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Increasing Isotropy of Intrinsic Compliance in Robot Arms through Biarticular Structure ⋆

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Abstract: In human-robot interaction passive compliance is fundamental for safety, however stiffness is necessary for performance. These two factors motivate intrinsic compliance modulation in robots interacting with humans. Variable Stiffness Actuators (VSAs) allow for simultaneous position and stiffness control of a joint, therefore they have been implemented in the realization of intrinsically compliant and high performance robot arms. Most applications employ VSAs in a monoarticular structure, that is one actuator produces torque about one joint. In the biological world however, biarticular muscles (muscles spanning two joints) play a fundamental role in motion control for humans, not only reducing link inertia, but also increasing isotropy of end effector force and compliance. In this work, a robot arm with VSAs and two interchangeable actuation structures (the traditional monoarticular and human-like biarticular) is built. The end effector intrinsic compliance in both the actuation structures is measured. Experimental results suggest that the biarticular VSA structure is more suitable for compliant robot arms.

Keywords: Mechatronic systems, Motion control systems, Robots manipulators

1. INTRODUCTION

In human-robot interaction, as well for robots operating in presence of humans, passive compliance is fundamental to guarantee safety Bicchi et al. (2001). A widely known approach to achieve passive compliance is through the use of elastic elements between the actuator and the joint, namely Series Elastic Actuators (SEAs) Pratt and Williamson (1995). A limit of SEAs is that the compliance can not be varied without the use of feedback control as compliance depends on the mechanical characteristic of the elastic elements, which is constant English and Russell (1999). In order to overcome the bandwidth limitations of feedback control, while at the same time allowing for passive compliance regulation, Variable Stiffness Actuators (VSAs) are rising in interest. VSAs allow for simultaneous position and stiffness control of a joint, and are therefore employed in intrinsically compliant manipulators Ham et al. (2009), Koganezawa et al. (2006), Migliore et al. (2005), Hurst et al. (2010), Ham et al. (2007), Wolf and Hirzinger (2008), Tsagarakis et al. (2009), Chalon et al. (2010), Palli et al. (2007). In most of these robot arms, the VSAs are implemented in a monoarticular structure (i.e. a VSA produces torque about a single joint).

Unlike conventional robot arms with monoarticular actuation, humans and animals incorporates bi-articular muscles — muscles spanning two consecutive joints — to regulate stiffness stabilizing unstable dynamics (for example running over rough terrain Daley et al. (2006)), to increase accuracy of movements Smeets (1994), and to transfer power from proximal to distal joints Van Ingen Schenau (1989). For these reasons interest in robots with bi-articular actuators has been rising. Implementation of biarticular actuation in robotic applications has shown numerous advantages. Biarticular actuators dramatically increase the range of end effector impedance which can be achieved without feedback Hogan (1985), increase the capability of path tracking and disturbance rejection Salvucci et al. (2011c), Horita et al. (2002), allow for precise output force control Salvucci et al. (2013b), improve balance control for legged robots without force sensors Oh et al. (2010). and increase isotropy of maximum end effector force Salvucci et al. (2013a), Salvucci et al. (2013c). However, the combination of VSAs and biarticular structure is a new approach which has not yet been deeply investigated.

In this work, a robot arm with VSAs and two interchangeable actuation structures — the traditional monoarticular and human-like biarticular — is built. The end effector compliance in both the actuation structures is measured.

The paper is organized as follows. Modeling of bi-articularly actuated robot arms is shown in section 2. In section 3 the variable stiffness mono- and bi-articular actuator structures are illustrated. In section 4, the two-link planar robot arm with VSAs is described together with the experimental setup. The results are shown and analyzed in section 5. Finally, this work is concluded in section 6.

2. MODELING BI-ARTICULAR ACTUATION IN ROBOT ARMS

Animal and human limbs present a complex musculoskeletal structure based on mono- and multi- articular muscles:

(1) Mono-articular muscles produce torque about one joint.

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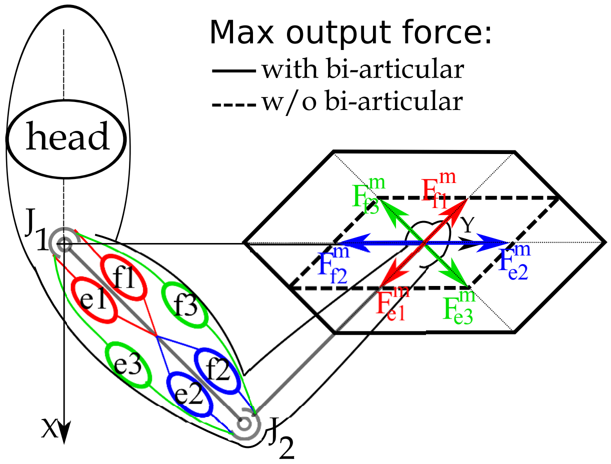
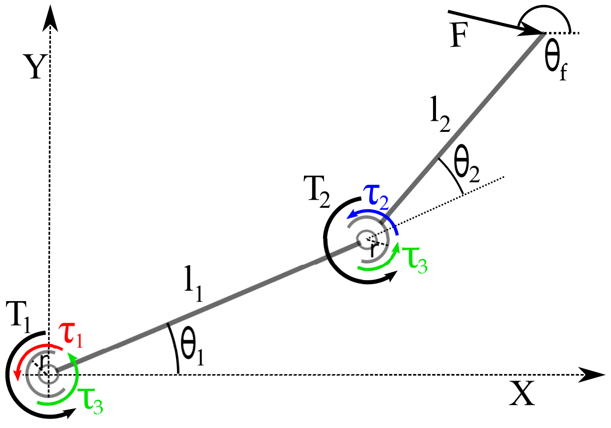


