Control Engineering Practice 73 (2018) 26–39

Contents lists available at ScienceDirect

Control Engineering Practice

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

Nonlinear position and stiffness Backstepping controller for a two Degrees of Freedom pneumatic robot

Nicolas Herzig [a,*], Richard Moreau [b], Tanneguy Redarce [b], Frédéric Abry [b], Xavier Brun [b]

[a] *Dyson School of Design Engineering, Imperial College London, South Kesington, SW7 2AZ, London, United Kingdom*
[b] *Laboratoire Ampère UMR CNRS 5005, Université de Lyon, INSA-Lyon, F-69621 Villeurbanne Cedex, France*

ARTICLE INFO

Keywords:
Backstepping controller design
Damping control
Electropneumatic robot
Nonlinear control
Stiffness control

ABSTRACT

This paper presents an architecture of a 2 Degrees of Freedom pneumatic robot which can be used as a haptic interface. To improve the haptic rendering of this device, a nonlinear position and stiffness controller without force measurement based on a Backstepping synthesis is presented. Thus, the robot can follow a targeted trajectory in Cartesian position with a variable compliant behavior when disturbance forces are applied. An appropriate tuning methodology of the closed-loop stiffness and closed-loop damping of the robot is given to obtain a desired disturbance response. The models, the synthesis and the stability analysis of this controller are described in this paper. Two models are presented in this paper, the first one is an accurate simulation model which describes the mechanical behavior of the robot, the thermodynamics phenomena in the pneumatic actuators, and the servovalves characteristics. The second model is the model used to synthesize the controller. This control model is obtained by simplifying the simulation model to obtain a MIMO strict feedback form. Finally, some simulation and experimental results are given and the controller performances are discussed and compared with a classical linear impedance controller.

1. Introduction

Many robotic applications require an interaction between the end-effector of the robot and an uncertain environment. For instance, for human rehabilitation, for haptic interfaces, or for prosthetic devices, human–robot interactions are necessary. When these interactions occur, most of the time, a compliant behavior of the robot is required in order to avoid human injuries or to avoid damaging the robot itself. But on the other hand, these robots have to be stiff for some tasks. Therefore it is necessary to control the stiffness and damping of the robots. To ensure a compliant behavior of a robot, various Variable Stiffness Actuators (VSAs) or Variable Impedance Actuators (VIAs) have been developed during last decades. These actuators allow the equilibrium position and the stiffness to be tuned independently. Van Ham, Sugar, Vanderborght, Hollander, and Lefeber (2009) present a state of the art in the design of VSAs. Most of these actuators are designed with two internal motors and passive compliant elements. An advantage of this design is that the position and stiffness control of the VSA is obtained by controlling the position of two electric motors. The main drawbacks of this kind of VSAs are the cost and the stiffness range. Indeed, these actuator are often expensive because two electric actuators are needed to control one Degree Of Freedom (DOF). The range of the stiffness is also often limited (Huang et al., 2013) due to the use of passive stiffness components.

Another approach to obtain a compliant behavior for the robot is based on control strategies such as stiffness control (Salisbury, 1980), impedance control (Hogan, 1987) or hybrid force position control (Hayati, 1986). Most of these strategies have been developed for electromechanically actuated robots. The disadvantages of the electromechanical actuation are that, in order to implement these control strategies, a force/torque sensor is needed. This sensor is required to measure the environment interaction which implies knowing where this interaction will occur. Moreover, these sensors are often expensive and fragile. If force/torque sensors are not used, the actuators have to be backdrivable which mean reducing gear ratio and, consequently, the torque or force range of the robot.

On the other hand, due to their nonlinear behaviors, pneumatic cylinders were traditionally only use as bi-stable position actuators. The recent development of new servovalves and modern robust nonlinear control laws based on sliding mode and Backstepping allowed the

---

[*] Corresponding author.

E-mail addresses: n.herzig@imperial.ac.uk (N. Herzig), richard.moreau@insa-lyon.fr (R. Moreau), tanneguy.redarce@insa-lyon.fr (T. Redarce), frederic.abry@insa-lyon.fr (F. Abry), xavier.brun@insa-lyon.fr (X. Brun).

https://doi.org/10.1016/j.conengprac.2017.12.007
Received 8 December 2016; Received in revised form 11 May 2017; Accepted 18 December 2017
0967-0661/

Table 1
Main characteristics of the cylinders.

Reference	DSNU-25-400-PPV-A-Q	DSNU-25-200-PPV-A
Notation	cylinder 2	cylinder 1
Position	horizontal	vertical
Stroke	400 mm	200 mm
Piston diameter	25 mm	25 mm
Theoretical force at 6 bar, advancing	295 N	295 N
Theoretical force at 6 bar, retracting	247 N	247 N
Rod geometry	9 mm ×9 mm (square)	Ø10mm (circle)

Fig. 1. 2 DOF actuated pneumatic haptic interface.

