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Experimental Verification of Infinity Norm Approach for Precise Force Control of Manipulators Driven by Bi-articular Actuators ⋆

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Abstract: In recent years there has been increasing interest in manipulators presenting animal musculo-skeletal characteristics such as bi-articular actuators. Manipulators driven by bi-articular actuators usually have more actuators than joints, resulting in actuator redundancy.
In this paper, our approach based on infinity norm to resolve actuators redundancy is implemented on Biwi, Bi-articularly actuated and Wire driven robot arm, and compared with the Phase Different Control (PDC) approach, which is based on human muscle activation level patterns.
It is shown that the infinity norm approach produces no error in calculation of output force, while the PDC approach produces non-zero error. Such error is not significant when the angle between the manipulator links is about 120 degrees, but increases as the manipulator moves towards singular configurations. The experimental results agrees with the calculation.

Keywords: Mechatronics system, Modeling for control optimization, Robots manipulators

1. INTRODUCTION

Robot manipulators presenting animal musculo-skeletal characteristics such as bi-articular actuators have been proposed for more than two decades (Hogan (1985)). In recent years there has been increasing attention on such animal inspired robot arms, both in hardware and control design aspects (Tsuji (2010), Umemura et al. (2010), Kimura et al. (2010), Fukusho et al. (2010), Oh and Hori (2009)).

Manipulators driven by bi-articular actuators usually have more actuators than joints, presenting therefore actuator redundancy. In order to resolve this torque load sharing problem many approaches have been proposed.

There are researches such as (Yoshida et al. (2009)) in which pseudo-inverse matrices are used to resolve the actuator redundancy. This type of approach have been also widely used for resolution of kinematics redundant manipulators. Moore-Penrose is the most simple pseudo-inverse, and correspond to the minimization of the $2-norm$ (euclidean norm) (Klein and Huang (1983)).

A nature inspired approach widely used to resolve actuator redundancy in robot applications (Fukusho et al. (2010), Tsuji (2010), Umemura et al. (2010)) is the Phase Different Control (PDC) that is based on human muscle activation level patterns (Oshima et al. (2000)). According to this approach, the relationship between the output force at the end effector and the actuator joint torques can be determined using a linear model based on muscle activation level patterns, which have been derived from observation of electromyography activity of human muscles.

In (Salvucci et al. (2011b)) our new approach to resolve actuator redundancy based on infinity norm is described. The characteristics and advantages of this approach can be summarized as follows. The $\infty-norm$ approach maximizes the force at the end effector given the maximum actuator joint torques. Therefore, it can be used as an approach to optimize actuator design for manipulators driven by bi-articular actuators. Moreover, the $\infty-norm$ approach is based only on a piecewise linear function to resolve actuator redundancy. In comparison with the Moore-Penrose pseudo-inverse approach ($2-norm$), the $\infty-norm$ approach allows to obtain a greater output force at the end effector, for the same joint torque limitations (Salvucci et al. (2011b)).

In this paper, it is shown that the infinity norm approach produces no error in calculation of output force, while the PDC approach produces non-zero error. Such error is not significant when the angle between the manipulator links is about 120 degrees, but increases as the manipulator moves towards singular configurations. Experimental results are obtained using Biwi, Bi-articularly actuated and Wire driven robot arm, and confirm the calculation.

In Section 2, characteristics and modeling of robot arm with bi-articular actuators are described. In Section 3, two approaches for actuator redundancy resolution — PDC and $\infty-norm$ —

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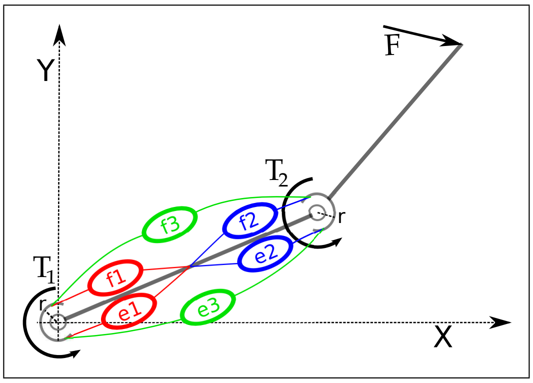