(a) Model and resulting forces at the end effector



(b) Statics

Fig. 1. Two-link arm with four mono- and two bi-articular actuators

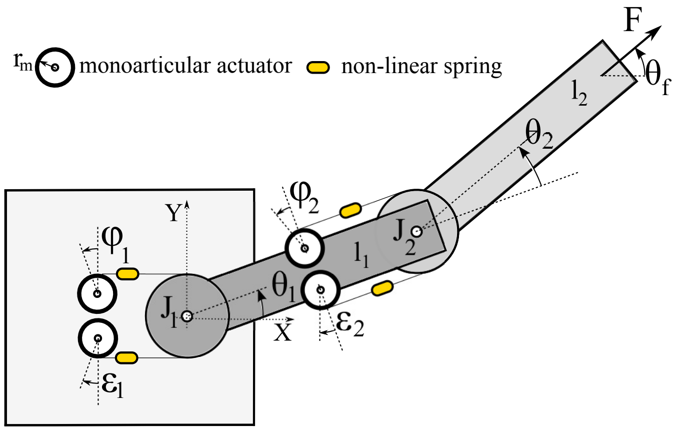
(2) Multi-articular muscles produce torque about more than one joint.

A widely used simplified model of the complex animal musculoskeletal system Fukusho et al. (2010), Kumamoto et al. (1994), Oh et al. (2011), Salvucci et al. (2011a), Salvucci et al. (2011b) with the maximum end effector forces at the end effector is shown in Fig. 1(a). This model is based on six contractile actuators — three extensors (e1, e2, and e3) and three flexors (f1, f2, and f3) — coupled in three antagonistic pairs:

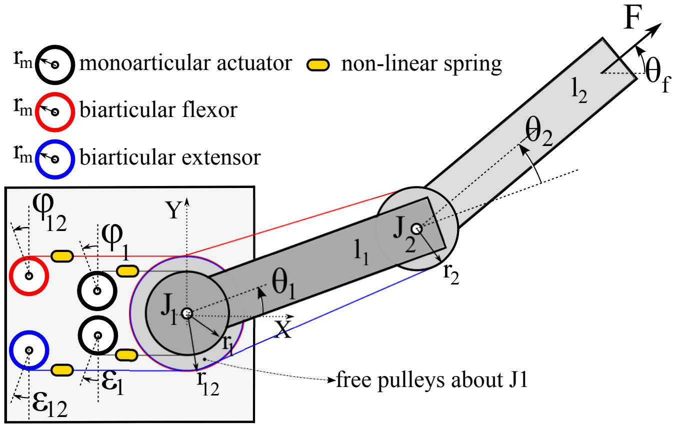
- e1–f1 and e2–f2: couples of mono-articular actuators that produce torques about joint 1 and 2, respectively.
- e3–f3: couple of bi-articular actuators that produce torque about joint 1 and 2 simultaneously.

The six actuators produce contractile forces e_i or f_i for $i = (1,2,3)$ with respective maximum value e_i^m or f_i^m. The resulting end effector forces are F_{ei} and F_{fi} for $i = (1,2,3)$ with respective maximum values F_{ei}^m and F_{fi}^m.

The resulting statics are shown in Fig. 1(b) where $\boldsymbol{F}$ is a general force at the end effector; $\boldsymbol{T} = [T_1, T_2]^T$ are total torques about joints 1 and 2, respectively; $\boldsymbol{\tau}$ represents the actuators torques: τ_1 and τ_2 are torques produced by mono-articular actuators about joints 1 and 2, respectively, while τ_3 is the bi-articular torque produced about both joints simultaneously. The resulting joint torques are Salvucci et al. (2013a):



(a) Two monoarticular VSAs (VSMA)



(b) One mono- and one bi-articular VSAs (VSBA)

Fig. 2. Two-link intrinsically compliant manipulators: monoarticular VSAs (VSMA) and biarticular VSAs (VSBA) structures

$$\boldsymbol{T} = \boldsymbol{B}\boldsymbol{\tau} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \tag{1}$$

3. VARIABLE STIFFNESS MONO- AND BI-ARTICULAR ACTUATOR STRUCTURES

3.1 Structure

In Fig. 2 two actuation structures for a two-link intrinsically compliant robot arm are shown. The VSA are made of two antagonistic motors, each one employing a nonlinear elastic element in the transmission system. The first one in Fig. 2(a), referred as Variable Stiffness Monoarticular Actuator (VSMA) structure in the following, is the conventional one implemented in intrinsically compliant robot arm. It consists of two VSAs, each connected to one joint as a monoarticular actuator. In Fig. 2(b), referred as Variable Stiffness Biarticular Actuator (VSBA) structure in the following, consists of one VSA connected to joint 1 as a monoarticular actuator, and a VSA connected to both joints 1 and 2 as a biarticular actuator by means of a free pulley system.

3.2 Modelling

Given the reference system in Fig. 2, the spring displacements between joints and respective actuator are:

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