

Parallel Force/Position Control of a Novel Biomechatronic Hand Prosthesis

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Abstract

Commercially available prosthetic hands are basically simple grippers having one or two degrees of freedom, which barely restore the capability of the thumb-index pinch.

The development of novel prosthetic hands based on a “biomechatronic” design attempts at increasing the dexterity while keeping the same dimension and weight of a traditional prosthetic device.

This paper concerns with the study of a particular kind of grasp task performed by the hand: a cylindrical grasp of a cylindrical object. On the basis of a previous grasp analysis, a parallel force/position control is developed that ensures stability of the grasp.

Simulation results are discussed to validate the proposed controller in a number of case studies.

1 Introduction

The importance of dexterity in human hands is well known since the oldest time [1].

Several hands have been developed in the robotics community, such as the Stanford/JPL hand [2], the Utah/MIT hand [3], and the Hitachi hand [4], to mention only a few. Although these hands can achieve good performance in mimicking human capabilities, they cannot be utilized in prosthetic applications. The main drawbacks are their mass, size and complex controllers, whereas the main requirements of a prosthetic hand are cosmetic, controllability, lightness, low noise and low energy consumption.

At present, there are several solutions to restore the functionality of an amputated patient taking into account these requirements, but many of these have low or no grasping functionalities. This is due to the strict requirement of embedding all the components within the housing, closely replicating the shape, size and appearance of the human hand, thus leading to loss of degrees of freedom (DOFs). Indeed, in prosthetic hands active bending of joints is restricted to two or three joints (metacarpo-phalangeal joints of the thumb, of the index and of the middle finger), while the other joints are fixed.

The lack of DOFs does not allow flexibility and adaptability of artificial fingers with the consequent instability of the grasp in the presence of external perturbation.

A novel multi-DOF biomechatronic hand [5], named the RTR1 hand, has been recently designed and implemented to improve the limitations of current prosthetic hands while preserving their main advantages such as lightness and simplicity. This has been achieved by adopting small actuators (two for each finger) instead of a single large actuator (as in most current prosthetic hands) and by designing a kinematic architecture which is able to provide a better adaptation to the object's shape during grasping.

The use of “micro-motors” [6], integrated in the hand structure, allows increasing the number of DOFs, and obtaining larger contact areas [7]. This compensates for the reduction of power actuation and leads to enhanced grasp stability.

In this paper, the feasibility of this innovative approach is demonstrated by the possibility of performing a stable cylindrical grasp of a cylindrical object while respecting the limits in power actuation.

A grasp analysis is performed which allows calculating the maximum possible load of the manipulated object and the resulting forces at the contact points.

Stability of the grasp is ensured by devising a parallel force/position control on each finger, as demonstrated by simulation results for a number of significant case studies.

2 The RTR1 Biomechatronic Hand

The RTR1 hand has three fingers: a thumb with two active DOFs, plus two identical fingers (index and middle) each having 2 active DOFs and one passive DOF (Fig. 1).

The hand is conceived to perform two kinds of grasping tasks:

- cylindrical grasp
- tripod grasp

in two subsequent phases:

- reaching and shape-adapting phase
- grasping phase with thumb opposition.

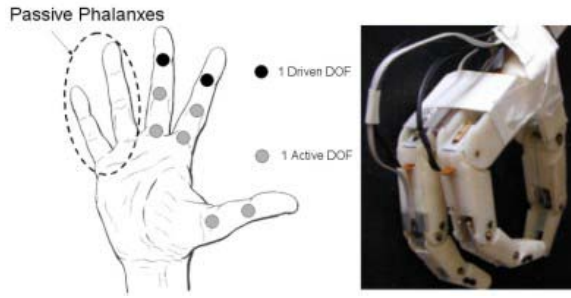


Fig. 1: Architecture (left) and photograph of the first prototype (right) of the RTR1 hand.

The index/middle finger has been designed to reproduce as closely as possible the size and kinematics of a human finger. Each finger consists of three phalanges and a palm that houses the proximal actuator.

