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BiWi: Bi-Articularly Actuated and Wire Driven Robot Arm

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***Abstract*—Recently, there has been increasing attention on animal inspired robot arms equipped with bi-articular actuators.**

In this paper BiWi, bi-articularly actuated and wire driven robot arm, is proposed. The proposed manipulator is actuated by 6 motors arranged in three antagonistic pairs, so to reproduce the human musculo-skeletal system characteristics in terms of joint torques and end effector output force production. The wire based transmission allows to place the motors away from the links reducing links inertia and increasing important factors as energy efficiency and safety.

The proposed robot arm can produce a human-like force at the end effector by using a feedforward control strategy. Moreover, it is shown that the proposed manipulator presents perfect decoupling between mono- and bi-articular actuators joint torques thanks to the combination of antagonistic actuators and wire transmission.

***Index Terms*—Actuation Redundancy, Bi-articular Actuators, Biologically Inspired Robotics, Feedforward Control, Two-link Manipulator**

I. Introduction

Industrial robots are capable of accomplish very fast and precise movements in well known environment. On the other hand, robots that attempt to be animal- or human-like do not present the flexibility and smoothness of animals and humans.

Robots are often characterized by a simple actuator system and a control strategy based on inversed kinematics and dynamics. The complexity of the controller design increase exponentially with the number of degrees of freedom and actuators. On the contrary, humans present a complex muskuloskeletal system with a lot of kinematic and actuator redundancies, and a simpler control approach based not only on feedback but also on feedforward strategy.

Recently, bio-inspired robot arms presenting actuator redundancies have been raising interest both in hardware and control design aspects.

Regarding the hardware design, bi-articular actuators have been realized by means of pneumatic actuators [1], [2], [3], pulleys [4], [5], planetary gears [6], [7], wires [8], [9].

Concerning the control design for manipulators equipped with bi-articular actuators, and in particular the actuator redundancy resolution problem, approaches based on human muscle activation level patterns [4], [10], [11], and approaches based on pseudo inverse matrices are often used [5], [12]. Our approach to resolve actuator redundancy is instead based on $\infty - norm$ [13], [14].

As for the dynamics control of robot arm driven by bi-articular actuators, several researches have been focusing on stiffness control for disturbance rejection [5], [15], other researches on efficiency of bi-articular actuators in walking [8] and swimming [4] robots. There are also researches in which human walking patterns are used as feedforward control strategy for bi-articularly actuated walking robots [2].

In this paper a biologically inspired manipulator — BiWi, bi-articularly actuated and wire driven robot arm — is proposed. It is shown that the proposed manipulator can produce a human-like force at the end effector by using a feedforward control strategy. Moreover, it is shown that the proposed robot arm presents perfect decoupling between mono- and bi-articular actuators joint torques.

In section II, main characteristics and modelling of manipulators equipped with bi-articular actuators are described. In section III, the proposed manipulator equipped with mono- and bi-articular actuators is described in details. In section IV the experimental set up is illustrated. In Section V, the measured end effector output force of the proposed manipulator obtained with the feedforward control strategy is shown. Finally, in section VI, the conclusions.

II. Characteristics and Modeling of Robot Arms with Bi-Articular Actuators

In conventional manipulators each joint is driven by one actuator. On the contrary, animal limbs present a complex musculo-skeletal structure based on:

1) Mono-articular muscles, which produce a torque on one joint.
2) Multi-articular muscles, which produce torque on two (or more) consecutive joints at the same time. Gastrocnemius is a bi-articular muscle in the human leg.