Fig. 1. Scheme a two-link arm with 4 mono- and 2 bi-articular actuators

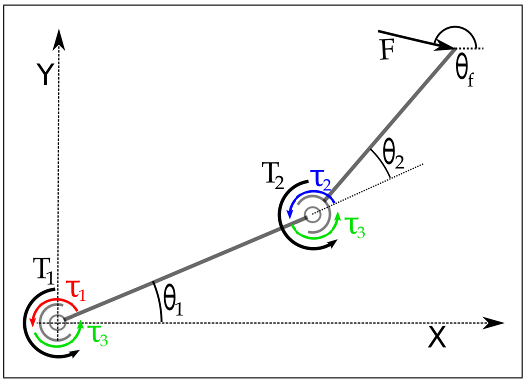


Fig. 2. Statics of a two-link arm with mono- and bi-articular actuators

are introduced. In Section 4, Biwi is described together with the feedforward control strategy used in the experiment. In Section 5, the $\infty - norm$ and PDC approaches are compared by both calculation and experimental results. Finally, in Section 6, the advantages of the $\infty - norm$ approach are summarized.

2. CHARACTERISTICS AND MODELING OF ROBOT ARM 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 two types of muscles:

(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 an example of 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 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 a bi-articularly actuated manipulator as the one in Fig. 1 is shown in Fig. 2 where:

- T_1 and T_2 are total torques at joint 1 and 2, respectively.

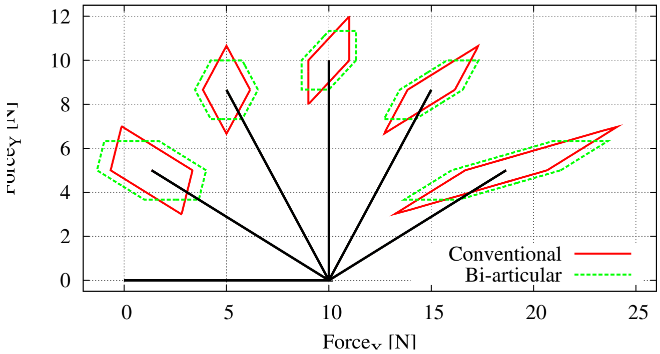


Fig. 3. Maximum output force at the end effector for conventional and arm driven by bi-articular actuators

- τ_1 and τ_2 are torques produced by 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.
- 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 are therefore expressed by:

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

Manipulator equipped with bi-articular actuators have numerous advantages: dramatical increase in range of end effector impedance which can be achieved without feedback (Hogan (1985)), and improvement of balance control for jumping robots that do not use force sensors (Oh et al. (2010)). Moreover, multi-joints actuators such as tri-articular actuators increase the efficiency in output force production (Tsuji (2010)).

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 (Fujikawa et al. (1999)). In Fig. 3 the maximum output force at the end effector for a two-link traditional manipulator and a arm equipped with bi-articular actuators is shown for comparison. In the case of traditional manipulator, 2 actuators with maximum joint torque $T_1 = T_2 = 10$ Nm are considered. On the other hand, for the bi-articularly actuated robot arm three actuators with maximum joint torque $\tau_1 = \tau_2 = \tau_3 = 6.66$ Nm are taken into account. Therefore the total maximum torque in the two cases is the same — 20 Nm. The conventional quadrilateral shape becomes an hexagon for arms driven by bi-articular actuators, which therefore produces a maximum force at the end effector with a more homogeneous distribution in respect to output force direction. This aspect is peculiar for application which interact with humans such as rehabilitation robots, as well as for jumping and waking robots (Oh et al. (2010), Iida et al. (2008)).

