Experimental Verification of Infinity Norm Approach for Force Maximization of Manipulators Driven by Bi-articular Actuators

Valerio Salvucci, Yasuto Kimura, Sehoon Oh and Yoichi Hori

Abstract— **Recently, there has been increasing attention on animal inspired manipulators equipped with bi-articular actuators. Bi-articular actuated manipulators usually present more actuators than joints, resulting in actuator redundancy. In order to resolve this torque load sharing problem, in this paper a new approach based on infinity norm is proposed and successfully implemented on BiWi, Bi-articularly actuated and Wire driven manipulator.**

The infinity norm model maximizes the force at the end effector given the maximum actuator joint torques. Therefore, it is an approach to optimize actuators design for bi-articularly actuated manipulators. The infinity norm approach is based only on linear functions for actuator redundancy resolution.

I. INTRODUCTION

Manipulators presenting animal musculo-skeletal characteristics such as bi-articular actuators have been proposed for more than two decades [1]. Recently, there has been increasing attention on such biologically inspired manipulators, both in hardware and control design aspects [2] [3] [4].

A manipulator based on such a model usually has more actuators than joints, resulting in actuator redundancy. In order to resolve this torque load sharing problem many approaches have been proposed.

Several animal inspired approaches to solve actuator redundancy as fatigue minimization [5], muscle force minimization [6] [7], total muscle metabolic energy consumption [8], total muscle stress minimization [9] [10] have been proposed. These approaches are mainly based on a phenomenological nature, which can make an implementation on robotics applications difficult.

Pseudo-inverse matrices are often used for kinematics redundancy resolution of manipulators [11]. This approach is also used to resolve actuator redundancy [12]. Moore-Penrose is the simplest pseudo-inverse matrix, and corresponds to the minimization of the $2 - norm$ (euclidean norm) [13].

In this paper, our new approach to resolve actuator redundancy based on infinity norm [14] is experimentally verified by using Biwi, Bi-articulated and Wire driven manipulator. The $\infty - norm$ approach maximizes the force at the end effector given the maximum actuator joint torques. Therefore, it is used as an approach to optimize actuators design for bi-articularly actuated manipulators. Moreover, the $\infty - norm$ approach is based only on linear functions to resolve actuator redundancy.

The $\infty - norm$ approach is compared with the Moore-Penrose pseudo-inverse approach $(2 - norm)$ in terms of maximum output force at the end effector by using both numerical calculation and experimental results. Under the same maximum actuator joint torques, the maximum output force at the end effector calculated using the proposed $\infty - norm$ approach is greater than the one obtained using $2 - norm$ approach. For the experimental results, BiWi, Bi-articulated and Wire driven manipulator is proposed.

In Section II, main features and statics of bi-articularly actuated manipulators are described. In Section III, $2 - norm$ and $\infty - norm$ approaches for actuator redundancy resolution are introduced. In Section IV, Biwi, Bi-articularly actuated and Wire driven manipulator is described together with the feedforward control strategy used in the experiment. In Section V, the proposed $\infty - norm$ approach is compared with $2 - norm$ approach in terms of maximum output force at the end effector. Finally, in Section VI, the advantages of the $\infty - norm$ approach are summarized. The proof of the closed form solution of the $\infty - norm$ approach is reported in Appendix I.

II. CHARACTERISTICS AND MODELING OF BI-ARTICULAR ACTUATED MANIPULATORS

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 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 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 are shown in Fig. 2 where:

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

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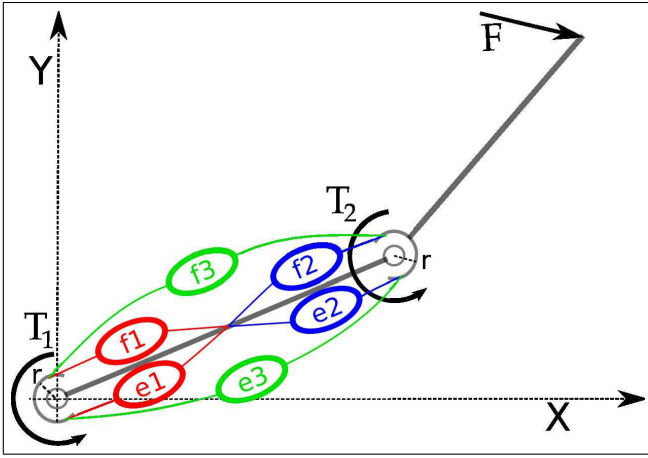
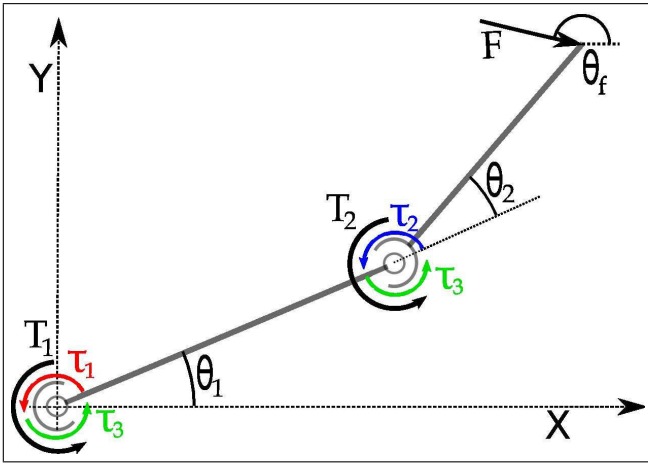Fig. 1. Scheme a two-link arm with 4 mono- and 2 bi-articular actuators

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

- 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:

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

- $\mathbf{F}$ is a general force at the end effector.

The statics of this system are therefore expressed by:

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

Manipulators equipped with bi-articular actuators have numerous advantages: dramatical increase in range of end effector impedance that can be achieved without feedback [1], realization of path tracking and disturbance rejection using just feedforward control [12], improvement of balance control for jumping robots that do not use force sensors
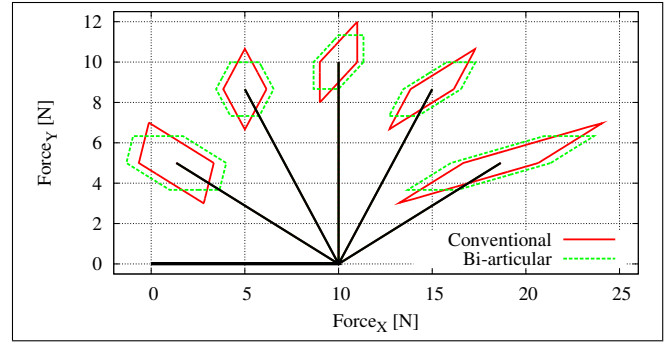

Fig. 3. Maximum output force at the end effector for conventional and arm driven by bi-articular actuators

[15]. Moreover, multi-joints actuators such as tri-articular actuators, increase the efficiency in force production [16].

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 traditional manipulator and a robot arm equipped with bi-articular actuators is shown for comparison. In the case of traditional manipulator, two actuators with maximum joint torque $T_1 = T_2 = 10$ Nm are considered. On the other hand, for the bi-articular actuators driven arm three actuators with maximum joint torque $\tau_1 = \tau_2 = \tau_3 = 6.66$ Nm are taken into account. Therefore, the total maximum actuator torque in the two cases is the same. The conventional quadrilateral shape becomes an hexagon for arms driven by bi-articular actuators that 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 waking robots [4] [15].

III. APPROACHES FOR ACTUATOR REDUNDANCY RESOLUTION

A two-link manipulator with the statics shown in Fig. 2 is driven at least by 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 — $2-norm$ and $\infty-norm$ — are described. It is assumed that $\tau_1^{max} = \tau_2^{max} = \tau_3^{max}$, where τ_i^{max} $(i = 1, 2, 3)$ is the maximum joint torque that the actuator i produces.