A simplified model of the complex animal musculo-skeletal system is shown in Fig. 1. This model is based on 6 contractile

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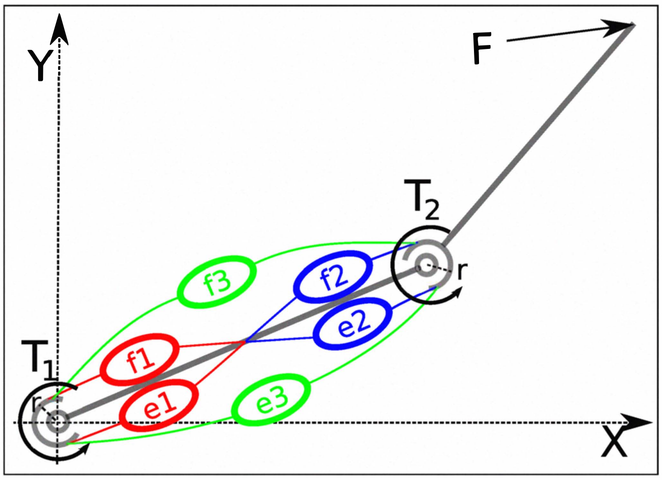


Fig. 1. Scheme a two-link arm with 4 mono- and 2 bi-articular actuators

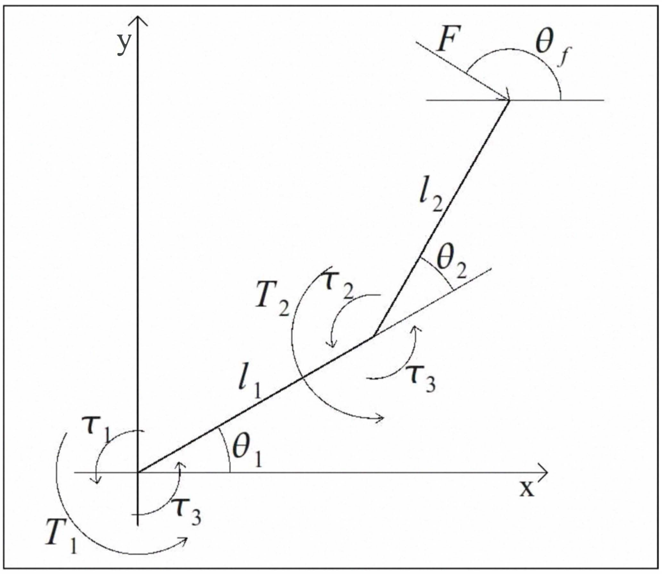


Fig. 2. Statics of a two-link arm with mono and bi-articular actuators

actuators — extensors (e_1, e_2 and e_3) and flexors (f_1, f_2 and f_3) — coupled in three antagonistic pairs.

- e_1–f_1 and e_2–f_2: pairs of mono-articular actuators which produce torques about joints 1 and 2, respectively.
- e_3–f_3: pair of bi-articular actuators which produce torque about joints 1 and 2 contemporaneously.

The statics of the arm driven by bi-articular actuators of Fig. 1 is shown in Fig. 2 where:

- T_1 and T_2 are total torques at joints 1 and 2, respectively.
- τ_1 and τ_2 are torques produced mono-articular actuators at joints 1 and 2 respectively, calculated as:

$$\tau_1 = (f_1 - e_1)r \tag{1}$$

$$\tau_2 = (f_2 - e_2)r \tag{2}$$

where r is the distance between the joint axis and the point where the force is applied.

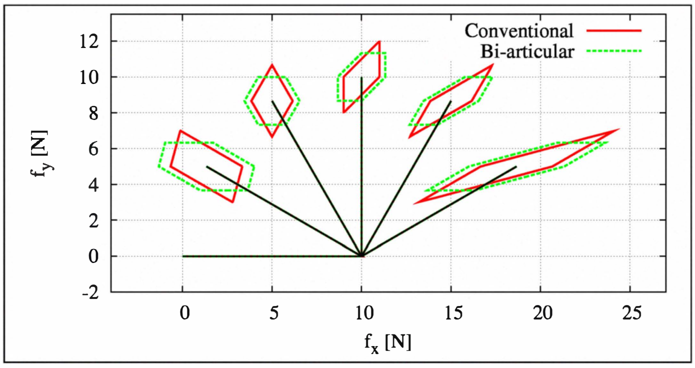


Fig. 3. Maximum output force at the end effector for conventional and arm driven by bi-articular actuators

- τ_3 is the bi-articular torque produced at both joints:

$$\tau_3 = (f_3 - e_3)r \tag{3}$$

- **F** is a general force at the end effector.