3. METHODS FOR ACTUATOR REDUNDANCY RESOLUTION

A two-link manipulator with the statics in Fig. 2 has at least three actuators, resulting in actuator redundancy. Given τ_1,

τ_2 and τ_3, it is possible to determine $\mathbf{T} = [T_1, T_2]^T$, and so $\mathbf{F} = [F_x, F_y]^T$ by using the transpose Jacobian:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = J^T \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{5}$$

where

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

F_x and F_y are the orthogonal projection of $\mathbf{F}$ on the x-axis and y-axis, respectively. On the other hand, given $\mathbf{F}$, and therefore $\mathbf{T}$, it is generally not possible to determine uniquely τ_1, τ_2 and τ_3 (see (4)).

In the following two approaches to resolve actuator redundancy — PDC and $\infty - norm$ — are described.

3.1 Phase different control approach

Fig. 4 shows the output force at the end effector of a manipulator driven by bi-articular actuators. There are 6 force vectors, one for each contractile actuator — e_1, e_2, e_3, f_1, f_2, f_3 — which therefore form an hexagon (Oshima et al. (2000)).

Fig. 5 shows six muscle activation level patterns in respect to the output force direction θ_f which is expressed in respect to points A-F of Fig. 4. These patterns are the linearization of the patterns observed by electromyography of human muscle activations under static conditions (Oshima et al. (2000)).

Given a desired force at the end effector with magnitude $|F^{des}|$ and angle θ_f^{des}:

(1) Calculate the values in degrees of points A-F of Fig. 5 on the basis of the actual configuration of the manipulator.
(2) Calculate the activation level of each muscle — e_1, e_2, e_3, f_1, f_2, f_3 — using the activation level patterns by setting $\theta_f^{des} = \theta_f$.
(3) The desired actuator joint torques are:

$$\begin{cases} \tau_1 = (f_1 - e_1) r \frac{|F^{des}|}{|F^{max}|} \\ \tau_2 = (f_2 - e_2) r \frac{|F^{des}|}{|F^{max}|} \\ \tau_3 = (e_3 - f_3) r \frac{|F^{des}|}{|F^{max}|} \end{cases} \tag{7}$$

where $|F^{max}|$ is the magnitude of the maximum force that can be produced in the direction θ_f^{des} in the actual configuration of the manipulator.

In order to realize force control, if $|F^{des}| < |F^{max}|$, a precise value of $|F^{max}|$ is required, and therefore the manipulator Jacobian is necessary. On the other hand, if just the application of maximum output force is required, the manipulator Jacobian is not necessary, as in this condition $\frac{|F^{des}|}{|F^{max}|} = 1$.

3.2 $\infty - norm$ approach

Given the desired joint torques $\mathbf{T}_1$, three actuators joint torques τ_1, τ_2, and τ_3 can be calculated using $\infty - norm$ by resolving the following problem (it is assumed that $\tau_1^{max} = \tau_2^{max} = \tau_3^{max}$, where $\tau_i^{max} (i = 1, 2, 3)$ is the maximum joint torque the actuator i can produce):

$$\text{minimize} \quad \max\{|\tau_1|, |\tau_2|, |\tau_1|\} \tag{8}$$

$$\text{subject to} \quad \begin{cases} T_1 = \tau_1 + \tau_3 \\ T_2 = \tau_2 + \tau_3 \end{cases} \tag{9}$$

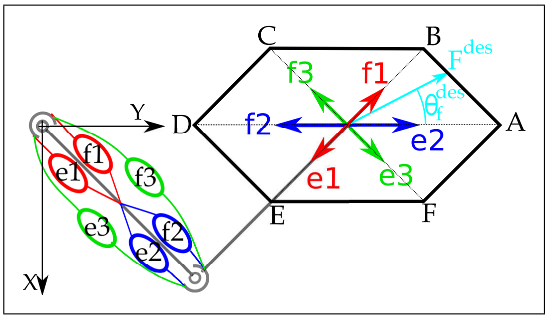


Fig. 4. Force hexagon at end effector of a manipulator equipped with bi-articular actuators (Oshima et al. (2000))

