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Normal and tangent force neuro-fuzzy control of a soft-tip robot with unknown kinematics

Rodolfo Garcia-Rodriguez [a,*], Vicente Parra-Vega [b]

[a] Facultad de Ingeniería y Ciencias Aplicadas, Universidad de los Andes, Chile
[b] Department of Robotics and Advanced Manufacturing, Research Center for Advanced Studies (CINVESTAV), México

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ABSTRACT

Assuming that contact kinematics is known, there exists many force robot control schemes, however the common practice of placing a deformable pad at contact makes difficult its implementation. The difficulty stems from the fact that the this pad introduces contact kinematics uncertainties due to the unknown deformation. In this paper, considering the full non-linear constrained rigid robot equipped with a hemispherical soft-tip as end-effector, a force regulator is proposed. To compensate the kinematic uncertainty at contact, induced by the unknown soft-tip deformation, a multi-input single-output (MISO) self-tuning fuzzy-rule emulated neural network (MiFRENN) is used. Additionally, the gravity compensation together with a damping injection term in the controller are used to guarantee local convergence of the normal and tangential force errors at a given equilibrium. The stability domain of the system varying depending on the knowledge-based contribution of the MISO-MiFRENN and the damping injection, which amounts for a novel scheme that can be used for other advanced robotic contact tasks, such as tactile exploration, dexterous manipulation or biped locomotion. Representative simulations illustrate the closed-loop numerical behavior.

1. Introduction

The *force* control problem of robot manipulators has became a basic operational mode for advanced robotic applications that involves contact. There exists proved force controllers for robot manipulators subject to holonomic constraints, (Arimoto et al., 1993), by assuming that rigid contact occurs at one point. In this case, only normal force appears as the constraint force. However, in practice a deformable pad is used at contact to increase friction and contact area at the expense of removing the basic assumptions of point contact and holonomic constraint, which introduces kinematic uncertainty at contact. Moreover, a deformable pad with hemispherical shape introduces additionally a tangential force. All these issues produce deviation of the assumed nominal modeling, which render low performance in practice. To tackle this problem, it must be acknowledged the nature of contact mechanics through deformable pad, that is, the normal and tangential forces appear at contact while the deformation is usually unknown. Then, the force control of robots using such pads requires stabilizing normal and tangential forces subject to uncertain contact kinematics, the contact Jacobian is unknown.

Clearly, both tangential and normal forces play a fundamental role in dexterity of human hands, (Flanagan et al., 2002), and have served as a basis to develop a variety of robotic fingers where the rolling contact is an essential feature for many skillful tasks, (Arimoto). However, there remains open problems on how to stabilize both forces with rolling when deformation is unknown. To address this problem, initially (Marigo and Bicchi, 2007) shows that using hemispherical rigid tips introduce purposely rolling constraints, however it is quite difficult to deal with pure rigid rolling based on point contact, (Yoshikawa, 2000). To circumvent this limitation, there has been proposed hemispherical deformable tips, which against all odds have proved right to stabilize normal and tangential forces assuming known contact kinematics, (Inoue and Hirai, 2009; Nguyen et al., 2006). However, if the Jacobian is uncertain, the sounds schemes (Doulgeri and Arimoto, 1999; Cheah et al., 2004; Wang, 2014) cannot be used. This leads to resort on soft-computing techniques, in Treesatayapun (2013), has been proposed a MiFRENN to exert a force with one degree of freedom (DoF), however an implicit knowledge of the normal direction is assumed while the tangential force is neglected, (Treesatayapun, 2014; Carreon et al., 2016). In contrast, (Armendariz et al., 2014; Parra-Vega et al., 2016), have

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[*] Corresponding author.
E-mail addresses: rgarcia1@miuandes.cl (R. Garcia-Rodriguez), vparra@cinvestav.mx (V. Parra-Vega).

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proposed a MiFRENN for n-DoF (MIMO) robots in free motion, and rigid point-based constrained motion but assuming full knowledge of the Jacobian. Nevertheless, the tangential and normal force control for an n-DoF robot manipulator subject to uncertain contact stands an open issue.

In this paper, we consider a constrained rigid robot whose end-effector is equipped with hemispherical and soft tip exerting force onto a rigid surface. Given that the deformation and penetration are difficult to measure, we assume that the elastic restitution force arises at the point of maximum penetration depth. Then, we have that the normal force vector encodes the normal unit vector. This observation leads to quest an alternative approach using AI-based networks, (Fateh et al., 2010; Lin and Lin, 2015; Balaghi et al., 2016) to estimate the contact differential kinematics by extracting knowledge of such unit-vector using a knowledge-based fuzzy rules of MiFRENN.

1.1. Our proposal

The deformable hemispherical soft-tip resembles to the human fingertip shape when engaging contact through rolling. Clearly, it is reasonable to claim that attempting to reproduce any human skill in machines will certainly be very costly somehow, either in hardware, in software, in theoretical aspects, or in human resources. In this circumstance, arguably it is preferred to resort on (deterministic) soft-computing techniques instead of model-based robust controllers given that contact and elastic deformation elements are involved. In this sense, we find reasonable to consider a MISO MiFRENN for a n-DoF nonlinear constrained robot equipped with hemispherical soft fingertip. Based on a judicious physics-based decomposition of rolling, and contact mechanics with deformation, a simple regulator is proposed that resembles the effect of the synergies (Zatsiorsky et al., 2004; Alessandro et al., 2013), with the damping injection, the gravity compensation and the underlying role of MiFRENN to estimate the span of the normal force subspace. Then, using the passivity property arising from torque input to velocity output due to the rolling (velocity) constraint, it is showed that damping injection is useful to the convergence of the force errors into a manifold. Subsequently, force error trajectories, driven by the MiFRENN, are induced to converge exponentially. This manuscript is organized as follows: Section 2 introduces the models, and Section 3 shows the whole control structure, with its stability analysis, and some remarks. Simulations are given in Section 4 and final conclusions are discussed in Section 5.