The statics of this system can be therefore expressed by:

$$\begin{cases} T_1 = \tau_1 + \tau_3 \\ T_2 = \tau_2 + \tau_3 \end{cases} \tag{4}$$

Manipulators equipped with bi-articular actuators have numerous advantages: dramatical increase in range of end effector impedance which can be achieved without feedback [16], realization of path tracking and disturbance rejection using just feedforward control [5], improvement of balance control for jumping robots that do not use force sensors [15]. Moreover, multi-joints actuators such as tri-articular actuators, can increase the efficiency in force production [4].

Another advantage of arm equipped with bi-articular actuators is the ability to produce a maximum output force at the end effector in a more homogeneously distributed way [17]. In Fig. 3 the maximum output force at the end effector for a two-link conventional manipulator and a bi-articular actuated robot arm is shown for comparison. The conventional manipulator has 2 actuators with maximum torque $T_1 = T_2 = 10\ Nm$, and the bi-articular actuated robot arm has 3 actuators with maximum torque $\tau_1 = \tau_2 = \tau_3 = 6.66\ Nm$. All the gear ratios of all the actuators are the same. Therefore, the sum of maximum actuator torques are the same (i.e. 20 Nm) in the two cases. The conventional quadrilateral shape becomes an hexagon for arms driven by bi-articular actuators, which can therefore produce a maximum force at the end effector more homogeneously distributed in respect to output force direction. This aspect is peculiar for applications which interact with humans such as rehabilitation robots, as well as for jumping and walking robots [15], [18].

Robot arms equipped with bi-articular actuators, as the two-link manipulator with the statics shown in Fig. 2, present actuator redundancy. Given τ_1, τ_2 and τ_3, it is possible to determine T_1 and T_2, and so **F** by using the transpose Jacobian:

$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = J^T \begin{pmatrix} f_x \\ f_y \end{pmatrix} \tag{5}$$