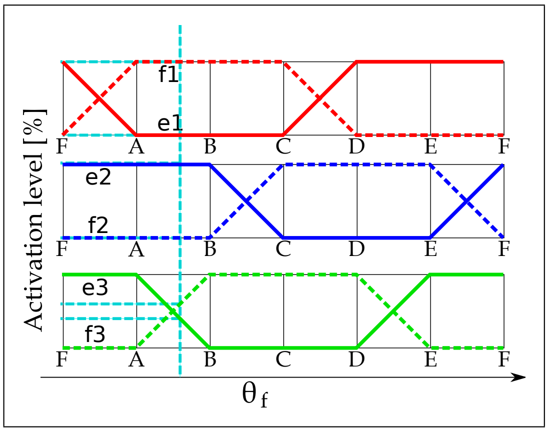


Fig. 5. Muscle activation level patterns deducted from EMG (Oshima et al. (2000))

A closed form solution of the problem can be determined on the basis of the values of T_1 and T_2 as follows:

- if $T_1 T_2 \le 0$

$$\begin{cases} \tau_1 = \frac{T_1 - T_2}{2} \\ \tau_2 = \frac{T_2 - T_1}{2} \\ \tau_3 = \frac{T_1 + T_2}{2} \end{cases} \tag{10}$$

- if $T_1 T_2 > 0$ and $|T_1| \le |T_2|$

$$\begin{cases} \tau_1 = T_1 - \frac{T_2}{2} \\ \tau_2 = \frac{T_2}{2} \\ \tau_3 = \frac{T_2}{2} \end{cases} \tag{11}$$

- if $T_1 T_2 > 0$ and $|T_1| > |T_2|$

$$\begin{cases} \tau_1 = \frac{T_1}{2} \\ \tau_2 = T_2 - \frac{T_1}{2} \\ \tau_3 = \frac{T_1}{2} \end{cases} \tag{12}$$

The proof of (10), (11), and (12) is in (Salvucci et al. (2011b)).

Given a generic force at the end effector $\mathbf{F}$, the actuators inputs τ_1, τ_2, and τ_3 can be calculated in the following way.

(1) Calculate the joint torques using the Jacobian (6)
(2) According to calculated T_1 and T_2, the desired actuators inputs can be directly determined using linear equations:
  - if $T_1 T_2 \le 0$ use (10)
  - if $T_1 T_2 > 0$ and $|T_1| \le |T_2|$ use (11)
  - if $T_1 T_2 > 0$ and $|T_1| > |T_2|$ use (12)

Therefore the proposed $\infty - norm$ approach is based on the Jacobian to determine the required joint torques, and uses only linear functions to resolve actuator redundancy.