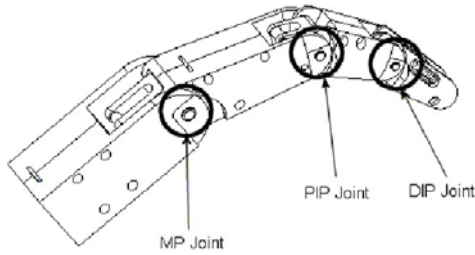


Fig. 2: Detail drawing of index/middle finger.

As shown in Fig. 2, the MP and PIP joints are driven by the actuators that transmit the movement to the phalanges through a slider-crank mechanism, thus providing flexion/extension movement. The slider is driven by the lead screw transmission mounted directly on the motor shaft (Fig. 3).

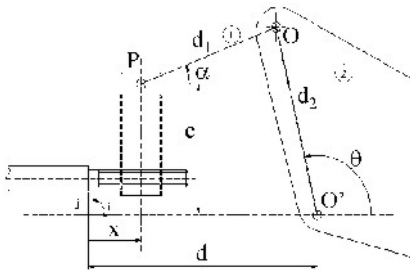


Fig. 3: Slider-crank mechanism.

The differences between the two fingers are in the working range of the joint angles (90° for the MP, 80° for the PIP) and in the working range of the slider (8.26 mm for the MP, 4.9 mm for the PIP).

The DIP joint is actuated passively by a four-bar link and its geometrical features have been designed to reproduce as closely as possible the natural DIP joint flexion.

The thumb has been obtained by simply removing the distal phalanx from the index/middle finger (Fig. 4).

The working range of the joint angles is 87.70° for the MP joint and 86.36° for the PIP joint, while the working range of the slider is 8.30 mm for the MP joint and 5.60 mm for the PIP joint.

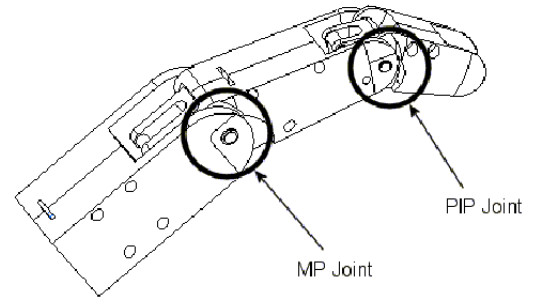


Fig. 4: Detailed drawing of thumb finger.

3 Grasp analysis

To test the feasibility of grasping tasks, a cylindrical grasp of a cylindrical object is considered, namely a can of 5 cm diameter (Fig. 5).



Fig. 5: Cylindrical grasp.

All the grasp configurations that ensure an infinitely stable grasp [8] have in common the following features:

- the first phalanx of the thumb and the second one are tangential to the object
- the palm is also tangential to the object
- only the first phalanx of the index/middle finger is tangential to the object
- the index and middle fingers are in the same configuration.

In order to find, among the infinite configurations, the one in which the thumb exerts the maximum force on the object, the following two problems have to be solved:

- knowledge of the maximum load grasped without slippage
- knowledge of the contact forces that ensure grasp of the maximum load.

The first problem has been solved according to the procedure illustrated in Fig. 6

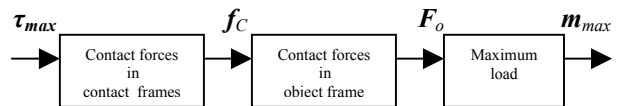


Fig. 6 : Procedure for maximum load calculation.

where τ_{max} are the maximum joint torques obtained by the application of a 12 N force on the slider.

Choosing at each contact point the contact coordinate frame $C_i(t_i, o_i, n_i)$ such that (Fig. 7):

- the n_i -axis points in the direction of the inward surface normal at the point of contact

- the t_i -axis is tangential to the surface in the n_i plane
- the o_i -axis is normal to the (n_i, t_i) plane.

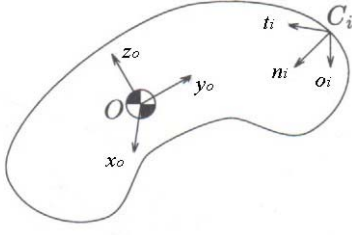


Fig. 7: Coordinate frames for contact and object forces.