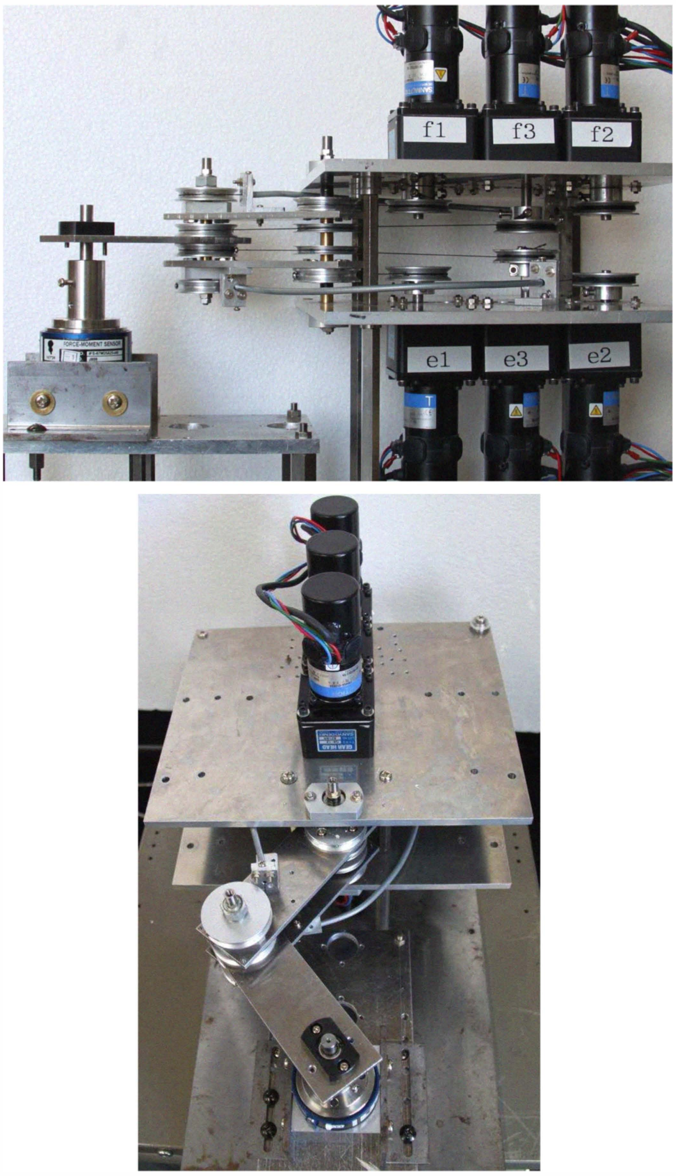


Fig. 4. BiWi, bi-articularly actuated and wire driven robot arm

where

$$J = \begin{bmatrix} -l_1\sin(\theta_1) - l_2\sin(\theta_1+\theta_2) & -l_2\sin(\theta_1+\theta_2) \\ l_1\cos(\theta_1) + l_2\cos(\theta_1+\theta_2) & l_2\cos(\theta_1+\theta_2) \end{bmatrix} \quad (6)$$

f_x and f_y are the orthogonal projection of **F** on the axis x and y, respectively. On the other hand, given **F**, and therefore T_1 and T_2, it is generally not possible to determine uniquely τ_1, τ_2 and τ_3 due to the actuator redundancy (see (4)). Our approach to resolve actuator redundancy is based on the $\infty - norm$ [14].

III. BiWi: Bi-Articularly Actuated and Wire Driven Robot Arm

The proposed robot arm, BiWi, bi-articularly actuated and wire driven is shown in Fig. 4 The two-link planar manipulator has 6 motors, each one representing one of the muscles in

TABLE I
MANIPULATOR CHARACTERISTICS

Parameter	value
Link 1	112 [mm]
Link 2	112 [mm]
Pulleys diameter (all)	44 [mm]
Thrust wire	30 [mm]

TABLE II
ACTUATOR AND SENSOR SYSTEM

Motors	Sanyo T404-012E59
Gear head	G6-12 (ratio 12)
Servo system	TS1A02AA
Force sensor	Nitta IFS-67M25A25-I40

Fig. 1. The power is transmitted to the joints through pulleys and polyethylene wires as shown in Fig. 5:

- A pair of antagonistic mono-articular motors (e_1–f_1) are connected by mean of polyethylene wires to 2 pulleys fixed on joint 1. This motor pair produces the torque τ_1 about joint 1 as in Fig. 2.
- A pair of antagonistic mono-articular motors (e_2–f_2) are connected by thrust wires to 2 pulleys fixed on joint 2. This motor pair produces the torque τ_2 about joint 2 as in Fig. 2.
- A pair of antagonistic bi-articular motors (e_3–f_3) are connected by mean of polyethylene wires to pulleys fixed on joint 2, and to free pulleys about joint 1. This motor pair produces the torque τ_3 about joint 1 and 2 as in Fig. 2.