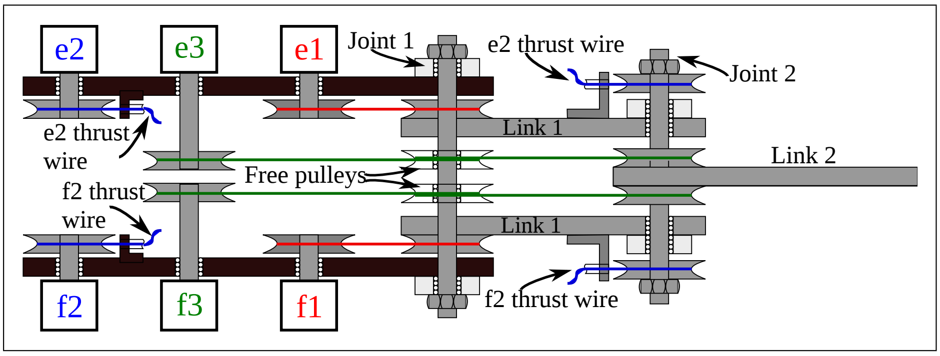


Fig. 7. Scheme of Wire-based torque transmission system

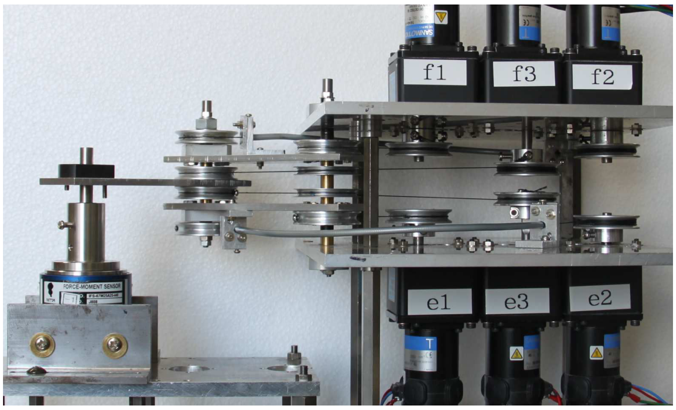


Fig. 6. Biwi, Bi-articularly actuated and Wire driven robot arm

Table 1. Manipulator characteristics

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

Table 2. Actuator and sensor system

Motors	Sanyo T404-012E59
Gear head	G6-12 (ratio 12.5)
Servo system	TS1A02AA
Force sensor	Nitta IFS-67M25A15-I40

4. EXPERIMENTAL SET-UP

BiWi, Bi-articularly actuated and Wire driven robot arm, is shown in Fig. 6. Biwi, is a two-link planar manipulator actuated by 6 motors, each representing one of the muscles in Fig. 1. The power is transmitted to the joints through pulleys and polyethylene wires as shown in Fig. 7:

- A pair of antagonistic mono-articular motors (e_1–f_1) are connected to 2 pulleys fixed on joint 1.
- A pair of antagonistic mono-articular motors (e_2–f_2) are connected by thrust wires to 2 pulleys fixed on joint 2.
- A pair of antagonistic bi-articular motors (e_3–f_3) are connected to pulleys fixed on joint 2, and to free pulleys about joint 1.

Basic characteristics of BiWi and of the actuator and sensor systems are shown in Tab. 1 and Tab. 2, respectively. Further characteristics of BiWi are in (Salvucci et al. (2011a)).

The feedforward control block diagram used in the experiment is shown in Fig. 8. F_x^* and F_y^* are the desired force at the end

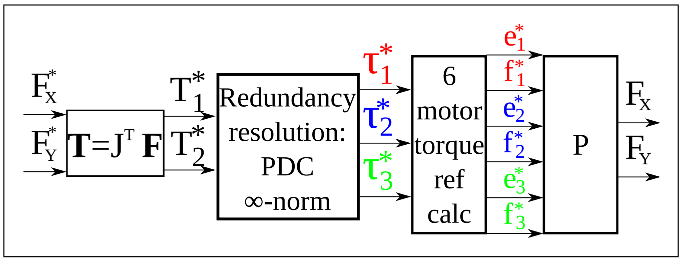


Fig. 8. Feedforward control block diagram

effector. J is the manipulator Jacobian. τ_1^*, τ_2^*, and τ_3^* are the desired actuator joint torques as in Fig. 2, which are calculated using the PDC or the $\infty-norm$ approach from the desired joint torques T_1^* and T_2^*. e_1^*, e_2^*, e_3^*, f_1^*, f_2^*, f_3^* are the 6 motor reference torques that correspond to the 6 muscles of Fig. 1. They are calculated as:

$$e_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$f_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$e_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