A. 2 − norm approach

Given the desired joint torques T_1 and T_2, three actuators joint torques τ_1, τ_2 and τ_3 are calculated using $2 - norm$ by solving the following problem:

$$\text{minimize} \quad \sqrt{(\tau_1)^2 + (\tau_2)^2 + (\tau_3)^2} \tag{7}$$

$$\text{subject to} \quad \begin{cases} T_1 = \tau_1 + \tau_3 \\ T_2 = \tau_2 + \tau_3 \end{cases} \tag{8}$$

The solution of the problem is:

$$\begin{cases} \tau_1 = \frac{2}{3}T_1 - \frac{1}{3}T_2 \\ \tau_2 = -\frac{1}{3}T_1 + \frac{2}{3}T_2 \\ \tau_3 = \frac{1}{3}T_1 + \frac{1}{3}T_2 \end{cases} \tag{9}$$

B. ∞ − norm approach

Given the desired joint torques T_1 and T_2, three actuators joint torques τ_1, τ_2 and τ_3 are calculated using $\infty - norm$ by solving the following problem:

$$\text{minimize} \quad \max\{|\tau_1|, |\tau_2|, |\tau_3|\} \tag{10}$$

$$\text{subject to} \quad \begin{cases} T_1 = \tau_1 + \tau_3 \\ T_2 = \tau_2 + \tau_3 \end{cases} \tag{11}$$

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

- if $T_1 T_2 \le 0$

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

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

$$\begin{cases} \tau_1 = T_1 - \frac{T_2}{2} \\ \tau_2 = \frac{T_2}{2} \\ \tau_3 = \frac{T_2}{2} \end{cases} \tag{13}$$

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

$$\begin{cases} \tau_1 = \frac{T_1}{2} \\ \tau_2 = T_2 - \frac{T_1}{2} \\ \tau_3 = \frac{T_1}{2} \end{cases} \tag{14}$$

Proof of (12), (13), and (14) is reported in Appendix I. It is trivial to verify that (12), (13), and (14) are continuous in all the domain $D = \{T_1, T_2\}$.

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

1) Calculate the joint torques by using (5), $\mathbf{T} = J^T \mathbf{F}$.
2) According to calculated T_1 and T_2, the desired actuators inputs are directly determined using linear equations:
   - if $T_1 T_2 \le 0$ use (12)
   - if $T_1 T_2 > 0$ and $|T_1| \le |T_2|$ use (13)
   - if $T_1 T_2 > 0$ and $|T_1| > |T_2|$ use (14)

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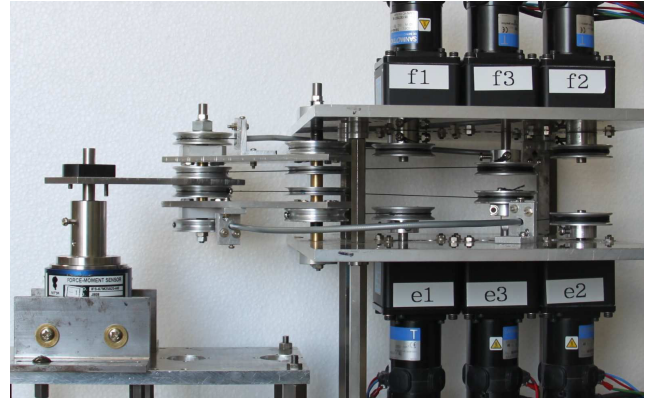

Fig. 4.   BiWi:Bi-articularly actuated and Wire driven manipulator

TABLE I

BIWI CHARACTERISTICS

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

TABLE II

ACTUATOR AND SENSOR SYSTEM

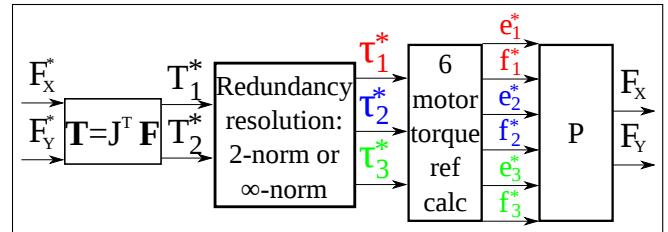| Motors	Sanyo T404-012E59
Servo system	TS1A02AA
Force sensor	Nitta IFS-67M25A15-I40

Fig. 5.   Feedforward control block diagram

IV. EXPERIMENTAL SET-UP

BiWi, Bi-articularly actuated and Wire driven manipulator, is shown in Fig. 4. BiWi has 6 motors, each representing one of the muscles in Fig. 1. The power is transmitted to the joints through pulleys and polyethylene wires. Basic characteristics of BiWi and of the actuator and sensor systems are shown in Tab. I and Tab. II, respectively. Further characteristics of BiWi are described in [18].