Further characteristics of the proposed manipulator and of the actuator and sensor systems are shown in Tab. I and Tab. II, respectively. In the following the main characteristics of the proposed robot arm are described:

- **Decoupling between mono- and bi-articular actuators joint torques**: in many manipulators equipped with bi-articular actuators coupling between mono- and bi-articular torques at joint level represent a problem [7], [19]. In fact, if such torque coupling is present, the maximum output force at the end effector results in a less homogeneously distribution in respect to force direction. On the other hand, the proposed manipulator thanks to the presence of antagonistic actuators and wire transmission presents no coupling between mono- and bi-articular torques at joint level.
- **Safety**: another peculiarity of the proposed manipulator is that all the motor are located away from the links, resulting in a great advantage in term of links inertia, which increases important factors as safety in case of impact with human beings [20].
- **Thrust wire transmission**: the use of thrust wires to transmit the torque of mono-articular actuators on joint 2 – e_2 and f_2 – allows the placement of the motors away from the links reducing their inertia, however implies the presence of transmission loss. As for the proposed manipulator, such a transmission loss is modelled as

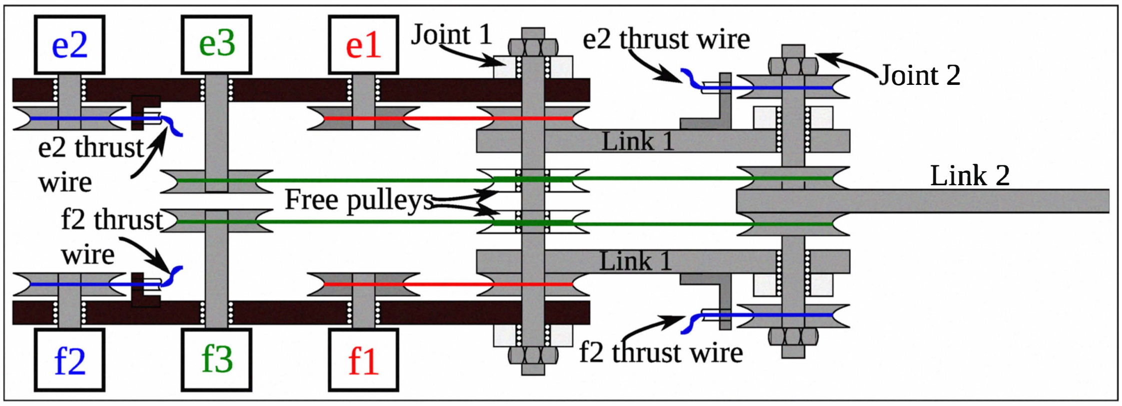


Fig. 5. Torque transmission system

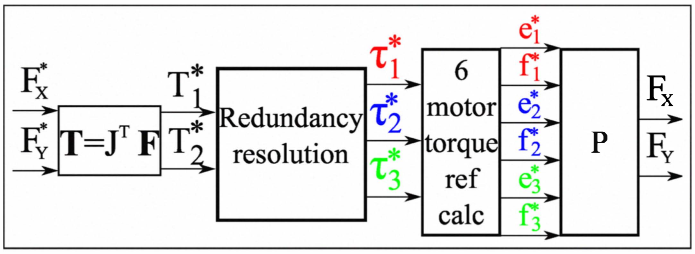


Fig. 6. Feedforward control block diagram

a constant value equal to 30% of the reference motor torque. Such a value is relatively high, due to the low cost of the thrust wires. However, by the use of more sophisticated thrust wires the transmission loss can be reduced to smaller value, for example to 5% of the reference motor torque as in [21].

- **Antagonistic Actuators**: the use of antagonistic actuators implies the capability of independent stiffness control at joint level by the presence of mono-articular actuators. This capability of stiffness control is furthermore dramatically increased by the presence of antagonistic bi-articular actuators [16].

IV. Experimental Set-up

In order to verify the human-like characteristics of the proposed robot arm in term of output force at end effector, and to show the perfect decoupling between mono- and bi-articular actuators joint torques, the output force at end effector is measured by a force sensor. The arm is placed in three different joint angle configuration:

1) $\theta_1 = -60°$ and $\theta_2 = 120°$
2) $\theta_1 = -45°$ and $\theta_2 = 90°$
3) $\theta_1 = -30°$ and $\theta_2 = 60°$

The output force is measured for θ_f — the force output angle as in Fig. 2 — varying from 0 to 360° every 5°. The maximum actuator joint torques are set to $\tau_1 = \tau_2 = \tau_3 = 1.5\ Nm$.