$$f_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

$$e_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

$$f_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

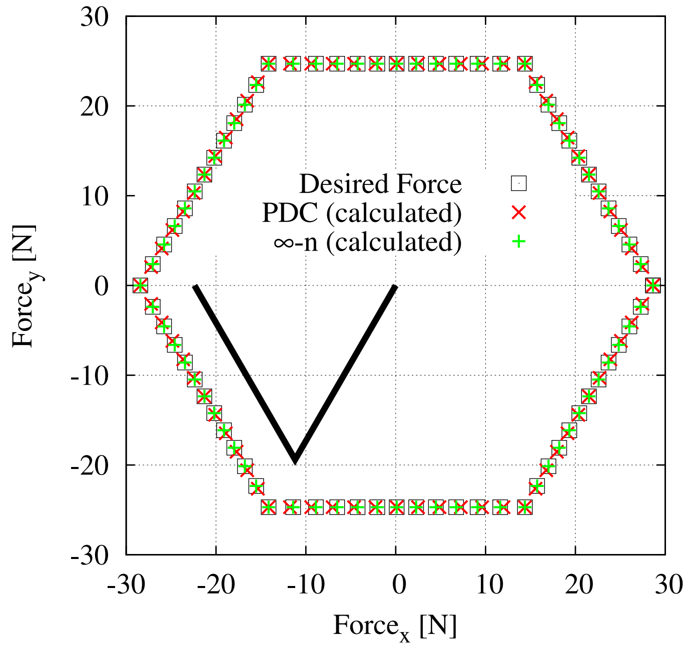
$K_{tl} = 1.33$ is a coefficient used to to compensate for the inevitable transmission loss in the thrust wires which connect the motors e_2^* and f_2^* to joint 2. A force sensor is used to measure the end effector output force $\mathbf{F} = [F_x, F_y]^T$, and its steady state value is considered. Maximum joint actuator torques are $\tau_1^{max} = \tau_3^{max} = 1.84$ Nm and $\tau_2^{max} = 1.38$ Nm.

5. RESULTS

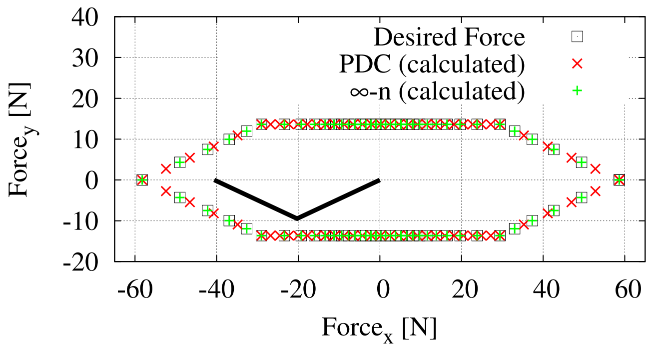
The PDC and the $\infty-norm$ approach are compared in two manipulator configurations:

- Configuration I: $\theta_1 = -60°$ and $\theta_2 = 120°$
- Configuration II: $\theta_1 = -25°$ and $\theta_2 = 50°$

The calculated maximum output force at the end effector of BiWi is shown in Fig. 9. The desired output force direction at the end effector (θ_f^{des}) varies from 0 to 360° every 5°. The two