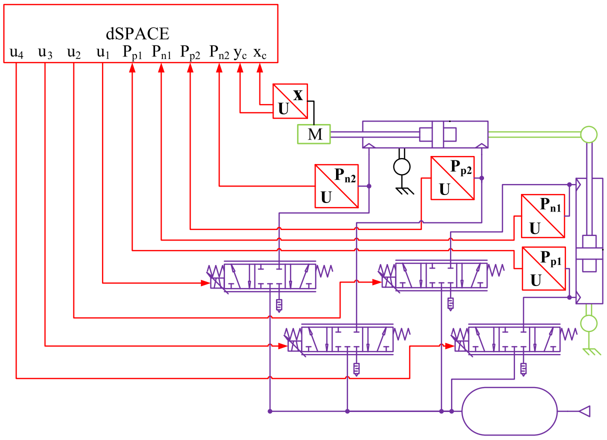

Fig. 2. Hardware architecture of the 2 DOF pneumatic robot.

development of position or force controller. Thus, since pneumatic cylinders are inexpensive and have a good power to weight ratio, there has been a recent surge of interest for this technology. If the independent force/stiffness or position/stiffness nonlinear controls of one pneumatic actuator have been addressed in literature (Abry, Brun, Sesmat, Bideaux, & Ducat, 2015; Shen & Goldfarb, 2007; Taheri, Case, & Richer, 2014), the extension of these nonlinear control strategies to multi DOF has not yet been studied. Thus, this article presents an nonlinear position/stiffness control strategy for a 2 DOF pneumatic robot adapted from the Abry et al. position and stiffness controller developed for a pneumatic cylinder (Abry et al., 2015). The synthesis of this controller is based on the Backstepping method and a gain tuning strategy which allows to reach a desired behavior of stiffness and damping.

The presented 2 DOF pneumatic robot is a part of a haptic interface. This haptic device will be used to develop a childbirth simulator. Herzig, Moreau, and Redarce (2014) and Herzig, Moreau, Redarce, Abry, and Brun (2015) give more details about the interest of using this kind of haptic interface to simulate a childbirth delivery.

This paper is structured as follows: In Section 2 the hardware architecture of the 2 DOF actuated robot is given. Then the models used for simulations and for control synthesis are described respectively in Sections 3 and 4. The controller synthesis based on the Backstepping method is described in Section 5. In Section 6 response to an external disturbance force and a strategy to ensure a desired closed-loop stiffness by control gains tuning are discussed. Simulation results and a comparison with a classical linear impedance controller without force sensor are presented in Section 7. Section 8 deals with the experimental results to compare performances of the two controllers for position tracking and disturbance rejection. Finally, Section 9 provides a conclusion and describes future works.

2. Robot hardware design

The 2 DOF robot studied in this paper is illustrated in Fig. 1. Its architecture is based on the BirthSIM (Herzig et al., 2014, 2015) design, which is composed of two pneumatic cylinders. The main characteristics of these two cylinders, respectively denoted cylinder 1 and cylinder 2 for the vertical one and the horizontal one, are given in Table 1. The second cylinder has been chosen with a square rod in order to prevent the inner rotation.

Four *Festo MPYE-5-M5-010-B* proportional servovalves supply the cylinder chambers. These servovalves control the air mass flow rates which enter or exit the chambers. Their characterization map is given in 3.4. The pressures inside the chambers are measured with *Honeywell 40PC100G2A* sensors. Moreover, the end-effector Cartesian position and orientation are measured using a *Trackstar* magnetic tracker. Finally, the controller board is a *dSPACE MicroLabBox* which is suitable for control prototyping. Fig. 2 illustrates the global hardware architecture of the studied robot.

It has to be noticed that to avoid some usual issues concerning the compression of air in air tubes, the diameter of the air tubes have been chosen small and the length of those tubes have been shortened to the maximum. Indeed, this issue is known for generating delays and also has an impact on the control strategies.

3. Simulation model

This section presents the models which are used to test the control law in simulation. To describe the behavior of the robot, mechanical and thermodynamic models have to be defined.

3.1. Kinematic model

The Forward Kinematic Model (FKM) and Inverse Kinematic Model (IKM) provide the relations between the location of the end-effector and the joint coordinates. Indeed, the FKM gives the position and orientation of the end-effector as a function of the joint variables whereas the IKM gives the joint variables as a function of the end-effector location. To obtain these models, the Khalil and Kleinfinger method has been used (Khalil & Kleinfinger, 1986). This method is particularly suitable for robots with closed chains. Fig. 3 presents the kinematic scheme of the studied robot.