The force applied at a contact can be modeled as a wrench F_{Ci} applied to the origin of the contact frame and represented with respect to a basis of directions which are consistent with the friction model [9], i.e.

$$F_{Ci} = B_{Ci} f_{Ci}$$

where

$$B_{Ci} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \text{ is the wrench basis}$$

and

$$f_{Ci} = \begin{pmatrix} f_{Cio} \\ f_{Cin} \end{pmatrix} \quad f_{Cio} \leq \mu f_{Cin}$$

are the independent forces that can be applied by the contact which must lie in the friction cone.

The force exerted by a single contact can be written in object coordinates $O(x_o, y_o, z_o)$ as

$$F_{oi} = \begin{bmatrix} R_{Ci}^o & 0 \\ S(p_{oCi}^o) R_{Ci}^o & R_{Ci}^o \end{bmatrix} F_{Ci} = \begin{bmatrix} R_{Ci}^o & 0 \\ S(p_{oCi}^o) R_{Ci}^o & R_{Ci}^o \end{bmatrix} B_{Ci} f_{Ci} = G_i f_{Ci}$$

where p_{oCi}^o and R_{Ci}^o define the position and orientation of the contact frame with respect to the object frame with

$$S(p_{oCi}^o) = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix}$$

and G_i is defined below.

On the assumption of L contact points, the net object wrench is

$$F_o = G_1 f_{C1} + G_2 f_{C2} + \dots + G_L f_{CL}$$

$$= [G_1 \quad G_2 \quad \dots \quad G_L] \begin{bmatrix} f_{C1} \\ f_{C2} \\ \vdots \\ f_{CL} \end{bmatrix}$$

where the grasp map is

$$G = [G_1 \quad G_2 \quad \dots \quad G_L]$$

Since

$$F_o = m_{max} g$$

where $g = [0 \ 0 \ g]^T$ ($|g| = 9.8062 \text{ m/s}^2$), the maximum load m_{max} in different contact conditions can be found according to the procedure in Fig. 6 along with the relationship between the forces above. The results are detailed in Tab. 1.

	$\mu = 3.5$	$\mu = 3.1$	$\mu = 2.2$	$\mu = 1$
m_{max}	1.4kg	1.3886kg	1.3283kg	1.0317kg

Tab. 1: Maximum load in different contact conditions: rubber on dry glass ($\mu = 3.5$), rubber on dry metal ($\mu = 3.1$), rubber on wet metal ($\mu = 2.2$), rubber on wet glass ($\mu = 1$).

Assuming to perform the grasp task in dry condition ($\mu = 3.5$), the effect P_f felt by the object in the object frame is related to the forces exerted to the object at the L contact points through [10]

$$P_f = WF$$

where

$$W = \begin{bmatrix} I_{3*3} & 0 & \dots & I_{3*3} & 0 \\ S(p_{oC1}^o) & I_{3*3} & \dots & S(p_{oCL}^o) & I_{3*3} \end{bmatrix}$$

For the known P_f , the general solution for the forces F is given by

$$F = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_L \end{bmatrix}$$

$$= \begin{bmatrix} (1/L)I_{3*3} \\ (1/L)I_{3*3} \\ \vdots \\ (1/L)I_{3*3} \end{bmatrix} P_f + \begin{bmatrix} (L-1)I_{3*3} & -I_{3*3} & \dots & -I_{3*3} \\ -I_{3*3} & (L-1)I_{3*3} & \dots & -I_{3*3} \\ \vdots & \vdots & \ddots & \vdots \\ -I_{3*3} & -I_{3*3} & -I_{3*3} & (L-1)I_{3*3} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_L \end{bmatrix} \quad i=1, \dots, L$$

where the second term represents the forces causing no motion but internal loading (tension, compression, etc.) of the object, being ϵ_i a vector of arbitrary forces. In this way, it is possible to separate the motion-inducing from the squeezing-inducing effects.