(a) $\theta_1 = -60°$, $\theta_2 = 120°$



(b) $\theta_1 = -25°$, $\theta_2 = 50°$

Fig. 9. Calculated maximum output force

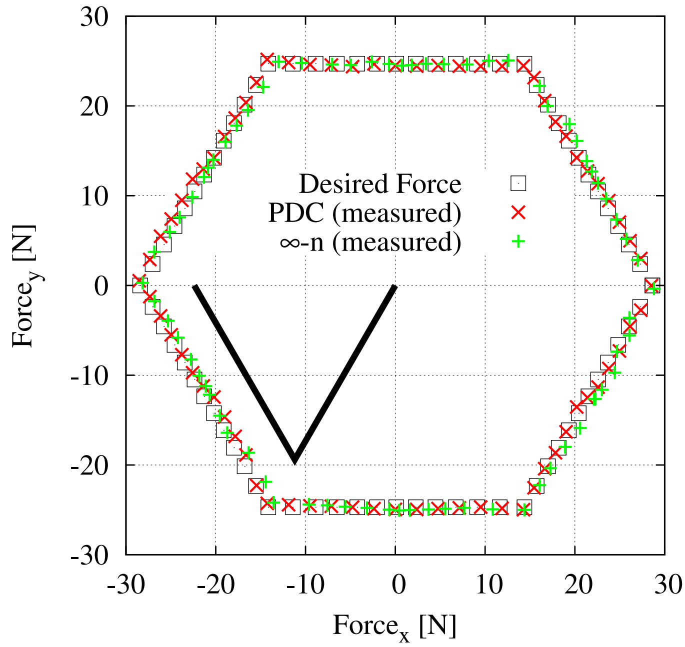
approaches produce a force at the end effector with the same hexagonal shape. For the $\infty - norm$ approach there is no error in output force. For the PDC approach the error in output force direction and magnitude ratio is small in configuration I, but is significant in configuration II. The experimental results shown in Fig. 10 confirm the calculation. The relative error of output force magnitude defined as:

$$F^{err} = \frac{|F^{measured}| - |F^{desired}|}{|F^{desired}|} \tag{19}$$

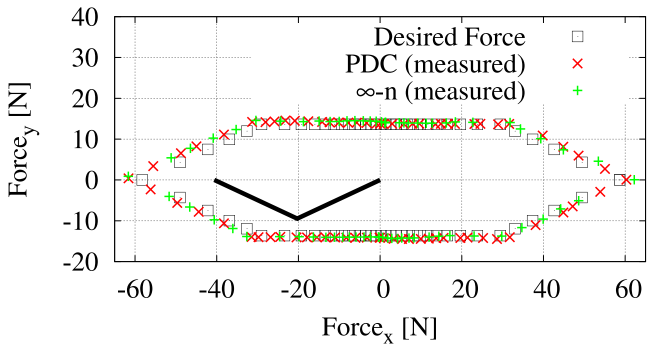
is shown in respect to θ_f in Fig. 11.

In configuration I, the two methods produce the same relative error of output force magnitude, about 0.04. This error is due to sensor noise and inevitable modelling errors. However, in configuration II, the relative error of output force magnitude obtained using PDC method has peaks of about 0.3. The output error in the PDC depends on three factors — the desired force direction (θ_f), the angle between the links (θ_2), and on the link length ratio — and can increase exponentially when the manipulator moves towards singular configurations (Salvucci et al. (2010)).

The joint actuator torque patterns used in the both calculation and experiment are shown in Fig. 12. They are almost identical