The feedforward control block diagram used to collect the data is shown in Fig. 5. 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, which are calculated using $2 - norm$ or $\infty - norm$ approach from the desired joint torques T_1^* and T_2^*. $t_1^* - t_6^*$ are the 6 actuator joint torque reference. They are calculated as:

$$e_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

$$f_1^* = \begin{cases} \tau_1^* & \text{if } \tau_1^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

$$e_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

$$f_2^* = \begin{cases} K_{tl}\tau_2^* & \text{if } \tau_2^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

$$e_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* < 0 \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

$$f_3^* = \begin{cases} \tau_3^* & \text{if } \tau_3^* > 0 \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

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 end effector output force (**F**) is measured by using a force sensor, and its steady state value is taken into account.

V. RESULTS

The $2-norm$ and the proposed $\infty-norm$ approaches are compared in terms of maximum output force at the end effector, under the same maximum actuator joint torque, that is $\tau_1^{max} = \tau_2^{max} = \tau_3^{max}$.

The calculated and measured maximum output force at the end effector of BiWi, obtained using the $2-norm$ and $\infty-norm$ approaches, are shown in Fig. 6(a) for $\theta_1 = -60.0°$ and $\theta_2 = 120.0°$, in Fig. 7(a) for $\theta_1 = -45°$ and $\theta_2 = 90°$ and in Fig. 8(a) for $\theta_1 = -30°$ and $\theta_2 = 60°$. The experimental results show that the measured force at the end effector agrees with the calculated one. Moreover, the maximum output force at the end effector is greater when using the $\infty-norm$ approach. The relative difference in maximum output force magnitude between the two approaches:

$$F^{diff} = \frac{|F_{\infty-n}^{max}| - |F_{2-n}^{max}|}{|F_{2-n}^{max}|} \tag{21}$$

is shown in Fig. 6(b), in Fig. 7(b) and in Fig. 8(b) for the three configurations. In case of robot legs an output force with $\theta_f = 0$ is perpendicular to the ground, an therefore important for standing, walking and jumping actions [15]. The output force for $\theta_f = 0$ using $\infty-norm$ is about 30% higher than the one using $2-norm$.

The actuator joint torque patterns of two approaches are shown in Fig. 6(c), in Fig. 7(c) and in Fig. 8(c) for the three configurations. For both the approaches the actuator joint torque patterns are continuous in respect to the output force angle (θ_f in Fig. 2). Hence, the 3 switching conditions used for the redundancy resolution in the $\infty-norm$ approach do not result in torque reference discontinuities, which could cause instability to the system.