A particular solution for F can be found by solving the following minimizing internal force problem [11] on

$$\epsilon = [\epsilon_1 \quad \epsilon_2 \quad \dots \quad \epsilon_L]^T$$

$$\min_{\epsilon} \|F\|$$

subject to

$$\begin{cases} \mathbf{P}_f = \mathbf{W}\mathbf{F} \\ \mathbf{n}_i^T \mathbf{F}_i \geq \eta_i \|\mathbf{F}_i\| \end{cases} \quad i = 1 \dots L$$

$$\eta_i = \frac{1}{\sqrt{(1 + \mu_i^2)}}$$

where the second constraint represents the static frictional condition.

4 Parallel force/position control

Typically, a finger is not able to exert forces in every direction.

The control objective is to specify a set of joint torque inputs $\boldsymbol{\tau}$ so that the desired grasping forces $\mathbf{h}_{Ad}$ along the constrained directions, and the desired position trajectory $\mathbf{x}_d$ along the unconstrained directions, are realized. Such torques should then be transformed to the actual torques at the crank axis.

Consider the joint space dynamic model of a general manipulator written as

$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{J}_A^T \mathbf{h}_A$$

where $\mathbf{B}(\mathbf{q})$ is the well known inertia matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis and centrifugal force matrix, $\mathbf{g}$ is the gravitational force vector and $\mathbf{h}_A$ is the vector of forces exerted on the environment. Using the inverse dynamics control law [12]

$$\boldsymbol{\tau} = \mathbf{B}(\mathbf{q})\ddot{\mathbf{y}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{y}} + \mathbf{g}(\mathbf{q}) + \mathbf{J}_A^T \mathbf{h}_A$$

where

$$\mathbf{y} = \mathbf{J}_A^{-1}(\mathbf{q})\mathbf{M}_d^{-1}(-\mathbf{K}_D \dot{\mathbf{x}} + \mathbf{K}_P(\mathbf{x}_F - \mathbf{x} + \mathbf{x}_d) - \mathbf{M}_d \mathbf{J}_A(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}})$$

which makes the end-effector dynamics equivalent to that of mechanical impedance with mass $\mathbf{M}_d$, stiffness $\mathbf{K}_P$ and damping $\mathbf{K}_D$.

Then, the parallel force/position control action can be chosen as

$$\mathbf{x}_F = \mathbf{C}_F(\mathbf{h}_{Ad} - \mathbf{h}_A)$$

where the position reference is related to the force error by a PI controller, i.e.

$$\mathbf{C}_F = \mathbf{K}_F + \mathbf{K}_I \int (\cdot) d\zeta$$

The resulting scheme is illustrated in Fig. 8.

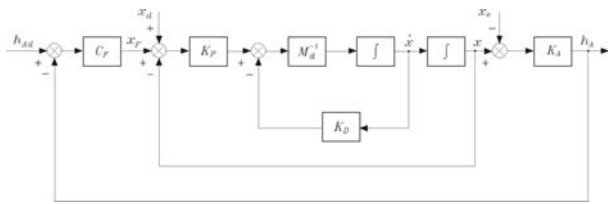


Fig. 8: Parallel force/position control scheme.

4.1 Thumb control

In the grasp configuration the thumb can be seen as an open-chain robotic mechanism with two operational

points: one on the first phalanx and another on the second one. In this case, the joint space dynamic equations of motion may be written as [13]

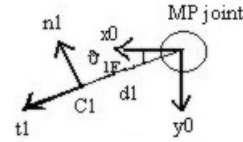
$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{J}_{Ac}^T \mathbf{h}_{Ac}$$

where $\mathbf{J}_{Ac}$ is the vertically concatenated matrix of the Jacobian matrix of each end-effector and $\mathbf{h}_{Ac}$ is a vertically concatenated vector of the force exerted on the environment by each end-effector:

$$\mathbf{J}_{Ac} = \begin{bmatrix} \mathbf{J}_{A1} \\ \mathbf{J}_{A2} \end{bmatrix} \quad \mathbf{h}_{Ac} = \begin{bmatrix} \mathbf{h}_{A1} \\ \mathbf{h}_{A2} \end{bmatrix}$$

Interaction forces are modeled under the assumption of an elastically compliant environment, where $\mathbf{K}_A$ denotes the stiffness matrix. The two virtual manipulators with their respective Jacobians and forces are detailed below.