(a) $\theta_1 = -60°$, $\theta_2 = 120°$



(b) $\theta_1 = -25°$, $\theta_2 = 50°$

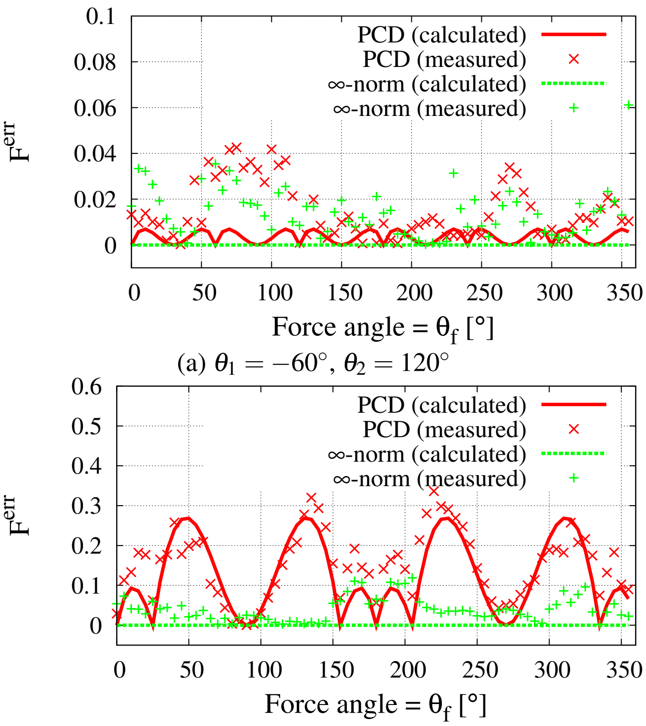
Fig. 10. Measured maximum output force

in configuration I, but different in configuration II. In both the approaches the input torque patterns are continuous in respect to the output force angle (θ_f in Fig. 2). Therefore, the 3 switching conditions in the $\infty - norm$ approach do not cause torque reference discontinuities, which could cause instability to the system.

6. CONCLUSIONS

In this paper, a new approach based on $\infty - norm$ to resolve actuators redundancy is implemented on BiWi, Bi-articularly actuated and Wire driven robot arm, and compared with the Phase Different Control (PDC) approach, which is based on human muscle activation level patterns.

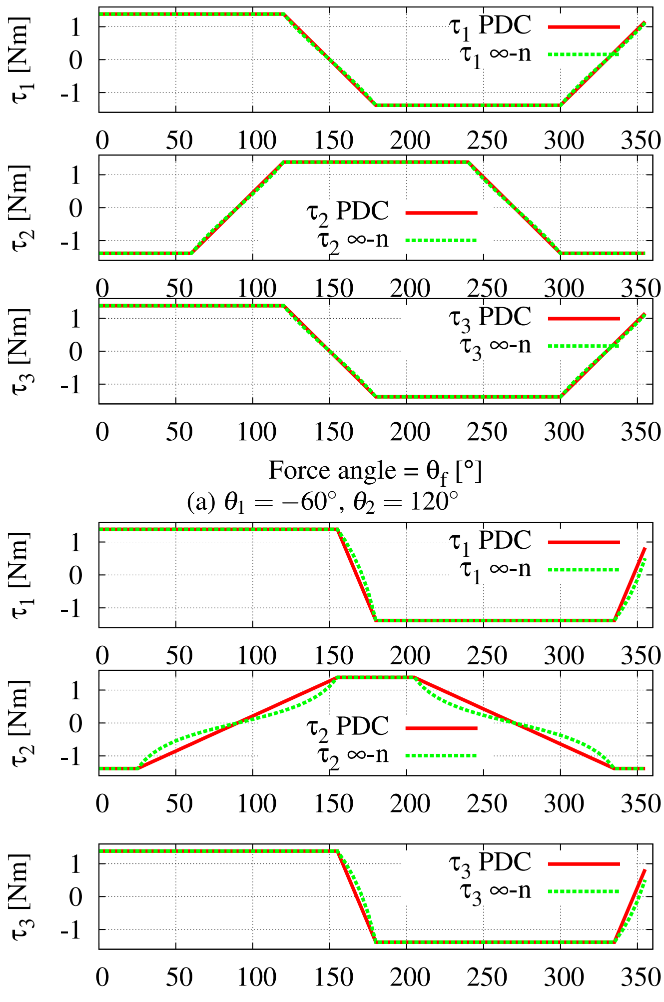
It is shown by calculation that the proposed $\infty - norm$ approach produces no error in calculation of output force, while the PDC approach produces non-zero error. The experimental results confirm that the relative error of output force magnitude (F^{err}) has no significant difference when the angle between link 1 and 2 (θ_2) is about 120°. However, F^{err} in both calculation and experimental measurement increases when the arm moves towards singular configurations. For $\theta_2 = 25°$, F^{err} has peaks of about 0.3 for the PDC approach.



(a) $\theta_1 = -60°$, $\theta_2 = 120°$

(b) $\theta_1 = -25°$, $\theta_2 = 50°$

Fig. 11. Relative error of output force magnitude



(a) $\theta_1 = -60°$, $\theta_2 = 120°$

(b) $\theta_1 = -25°$, $\theta_2 = 50°$

Fig. 12. Actuator joint torque inputs

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