllers determine the required camera velocities in order to position the robot with respect a reference object [14]. Using this last approach, the internal robot controller computes the joint torques in order to achieve the previously mentioned camera velocities. However, the approach proposed in this paper to perform the RT guidance is based on direct visual servoing [15]. By means of direct visual servo, the internal control loop of servo motors is removed and the visual servo control is employed to stabilize the robot. Thus, the use of direct control eliminates the delay introduced by the use of an additional controller as it is the robot internal controller. The result is a faster and more accurate control that reacts more quickly to abrupt changes in the trajectories. This proposed visual controller performs high precision visual tracking in order to be applied to CNC machines. Additionally, an important contribution of the proposed controllers is to eliminate the chaotic joint behavior which appears during tracking of the quasi-repetitive trajectories required in the machining process.

In machining processes such as polishing, milling or cutting, the RT must track repetitive or quasi-repetitive trajectories. As described through the paper, a repetitive path tracked by the RT end-effector can produce a non-periodic motion in the joint space. This non-periodic joint trajectory presents a chaotic behavior, an undesirable nonlinear effect which can appear during some machining processes [16,17]. This chaotic behavior has embedded a large number of Unstable Periodic Orbits (UPOs). As previously indicated, the proposed visual controller determines appropriate motor references such that both RT's end-effector and joints behave correctly. To do this, a chaos compensator is integrated within the dynamic visual controller to eliminate the chaotic joint behavior and to obtain a quasi-repetitive joint trajectory when the end-effector also tracks a quasi-repetitive trajectory. This last aspect guarantees a smoother joint behavior and increases the safety obtaining predictable trajectories. This property improves the performance and accuracy of CNC machines as part of an intelligent robotic system.

Different kinematic configurations are studied in order to couple the RT to the end of another manipulator robot in order to perform complex machining tasks. The RT components and their constructive properties have been designed in order to facilitate its installation without any constraints to the manipulator robot functionalities. Therefore, the RT could perform a given machining task using a piece grasped from the workspace by the manipulator robot. The manipulator robot could be guided by visual information given by the RT, thereby obtaining an intelligent multi-robot platform controlled by only one camera.

This paper is organized as follows. Section 2 describes the kinematic and dynamic features of the RT, as well as showing uses for a multi-robot platform. Section 3 explains the visual control of the RT. At the beginning of this section, the dynamics and kinematics notation of the robot model are shown in detail. Section 4 describes the proposed controller used to track trajectories in the image space to solve the chaotic behavior of the RT. Section 5 verifies the controller using different velocities and the final section elaborates the conclusions reached by this paper and possible future works.

2. Robot tool kinematics and dynamics

This section describes the main kinematic and building properties of the RT. The RT is shown in Fig. 1, where $l_1=12.4$ cm, $l_2=15.2$ cm, $l_3=9.9$ cm. The corresponding mass properties of each link are $m_1=1.75$ kg, $m_2=0.8$ kg, $m_3=0.5$ kg, respectively. The robot is guided by an eye-in-hand camera system. A Gigabit Ethernet TM6740GEV camera is used, which acquires 200 images every second with a resolution of 640×480 pixels. Four rotational joints are employed (q_0, q_1, q_2, q_3) for the RT movement. The proposed controllers shown throughout the paper can be easily extended to a great number of joints. However, four degrees of freedom (d.o.f.) have been considered sufficient for a tool to perform the necessary machining and positioning tasks.

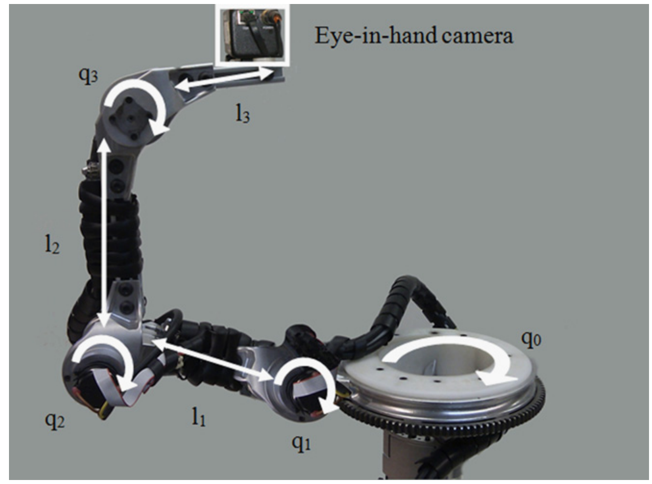

Fig. 1. Robot tool.

Table 1
Motor parameters of the joints q_0, q_1, q_2, q_3.

Motor	M_b (N m)	N_b (rpm)	η_m (%)
Joint q_0	0.510	6930	91
Joint q_1	0.316	10000	87
Joint q_2	0.131	15900	89
Joint q_3	0.0504	14700	88

The first joint has been designed with an inner space that permits affixing the RT at the end of a manipulator robot (without negatively affecting the functionality of the manipulator robot). The first joint has a rotational movement, q_0, independent of the robot manipulator and the other three joints, q_1, q_2 and q_3, are used to undertake the machining task. The main objective of the proposed design is to create a robust kinematic and dynamic structure with its basis in a known model, guided by direct visual servoing. As it is previously indicated, the RT is designed to be placed and coupled at the end of a manipulator robot. Therefore, the lightness of the RT is an important aspect to be considered in the design. For this reason, strong and lightweight materials (mainly duralumin and high resistance plastics) have been employed in its construction, resulting in a total weight of 5 kg.

In order to select the actuators, drivers, and power control devices for the RT, the 3D model design and the dynamic simulation of the robot movement were made. From the data calculated in this simulation, four geared motors (one per joint) were considered for the robot actuators. Table 1 shows the features of the selected engine motors of the joints q_0, q_1, q_2 and q_3, where M_b (N m) is the torque value, N_b (rpm) is the load speed engine, and η_m (%) is the energy efficiency. Table 2 shows the features of the selected gears, where R is the reduction, M_{cont} (N m) and M_{int} (N m) are the nominal and maximum torque supported by the device, and η_r (%) is the energy efficiency. The maximum torque of each geared-motor group was computed using $N_f=M_b\times R\times\eta_r\times\eta_m$. The results obtained for the torques were $\tau_{0f}=25.06$ N m, $\tau_{1f}=16.03$ N m, $\tau_{2f}=9.05$ N m and $\tau_{3f}=6.54$ N m.