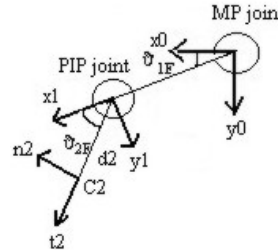
Virtual manipulator related to the first operational point



$$\mathbf{J}_{A1} = \begin{bmatrix} -d_1 s_{1F} & 0 \\ d_1 c_{1F} & 0 \end{bmatrix}$$

$$\mathbf{h}_{A1} = \mathbf{K}_{A1}(\mathbf{x}_1 - \mathbf{x}_{e1})$$

Virtual manipulator related to the second operational point



$$\mathbf{J}_{A2} = \begin{bmatrix} -a_1 s_{1F} - d_2 s_{1F2F} & -d_2 s_{1F2F} \\ a_1 c_{1F} + d_2 c_{1F2F} & d_2 c_{1F2F} \end{bmatrix}$$

$$\mathbf{h}_{A2} = \mathbf{K}_{A2}(\mathbf{x}_2 - \mathbf{x}_{e2})$$

Therefore, the control law becomes

$$\mathbf{y} = \mathbf{J}_{Ac}^{-1}(\mathbf{q})\mathbf{M}_d^{-1}(-\mathbf{K}_D \dot{\mathbf{x}} + \mathbf{K}_P(\mathbf{x}_F - \mathbf{x} + \mathbf{x}_d) - \mathbf{M}_d \mathbf{J}_{Ac}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}})$$

which must ensure, in the contact frame where dynamics are decoupled, that the forces along $\mathbf{n}_i$ -axis and the positions along $\mathbf{t}_i$ -axis ($i=1,2$) are regulated to their respective desired values.

Notice that control only acts in bi-dimensional space because of the planar nature of the manipulator.

In order to demonstrate the feasibility of the above controller, a model for simulating the hand grasp using the Simulink package associated with MATLAB™ has been developed to carry out numerical case studies.

A polynomial law is used to generate the reference trajectory from the starting joint position to the final one

$$\begin{cases} \theta_{1Fin} = 20^\circ \\ \theta_{2Fin} = -47^\circ \end{cases} \quad \begin{cases} \theta_{1Ffin} = 2^\circ \\ \theta_{2Ffin} = -65^\circ \end{cases}$$

The above thumb control has been developed in the contact frame, while simulation is performed in the reference frame attached to the first joint. As for the design of the impedance parameters, the end-effector dynamics has been specified in the contact frame in

terms of the damping ratio ζ_i ($i=1,2$) and the time constant $\tau_i = \zeta_i \omega_{ni}$, where

$$\mathbf{K}_{PC} = \text{diag}\{m_{dC1}\omega_{n1}^2, \dots, m_{dCn}\omega_{nn}^2\}$$

$$\mathbf{K}_{DC} = \text{diag}\{2m_{dC1}\zeta_1\omega_{n1}, \dots, 2\zeta_n m_{dCn}\omega_{nn}\}$$

for a given value of $\mathbf{M}_{dC} = \text{diag}\{m_{dC1}, \dots, m_{dCn}\}$.

A satisfactory dynamic has been obtained by imposing

$$\begin{cases} \tau_1 = 10 \\ \zeta_1 = 0.5 \end{cases} \quad \begin{cases} \tau_2 = 9 \\ \zeta_2 = 0.5 \end{cases}$$

As for the force control, that has been designed in terms of the position of the zero and the cross-over frequency of the PI controller. These have been chosen as

$$\begin{cases} \frac{k_{IC1}}{k_{FC1}} = 100 \\ \omega_{i1} = 50 \end{cases} \quad \begin{cases} \frac{k_{IC2}}{k_{FC2}} = 100 \\ \omega_{i2} = 10 \end{cases}$$

Notice that the above control gains have to be projected to the reference frame.

The following results have been obtained (Figs. 9,10).

