Expert Systems With Applications 42 (2015) 8929–8935

Contents lists available at ScienceDirect

Expert Systems With Applications

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

Indirect adaptive fuzzy control for industrial robots: A solution for contact applications

Nuno Mendes, Pedro Neto*

Department of Mechanical Engineering (CEMUC) – POLO II, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

ARTICLE INFO

Keywords:
Adaptive fuzzy control
Hybrid force/motion control
Robot contact
Robotics

ABSTRACT

Robots have been increasingly used in uncertain environments where direct contact with the surrounding environment exists. A design procedure of an adaptive fuzzy control, which can be carried out systematically, is suggested in this paper. The developed adaptive laws learn on-line the fuzzy rules of the control system and the uncertainties of the plant. Adaptive fuzzy control is integrated in a hybrid force/motion control system of an industrial robot to deal with a scenario of contact between the end-effector of the robot and a given surface. The controller is designed according to the previous knowledge about the process. The effectiveness of the proposed control system is shown through simulation and experimental results. Experimental results demonstrate superior stability and robustness of the proposed controller in relation to controllers of the same nature applied to industrial robotics, namely when there is contact between robot and surround environment.

1. Introduction

Traditionally, industrial robots are designed to allow accurate and repeatable control of the position and velocity of the robot's end-effector. Increasingly, robots are often also required to perform complex tasks requiring robust and stable force control strategies to deal with uncertain environments. In addition, task constraints sometimes require position or velocity control in some Degrees-Of-Freedom (DOF) and force control in others. Thus, to fulfill these extra demands, an important area of robotics research is the implementation of stable and accurate force control. However, this is often difficult to achieve in practice due to the technological limitations of current controllers, coupled with the demanding requirements placed upon them by the advanced control schemes that are needed in cases where robots are operating in unstructured environments. Hybrid control (force and motion) allows forces to be controlled in the constraint directions by a force controller, while simultaneously, positions in the free direction are controlled by a motion controller (Mendes, Neto, Pires, & Loureiro, 2013).

A survey on industrial applications of fuzzy control is presented in Precup and Hellendoorn (2011). Some techniques of adaptive fuzzy control are highlighted and industrial applications are pointed out. An observer-based indirect adaptive fuzzy sliding mode controller is proposed in Kung and Chen (2005). This controller is tested by simulation in an inverted pendulum system. Results of the simulation report that this control strategy presents a good tracking performance and is robust against external noise. A fuzzy adaptive output feedback control based on an observer for a single-input-single-output (SISO) is proposed by Boulkroune, Tadjine, M'Saad, and Farza (2008). An approach to adaptive fuzzy sliding mode control with a self-tuning mechanism adapting control parameters and switching gains is introduced in Cerman and Hušek (2012). Other authors suggest an adaptive fuzzy system to reduce the oscillation in power systems (Hussein, Saad, Elshafei, & Bahgat, 2009). An adaptive fuzzy control scheme for trajectory tracking of mobile robots is proposed by Liang, Xu, Wei, and Hu (2010). A Takagi–Sugeno fuzzy model for indirect adaptive control is proposed to SISO and multiple-input-multiple-output (MIMO) (Qi & Brdys, 2009). Other studies report the contact along the entire length of the robotic arm using force control strategies based on probabilistic estimation (Petrovskaya, Park, & Khatib, 2007). An interesting paper in the field exposes from a practical point of view the importance of sensor integration and force control for the application of robots in new manufacturing scenarios (Blomdell et al., 2005). An intelligent adaptive control system for MIMO uncertain nonlinear systems is proposed to control a mass–spring–damper mechanical system and a Chua's chaotic circuit (Chen, Lin, & Chen, 2008). A design method of an adaptive fuzzy logic controller for DC-DC converter is proposed by Elmas, Deperlioglu, and Sayan (2009).

A study approaching adaptive cruise control of a hybrid electric vehicle using sliding mode control is presented by Ganji, Kouzani, Khoo, and Shams-Zahraei (2014). The design of an in-process

* Corresponding author. Tel.: +351239790700; fax: +351239790701.
E-mail addresses: nuno.mendes@dem.uc.pt (N. Mendes), pedro.neto@dem.uc.pt (P. Neto).