2. Kinematic and dynamic models

Soft hemispherical tip leads to modeling a workless tangent force (the constrained Lagrangian), as well as a restitution normal force (due to elastic deformation) for n-DoF robot manipulator in contact to a rigid (undeformable) environment, in lossless elastic regime, (Arimoto, 0000). Without loss of generality, let a $n = 3$ planar robot be in contact to a rigid plane collinear to x, see Fig. 1, where inertial frame $\vec{O}_0 = (x, y, z)$ sets the origin of the robot, and the end-effector $\vec{O}_4 = (D_x, D_z)$ is parameterized by generalized joints q_i, and link lengths l_i.

2.1. Kinematic model at contact

When the end-effector engages contact throughout a deformable hemispherical tip, it is considered that exerts a normal force at the point of maximum penetration depth $p > 0$, computed along the z-axis, see Fig. 1. In this condition, one has that $r = p + D_z$ is measured along the line $\vec{O}_4 - \vec{O}_5$, where

$$p = r - l_1 \sin(q_1) - l_2 \sin(q_{12}) - l_3 \sin(q_{123}) \tag{1}$$

for $q_{ijk} = q_i + q_j + q_k$, and the fingertip radius r centered at $\vec{O}_4$, where $\vec{O}_5$ stands for the contact point of maximum deformation, which coincides with the projection of $\vec{O}_4$ along z, but it may not coincide with middle point of $\vec{O}_6 - \vec{O}_7$ where is applied the force f_c, Fig. 2.

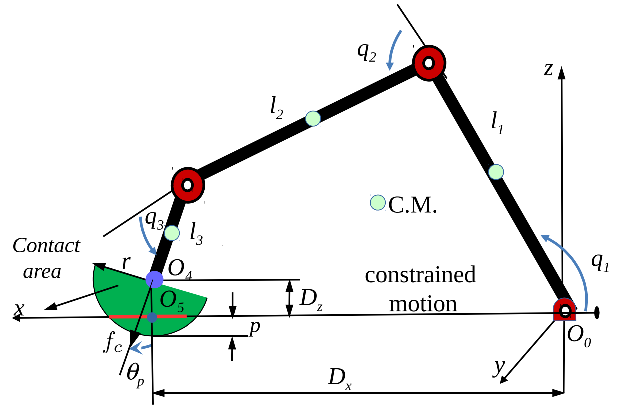

Fig. 1. Representation of a 3 DoF soft-fingered robot in the phase plane x, z, wherein applied force is achieved through elastic deformation of hemispherical fingertip.

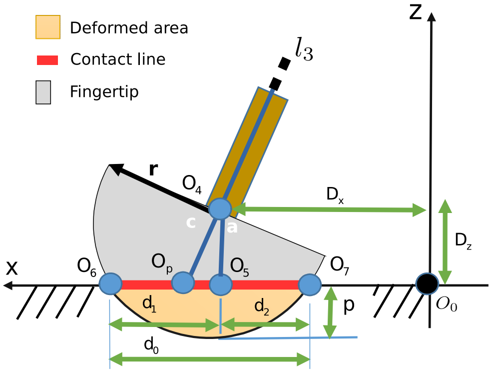

Fig. 2. Restitution force depends on fingertip material from the elastic deformation.

See that in general $\vec{O}_p \neq \vec{O}_5$, and $d_1 \neq d_2$, where $d_1 = \vec{O}_6 - \vec{O}_5$ and $d_2 = \vec{O}_5 - \vec{O}_7$. In these conditions, the forward kinematics of $\vec{O}_p$, with respect to inertial frame $\vec{O}_0$ is unknown, because d_1 and hypotenuse $c = \sqrt{(\vec{O}_p - \vec{O}_5)^2 + D_z^2}$ are unknown, consequently, the Jacobian from $\vec{O}_p$ to $\vec{O}_0$ is unknown.

2.2. Contact force model

Consider the deformable fingertip in a lossless elastic regime, whose restitution force f_c stands for the applied normal force along the projection of link l_3, intersecting x-axis at $\vec{O}_p$, (Inoue and Hirai 2005, 2006),

$$f_c = \frac{E\pi p^2}{\cos(\theta_p)} \tag{2}$$

where E stands for the elastic Young modulus, and $\theta_p = -\frac{\pi}{2} - q_1 - q_2 - q_3$ represents the contact relative angle with respect to z-axis, see Fig. 1. Notice that the normal force arises at the point of maximum penetration depth when the contact relative angle θ_p is zero. At the same time notice that from (2) we have that $p = \sqrt{f_c \cos(\theta_p)/E\pi}$. So that, if the objective is to exert $f = 1\ N$ with a smooth silicone-made fingertip of, say $E = 50{,}000$, at a small angle $\theta_c = 10°$, we obtain that $p \approx 0.58 \times 10^{-5}$, or about 6 μm, well below state of the art robot technology. Thus, this fact substantiates the following:

- If the fingertip is at initial contact, i.e. $p = 0$ (the hemispherical fingertip is undeformed yet), then since $r = D_z + p$ meaning that $r = D_z$, see Fig. 2. In this way, the translational velocity