VI. CONCLUSIONS

In this paper, a new approach based on $\infty-norm$ to resolve actuator redundancy for bi-articular actuated manipulators is proposed. A closed form solution for the proposed method is derived. The $\infty-norm$ approach maximizes the force at the end effector given the maximum actuator joint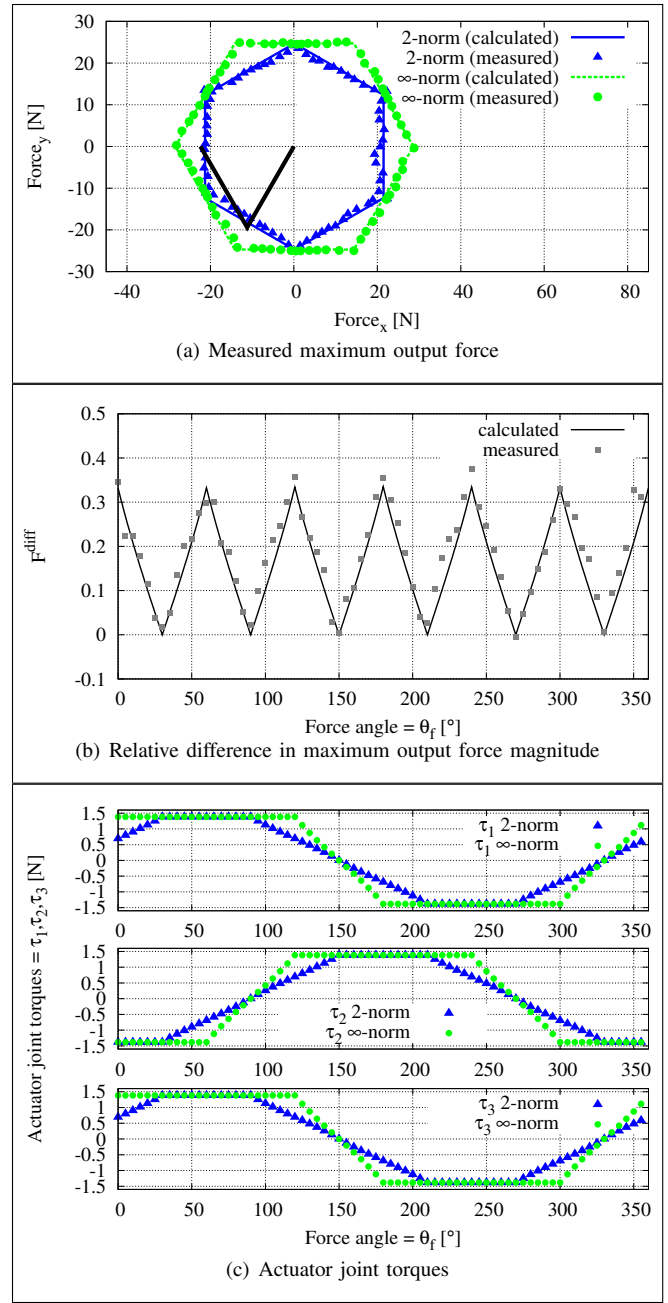 torques. Therefore, it is an approach to optimize actuators design for bi-articularly actuated manipulators. Moreover, only linear functions are used to resolve actuator redundancy.

The proposed approach is compared in terms of maximum output force at the end effector with Moore-Penrose pseudo-inverse model which is based on $2-norm$. Under the same maximum actuator joint torques, the proposed approach allows to obtain a greater output force at the end effector (up to 30%), especially in output force direction peculiar for applications which interact with humans such as rehabilitation robots, as well as for jumping/waking robots.

Biwi, Bi-articularly actuated and Wire driven manipulator, and a feedforward control strategy are used to experimentally validate the proposed $\infty-norm$ approach.
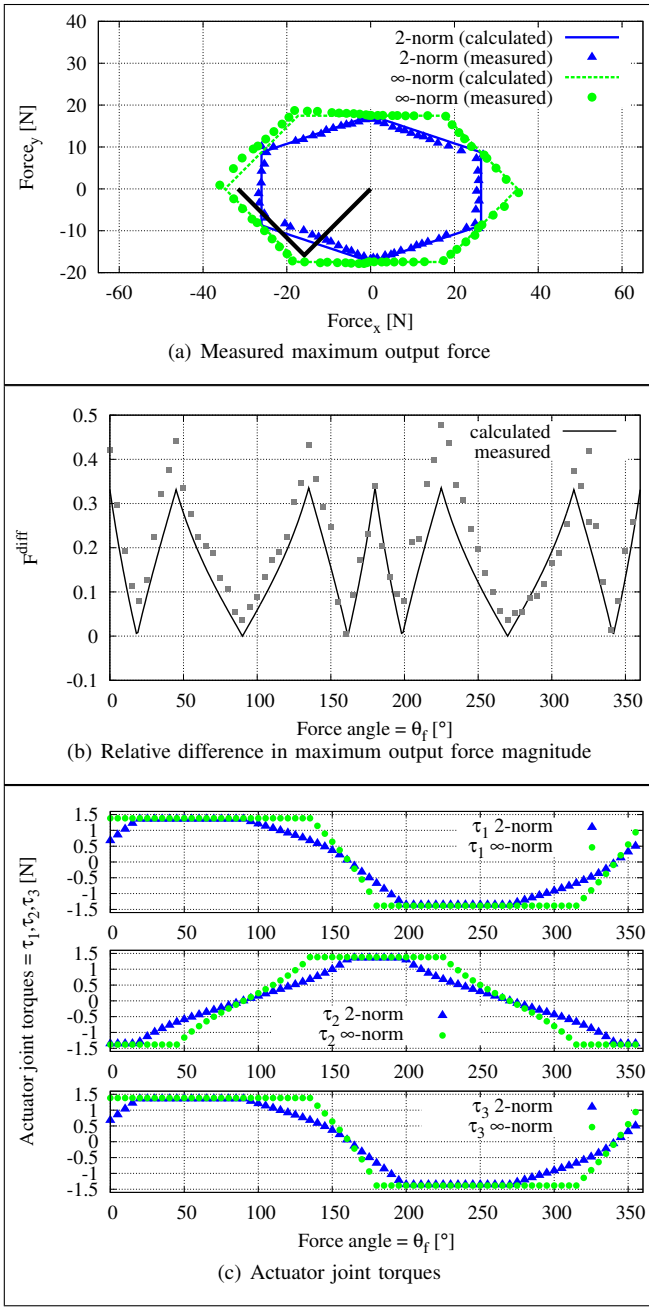