The feedforward control strategy used to collect the experimental data is shown in Fig. 6. f_x^* and f_y^* are the desired force at the end effector. J is the manipulator Jacobian. τ_1^*, τ_2^* and τ_3^* are the desired actuator joint torques as in Fig. 2. These torques are calculated using $\infty - norm$ approach from the desired joint torques T_1^* and T_2^* [14]. The 6 motor reference torques that correspond to the 6 muscles of Fig. 1 – e_1^*, f_1^*, e_2^*, f_2^*, e_3^*, f_3^* – are calculated as:

$$e_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

$$f_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$e_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

$$f_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

$$e_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

$$f_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

Equations (7)–(12) shows that the manipulator can also realize independent stiffness control on τ_1, τ_2 and τ_3. This is possible by defining a minimum input torque reference greater than zero for any of the actuators pair $e_i - f_i$, $(i = 1, \ldots, 6)$. The capability of the manipulator to perform stiffness control is however not relevant for the purpose of this work, therefore the minimum value is set to zero in the experiment.

In order to compensate for the inevitable transmission loss in the thrust wires the reference motor torques for joint 2 – e_2^* and f_2^* – are multiplied by a constant $K_{tl} = 1.33$.

The manipulator end effector output force $\mathbf{F} = [f_x, f_y]$ is measured by a force sensor, and its steady state value is taken into account.

V. Results

Fig. 7 shows the output force distribution at end effector for an arm with the simplified musculo-skeletal structure illustrated in Fig. 1. The measured output force at the end effector for the manipulator in Fig. 4, obtained using the

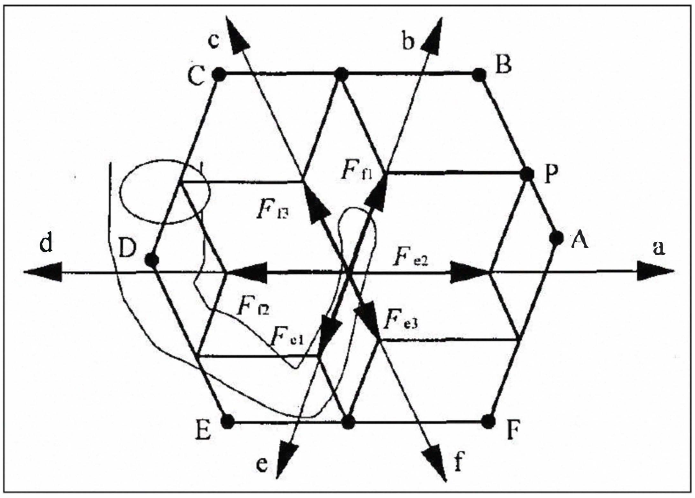


Fig. 7. Output force distribution at end effector for a human arm ([10])

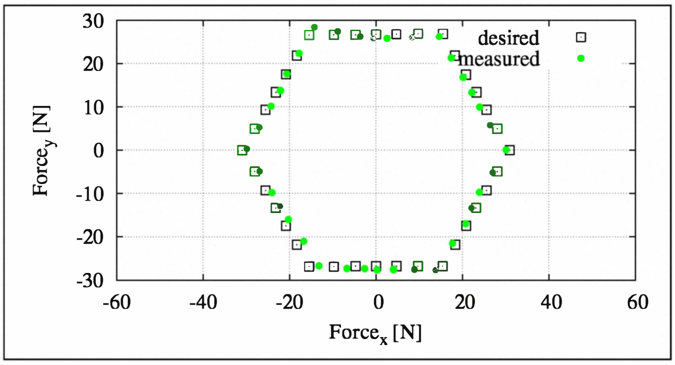
motor torque input patterns calculated with the feedforward control strategy described in Section IV, are shown in Fig. 8 for $\theta_1 = -60°$ and $\theta_2 = 120°$, in Fig. 9 for $\theta_1 = -45°$ and $\theta_2 = 90°$, and in Fig. 10 for $\theta_1 = -30°$ and $\theta_2 = 60°$. The experimental results show that the proposed robot arm is capable of producing a human-like shape force as in Fig. 7.