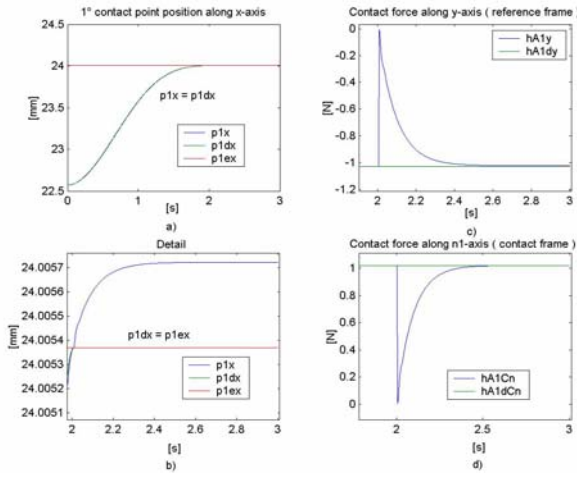


Fig. 9: a) First contact point position along x-axis, b) detail, c) contact force along y-axis in reference frame, d) contact force along n1-axis in contact frame.

It is worth noticing that, as expected, force regulation in the contact frame is ensured (Fig. 9d). Yet, the results in the reference frame are acceptable (Fig. 9a, 9c).

On the other hand, for the second contact point, in the face of good performance in the contact frame (Fig. 10d), a force error is observed in the reference frame (Fig. 10c). This is due to the large weight of the force error along the t2-axis in the contact force projection on the reference frame.

It can be concluded that force regulation at the contact points is achieved which, in view of the absence of slippage guaranteed by the maximum load analysis, ensures a stable grasp.

4.2 Index/middle finger control

Also in this case, fingers can be seen as an open-chain robotic mechanism with two operational points: one on the first phalanx and another on the second phalanx end so that the dynamic model is the same as that for the thumb. As above, the two virtual

manipulators with their respective Jacobians and forces are detailed below.

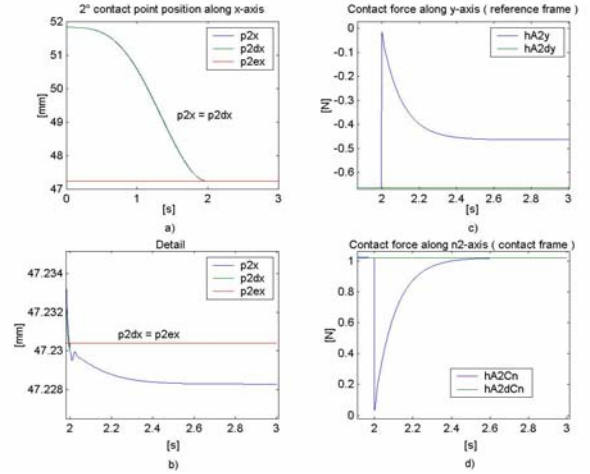
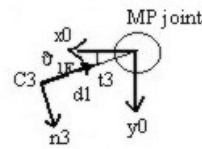


Fig. 10: a) Second contact point position along x-axis, b) detail, c) contact force along y-axis in reference frame, d) contact force along n2-axis in contact frame.

Virtual manipulator related to the first operational point



$$\mathbf{J}_{A1} = \begin{bmatrix} -d_1 s_{1F} & 0 \\ d_1 c_{1F} & 0 \end{bmatrix}$$

$$\mathbf{h}_{A1} = \mathbf{K}_{A1}(\mathbf{x}_1 - \mathbf{x}_{e1})$$

Virtual manipulator related to the second operational point

In this case, new operational space variables are defined as

$$\mathbf{x}_2 = \mathcal{G}_{2F}$$

so that

$$\mathbf{J}_{A2} = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

while no contact forces act on the virtual end-effector

$$\mathbf{h}_{A2} = 0$$

This time, the control law must ensure that the contact force reference along $\mathbf{n}_3$ -axis, the position reference along $\mathbf{t}_3$ -axis and the position reference at the second phalanx end are realized, becoming

$$\mathbf{y} = \mathbf{J}_{Ac}^{-1}(\mathbf{q}) \begin{bmatrix} \mathbf{M}_{d1}^{-1}(-\mathbf{K}_{D1}\dot{\mathbf{x}}_1 + \mathbf{K}_{P1}(\mathbf{x}_{F1} - \mathbf{x}_1 + \mathbf{x}_{d1}) - \mathbf{M}_{d1}\mathbf{J}_{A1}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}}) \\ \ddot{\mathbf{x}}_{d2} + k_{D2}(\dot{\mathbf{x}}_{d2} - \dot{\mathbf{x}}_2) + k_{P2}(\mathbf{x}_{d2} - \mathbf{x}_2) - \mathbf{J}_{A2}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} \end{bmatrix}$$

The controller is designed in the contact frame for the first operational point, and in the reference frame for the second one.