(a) Measured maximum output force

(b) Relative difference in maximum output force magnitude

(c) Actuator joint torques

Fig. 6. $\theta_1 = -60°$, $\theta_2 = 120°$

(a) Measured maximum output force

(b) Relative difference in maximum output force magnitude

(c) Actuator joint torques

Fig. 7. $\theta_1 = -45°$, $\theta_2 = 90°$

(a) Measured maximum output force

(b) Relative difference in maximum output force magnitude

(c) Actuator joint torques
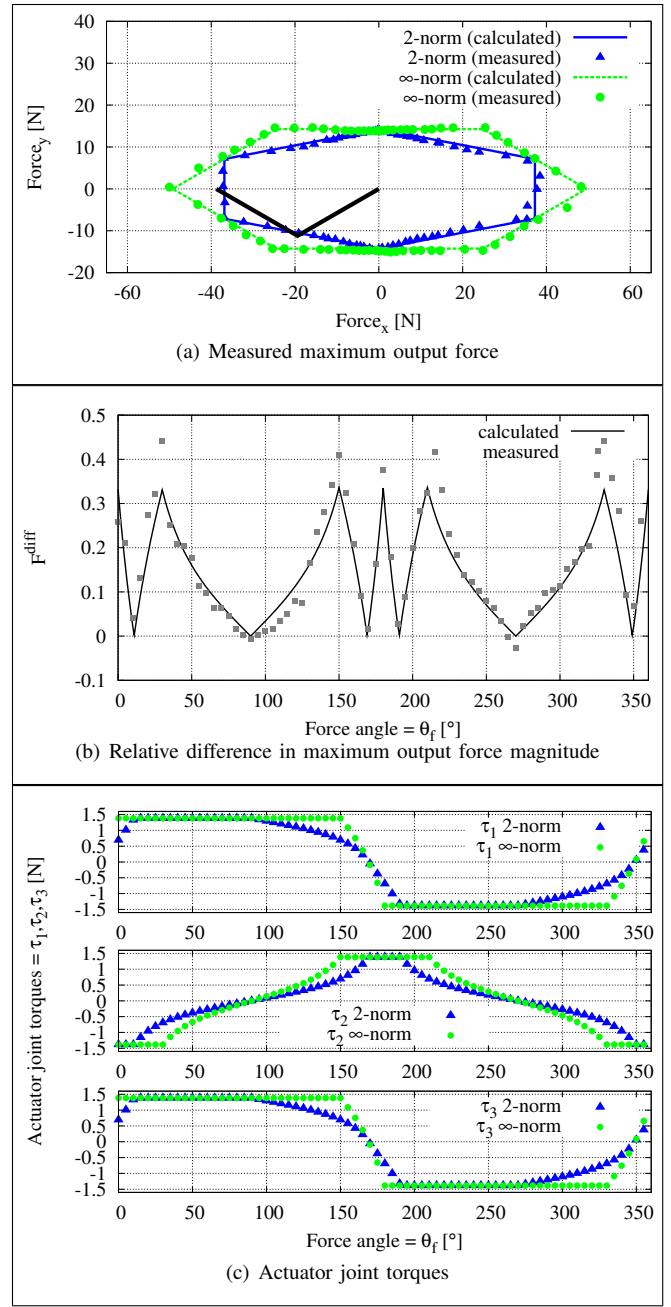
Fig. 8. $\theta_1 = -30°$, $\theta_2 = 60°$

APPENDIX I

PROOF OF CLOSED FORM SOLUTION FOR THE $\infty - norm$ APPROACH

Actuator redundancy problem based on $\infty - norm$ approach expressed by (10) and (11) can be written for a simpler notation as:

$$\text{minimize} \quad \max\{|x|, |y|, |z|\} \tag{22}$$

$$\text{subject to} \quad \begin{cases} T_1 = x + z \\ T_2 = y + z \end{cases} \tag{23}$$

where k_1 and k_2 are the joint torques T_1 and T_2, and x, y, z are the actuator joint torques τ_1, τ_2, τ_3, respectively. A closed form solution is determined as in the following.