In addition, the produced force can track the desired force output with a very small error due to inevitable modeling errors and sensor noise. No feedback control is used, nor any torque decoupling strategies as for example in [7] is implemented. As a consequence, a perfect decoupling between mono- and bi-articular actuators joint torques is realize.

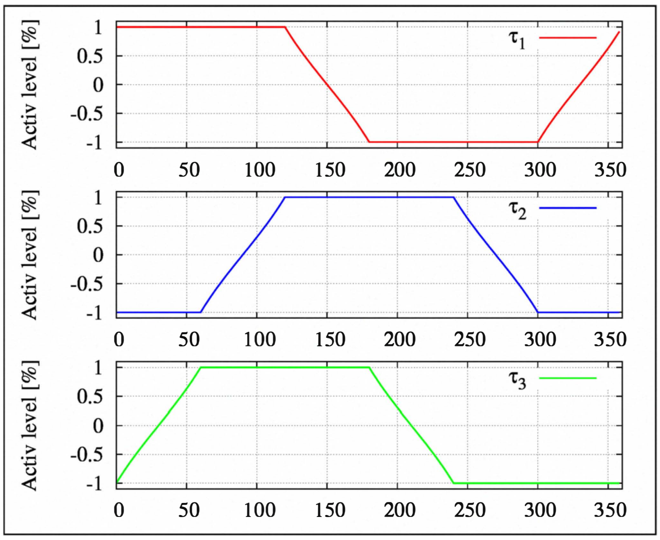
VI. Conclusions

In this paper, BiWi, a biologically inspired robot arm equipped with bi-articular actuators and wire driven is proposed. The proposed manipulator is actuated by 6 motors arranged so to reproduce the human musculo-skeletal system characteristics in term of force production. The wire based transmission system allows several advantages: reducing link inertia thanks to the placement of motors away from the links, increasing important factors such as as energy efficiency and safety. The use of antagonistic actuators implies the capability of independent stiffness control at joint level. The stiffness control capability is furthermore dramatically increased by the presence of antagonistic bi-articular actuators. The combination of antagonistic actuators and wire transmission allow a perfect decoupling between mono- and bi-articular actuators joint torques, resulting in a homogeneous distribution of force the end effector in respect to force direction.

In order to verify the human-like characteristics of the proposed robot arm in term of output force at end effector, and to show the perfect decoupling between mono- and bi-articular actuators joint torques, the output force at end effector was measured by a force sensor. The arm was placed in three different joint angle configurations. As a result, the proposed manipulator can produce a force at the end effector with an hexagonal shape as human arms can do. In addition, it is shown that the proposed robot arm can precisely track the desired force by using a feedforward control strategy.