A polynomial law is used to generate the reference trajectory from the starting joint position to the final one

$$\begin{cases} \mathcal{G}_{Fin} = -30^\circ \\ \mathcal{G}_{2Fin} = 20^\circ \end{cases} \quad \begin{cases} \mathcal{G}_{1Fin} = -26^\circ \\ \mathcal{G}_{2Fin} = 57^\circ \end{cases}$$

and the following parameters are chosen for the controller

$$\begin{cases} \tau_1 = 10 \\ \zeta_1 = 0.5 \end{cases} \quad \begin{cases} k_{IC1} = 100 \\ k_{FC1} \\ \omega_{t1} = 100 \end{cases}$$

according to a similar procedure as above.

The following results have been obtained (Figs. 11,12).

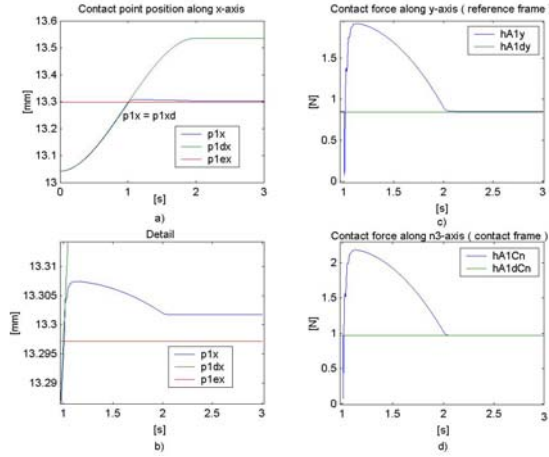


Fig. 11: a) First contact point position along x-axis, b) detail, c) contact force along y-axis in reference frame, d) contact force along n3-axis in contact frame.

Also in this case the control, designed in the contact frame, is able to regulate force along n_3 -axis to its desired value while the results in the reference frame are still acceptable (Fig. 11c,d). Further, the position control on PIP joint ensures tracking of the desired position value (Fig. 12a), in order to avoid interference between the fingers. Note that the position error on PIP joint (Fig. 12b) is transmitted to DIP joint (Fig. 12d) whose position is obviously a function of the former.

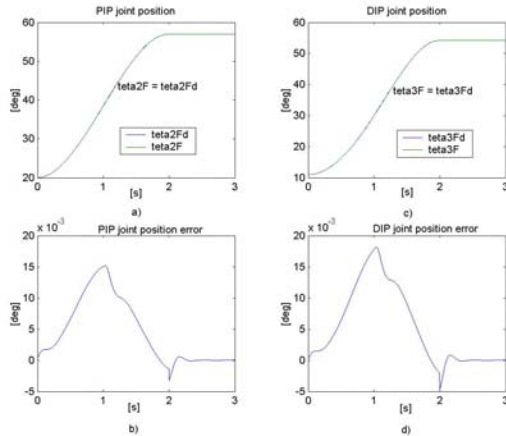


Fig. 12: a),c) Joint position, b),d) joint position error.

5 Conclusions

In this paper a procedure to obtain maximum load and contact force distribution for a given particular grasp task has been presented. The result is useful to gain information about load and forces using objects with different shape and weight.

Furthermore, in order to demonstrate the feasibility of the new biomechatronic approach, a parallel force/position control of the fingers has been devised which has been tested in a number of significant case studies.

In the future, the model will be used for testing robustness of the control system when real models of the force sensors are used, and for analyzing the RTR1 hand's performance whenever new solutions with different kinds of actuators and sensors are envisaged.

Acknowledgements

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