The searched solution has to satisfy at least one of the three equations $|x| = |y|$, $|y| = |z|$, $|x| = |z|$. In fact, when one of three variable's absolute value decreases at least one of the other two increases. Therefore, for any solution of the problem with $|x| \neq |y| \neq |z|$ it is possible to decrease the higher value among the three so to be equal to at least one of the other two. Therefore, the searched solution is one among the following 6:

1) $x = -y$:

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ x = -y \end{cases} \Rightarrow \begin{cases} x = \frac{k_1-k_2}{2} \\ y = \frac{k_2-k_1}{2} \\ z = \frac{k_1+k_2}{2} \end{cases} \quad (24)$$

2) $y = z$:

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ y = z \end{cases} \Rightarrow \begin{cases} x = k_1 - \frac{k_2}{2} \\ y = \frac{k_2}{2} \\ z = \frac{k_2}{2} \end{cases} \quad (25)$$

3) $x = z$:

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ x = z \end{cases} \Rightarrow \begin{cases} x = \frac{k_1}{2} \\ y = k_2 - \frac{k_1}{2} \\ z = \frac{k_1}{2} \end{cases} \quad (26)$$

4) $x = y$:

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ x = y \end{cases} \quad (27)$$

If $k_1 \neq k_2$ there is no solution. If $k_1 = k_2 = k$ there are infinite solution and the best one is

$$\begin{cases} x = \frac{k}{2} \\ y = \frac{k}{2} \\ z = \frac{k}{2} \end{cases} \quad (28)$$

which is equal to (25) or (26).

5) $y = -z$:

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ y = -z \end{cases} \quad (29)$$

If $k_2 \neq 0$ there is no solution. If $k_2 = 0$ there are infinite solution and the best one is

$$\begin{cases} x = \frac{k_1}{2} \\ y = -\frac{k_1}{2} \\ z = \frac{k_1}{2} \end{cases} \quad (30)$$

which is equal to (26).

6) $x = -z$;

$$\begin{cases} x+z = k_1 \\ y+z = k_2 \\ x = -z \end{cases} \quad (31)$$

If $k_1 \neq 0$ there is no solution. If $k_1 = 0$ there are infinite solution and the best one is

$$\begin{cases} x = -\frac{k_2}{2} \\ y = \frac{k_2}{2} \\ z = \frac{k_2}{2} \end{cases} \quad (32)$$

which is equal to (25).

Therefore, the searched solution is (24) or (25) or (26).

Among the 3 possible solutions the searched one is directly selected on the basis of k_1 and k_2 as follows (the variable subscript represents the respective equation number):

- if $k_1 k_2 \leq 0$

$$\begin{cases} |z_{24}| \leq |x_{24}| = |y_{24}| \\ |x_{24}| \leq |x_{25}| \\ |y_{24}| \leq |y_{26}| \end{cases} \quad (33)$$

Therefore, solution is (24) which corresponds to (12).

- if $k_1 k_2 > 0$ and $|k_1| \leq |k_2|$

$$\begin{cases} |x_{25}| \leq |y_{25}| = |z_{25}| \\ |y_{25}| \leq |y_{26}| \\ |z_{25}| \leq |z_{24}| \end{cases} \quad (34)$$

Therefore, solution is (25) which corresponds to (13).

- if $k_1 k_2 > 0$ and $|k_1| > |k_2|$

$$\begin{cases} |y_{26}| \leq |x_{26}| = |z_{26}| \\ |x_{26}| \leq |x_{25}| \\ |z_{26}| \leq |z_{24}| \end{cases} \quad (35)$$

Therefore, solution is (26) which corresponds to (14).

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