(a) Measured maximum output force



(b) τ_1, τ_2, τ_3

Fig. 8. $\theta_1 = -60°$, $\theta_2 = 120°$

Acknowledgment

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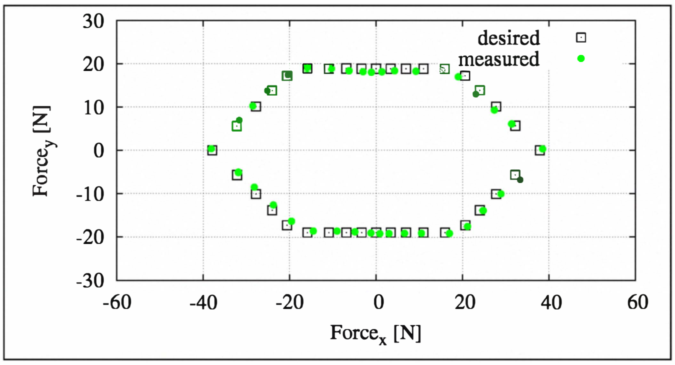
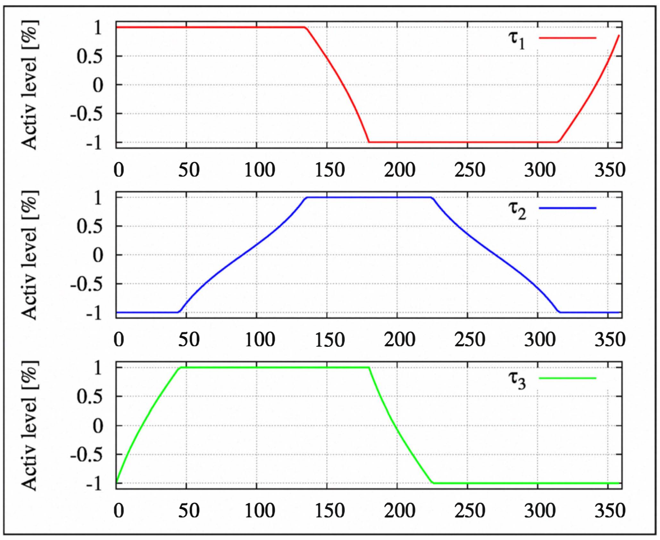
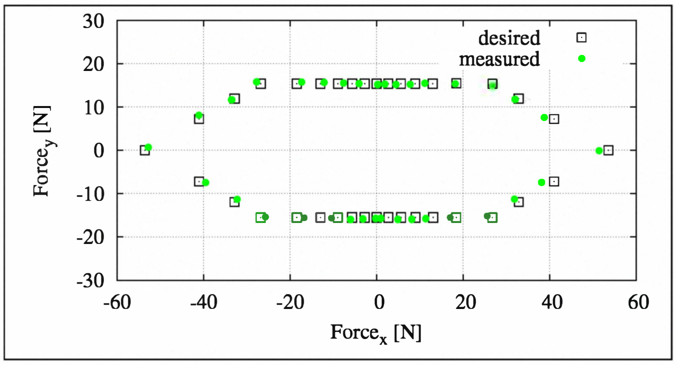


(a) Measured maximum output force

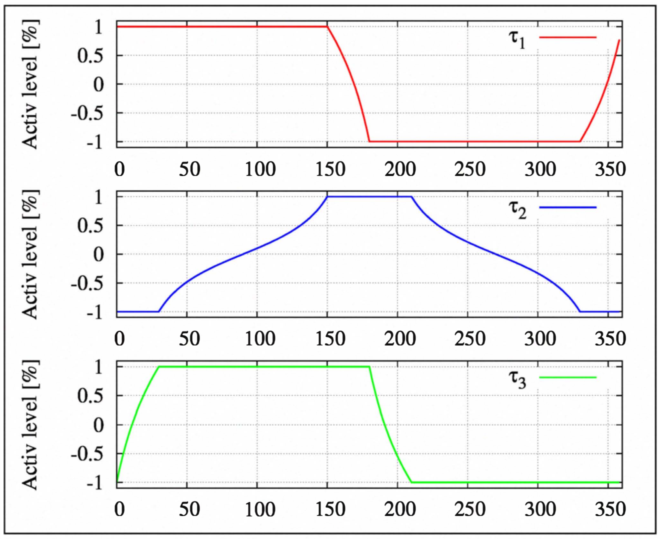


(b) τ_1, τ_2, τ_3

Fig. 9. $\theta_1 = -45°$, $\theta_2 = 90°$



(a) Measured maximum output force



(b) τ_1, τ_2, τ_3

Fig. 10. $\theta_1 = -30°$, $\theta_2 = 60°$

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