http://dx.doi.org/10.1016/j.eswa.2015.07.047
0957-4174/

surface roughness adaptive control system for a CNC turning operation, using fuzzy-nets modeling and tool vibrations measurements, is presented by Kirby, Chen, and Zhang (2006). Macías-Escrivá, Haber, del Toro, and Hernandez (2013) presented a survey about recent progress on self-adaptive systems. An industrial system composed by two DC motors was employed to study the performance of three different adaptive fuzzy control architectures: direct adaptive; indirect adaptive; and combined direct/indirect adaptive (Mendes, Araújo, Sousa, Apóstolo, & Alves, 2011). A learning method of a Takagi–Sugeno fuzzy model is performed to approximate unknown nonlinear processes by a hierarchical genetic algorithm (Mendes, Araújo, & Souza, 2013). This approach was successfully applied on identification of a model for the estimation of the flour concentration in the effluent of a real-world wastewater treatment system. Adaptive neuro fuzzy inference strategies was used to control input displacement of a new adaptive compliant gripper (Petković, Issa, Pavlović, Zentner, & Ćojbašić, 2012; Petković, Pavlović, Ćojbašić, & Pavlović, 2013). An adaptive charged system search (ACSS) algorithm for the optimal tuning of Takagi–Sugeno proportional–integral fuzzy controllers is proposed for the position control of a nonlinear servo system (Precup, David, Petriu, Preitl, & Rădac, 2014). In order to control a heating, ventilating and air-conditioning (HVAC) system, conventional PID control was implemented and fuzzy adaptive control was performed to tune the PID controller gains to maximize the performance of the system (Soyguder & Alli, 2010). An indirect adaptive interval type-2 fuzzy PI sliding mode controller is presented by Ghaemi and Akbarzadeh-Totonchi (2014). Although this system achieves good performance in terms of stability and asymptotic convergence, especially when human expert knowledge is used to initialize its parameters, the controller is computationally expensive. A robust stable controller based on indirect adaptive fuzzy sliding mode for stabilizations of power systems is reported as able to eliminate chattering (Saoudi & Harmas, 2014). Simulation results illustrate the good performance of observer-based fuzzy indirect adaptive controllers (Boulkroune, Bounar, M'Saad, & Farza, 2014; Li, Li, & Jing, 2014). Three model-free indirect adaptive controllers are proposed to control the tip displacement of a conducting polymer actuator, which has an unknown behavior (Beyhan & Itik, 2015). The control methods are based on convention indirect adaptive fuzzy, Chebychev functional-link network, and a hybrid solution of the two previous methods. All of the control methods present satisfactory performance with the hybrid controller providing better results in terms of root-mean-squared error, required input signal power, and settling time. However, the hybrid controller is extremely noisy which prevents its use in many applications.

The above referred literature proved that a controller based on indirect adaptive fuzzy control may provide a stable and robust solution capable to cope with plant disturbances. However, these solutions are neither easy to implement nor in many cases computationally viable. Thus, a purpose of this study is cope with both these challenges providing a systematic procedure to implement an effective controller. A hybrid force/motion control system is proposed to cope with contact issues when industrial robots are involved. The proposed control system is composed by a force control loop and a motion control loop. It is highlighted the force control loop which is based on an indirect adaptive fuzzy control. The great advantage of this system is the on-line generation of the fuzzy rules without previous knowledge about the plant or without rigorous previous knowledge about the plant. Furthermore, the uncertainties of the plant are learned on-line and adaptively compensated for.

2. Architecture

This study is taking into consideration two common scenarios in industrial robotics field:

- There is contact between the robot end-effector and the surrounding environment;
- The robot is programmed off-line.

These two points contribute to the appearance of end-effector positional errors. Since robots are subjected to positional errors from several sources (see below), it becomes important to develop a controller to reduce/eliminate the effect of the positional errors. A hybrid force/motion control system is proposed to cope with positional errors.

2.1. Robot positional error

Within the mechanical robot structure two categories of errors can be distinguished: geometrical errors and non-geometrical errors (Mustafa, Tao, Yang, & Chen, 2010). The former encompasses all the deviation due to imperfect geometries, mating or assembly errors. These errors exist whether the robot is moving or not. The latter include all the error sources related to the dynamical behavior of the robot. In addition, unlike the former, they are time-varying and change in magnitude during manipulator operations. The main effect of both of these error sources is causing discrepancies between the real robot and its kinetostatic and dynamic model from which its characteristics are derived (Legnani, Tosi, Fassi, Giberti, & Cinquemani, 2010) and on which control is based (Dietz et al., 2012).

Geometrical errors, which are generally compensated by calibration, arise from manufacturing or machining tolerances of robot components. Non-geometric errors also occur in a local environment and therefore, cannot be compensated by calibration. They arise from structural deformations of load-transmitting components, links and energy-transforming devices as well as from wear and nonlinear effects such as nonlinear stiffness, stick-slip motion and hysteresis in servo drives (Gong, Yuan, & Ni, 2000; Ruderman, Hoffmann, & Bertram, 2009). The compliance errors are due to the compliance of the links and joints under inertial and external load. In particular, joint compliance results from the torsional stiffness of the gearbox and the output drive shaft actuating the joint. Besides, the masses of the links cause an additional torque on the gears due to gravity effects. Especially during contact tasks, forces add on the load of the gears and cause additional deflection. Link and joint compliance, causing the deflection of the links and finally the end-effector, contribute up to 8–10% of the position and orientation errors of the end-effector (Mustafa, Tao, Yang, & Chen, 2010).

2.2. Programming

The programming process starts with the definition of the nominal robot paths that during the process will be adjusted according to the forces being exerted on the end-effector. The robot is pre-programmed (nominal paths) by off-line programming as described in previous studies in which target points are extracted from CAD (Neto & Mendes, 2013). In order to integrate the force control loop with the motion control loop the methods presented in (Mendes, Neto, Norberto Pires, & Loureiro, 2013) are implemented. During the movement of the robot the forces and torques measured by the force/torque (F/T) sensor and the current pose of the robot end-effector serve as input to the force/motion control system that outputs adjustments for the nominal path. This is done to keep a given set force between the end-effector and the surface (environment).

2.3. Hybrid force/motion controller

In a traditional hybrid force/motion control system applied to a robot manipulator, some robot directions are controlled in motion control and others are controlled in force control. Nevertheless, this study proposes the use of two control loops, an external control loop based on force and torque and an internal control loop based on motion. In this new hybrid force/motion control system, all directions are