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A Static Intrinsically Passive Controller to Enhance Grasp Stability of Object-based Mapping between Human and Robotic Hands

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***Abstract*— Replicating human hand capabilities on robotic hands is a great challenge in robotics. The high complexity of mechanical and actuation systems of available robotic device can be, however, considerably mitigated if a human inspired control is considered. In this paper the application of an object-based mapping to the control of robot hands is presented. The basic idea is to use a virtual object, e.g. a virtual sphere, to capture human hand motion generating suitable reference signals for a low level controller of the robotic hand. The low level controller considered, which shares the idea of virtual object to reduce the complexity of the control, is the static Intrinsically Passive Controller (s-IPC). This controller is inspired by the dynamic IPC, but provides a simpler and more efficient implementation. The proposed approach allows to map motion of a human hand model, controlled on the reduced subspace of postural synergies, onto robotic hands guaranteeing the stability of the robotic grasp. This concept, which has been experimentally validated in the paper, can be exploit for complex planning methods or used in telemanipulation application.**

I. INTRODUCTION

The complexity of the robotic hand design arises from the possibility of adapting hands to the many kinds of tasks required in unstructured environments, such as surgical rooms, industry, house, space and other domains, where robotic grasping and manipulation have become crucial [1]. One of the main issues is that a large number of motors is needed to fully actuate the degrees of freedom (DoFs). This makes the mechanical system design of robotic hands dramatically more complex when compared to simple grippers often used in industrial applications [2]. The same problems have to be faced if control is concerned. Consider, for instance, the automatic grasp synthesis problem. It is usually solved through optimization problems that maximize a certain quality function over a space of possible hand postures [3]. These problems are compounded by the high dimensionality of the optimization domain. The case of an anthropomorphic robot hand model, with 20 DoFs results in a 26-dimensional optimization domain (6 variables are necessary to determine the position of the wrist), rendering most optimization algorithms intractable. A possible simplification can be sought in imitating the human behaviour. Central to this view is the concept of constraints that are imposed by the embodied characteristics of the human hand and its sensorimotor apparatus on the learning and control strategies we use for such fundamental cognitive functions as exploring, grasping and manipulating [4]. In fact, several results on the organization of the human hand in grasping and manipulation have demonstrated that, notwithstanding the complexity of the human hand, few variables are able to account for most of the variance in patterns of the human hands configuration and movement [5]. This few variables are usually referred to as *postural synergies* and can be interpreted as correlation of DoFs in patterns of more frequent use.

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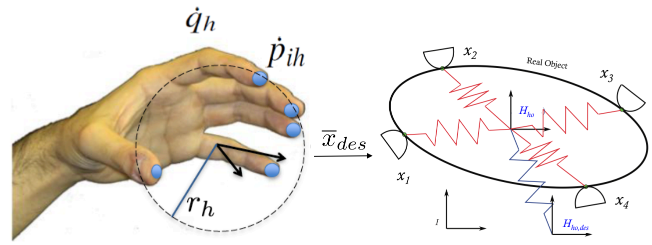


Fig. 1. The motion of the paradigmatic hand is described by the virtual sphere. The arising parameters $\bar{x}_{des}$ are used as input for the s-IPC controller.

In [6], [7], [8], it has been described how an object-based mapping is able to reproduce movements of a human hand model, with particular emphasis on the synergistic motion of a paradigmatic hand, in different robotic hands without considering the specific kinematics. The object-based mapping is obtained considering two virtual objects, one on the human and one on robotic hand. They are defined considering the minimum volume object containing opportune reference points placed on the respective hands (see left side of Fig. 1). A configuration variation of the human hand induces a motion and a deformation of the virtual object. In the proposed approach it is imposed that the object defined on the robotic hand moves and deforms according to that defined on the human hand. Through pseudo-inversion techniques, the mapped motion of the robotic hand is obtained. The final target of the mapping procedure is to create an abstraction layer where all the tasks are planned in the synergistic reduced human hand domain and then projected onto robotic hands avoiding the development of specific strategies for each robotic device. However, the possibility to abstract from the kinematics comes at a cost of a lost of precision in fine manipulation tasks. This is due principally to the fact that when focusing on the virtual object motion the single finger motion is neglected in favour of a whole hand motion. That means that during real manipulation tasks, possible contact sliding or possible contact lost due to the impossibility of the robotic hand to reproduce the desired motion could affect the stability of the grasp. In other words, the robotic hand should be able to guarantee the stability of a grasp also when the mapped motion leads to undesirable effects.

To overcome these problems we propose in this work the use of a low level controller, which shares the idea of virtual object to reduce the complexity of the control. The considered controller is the static Intrinsically Passive Controller (s-IPC) that has been presented in [9], [10]. This solution provides an intuitive control law for object-level manipulation that does not require robust contact detection/tracking. Furthermore, the arising controller guarantees intrinsic passivity, stability in the case of a finger losing contact during manipulation, an intuitive physical interpretation, and a damping design w.r.t. the desired object-level stiffness and the hand and object inertias.

In this paper we will use the concept of virtual spherical object introduced in [11] as a simplified way to describe human hand motion. The basic idea, represented in Fig. 1, is to use the motion of the virtual object, that embodies the motion of the human hand, to generate suitable reference inputs for the s-IPC controller. The proposed solution has been tested on the DLR Hand II [12]. The first two human hand synergies have been considered as input since they are able to reproduce around 80% of the human hand postures [5].

The paper is organized as it follows. In Sec. II the virtual sphere mapping used to map human hand synergies onto robotic hands is revised. In Sec. III the s-IPC controlled is described, while in Sec. IV the proposed integration between the two approaches is detailed. Finally, Sec. V deals with the obtained results on the DLR Hand II and in Sec. VI conclusion and future work are outlined.

II. The Virtual Sphere Algorithm

In this section the object-based mapping approach is reviewed. Further details can be found in [6], [7].

The proposed algorithm is based on a heuristic approach: a part of the hand motion is reproduced, which practically corresponds to move and squeeze a spherical virtual object. Although squeezing and moving an object explain a wide range of tasks, many other possibilities exist in manipulating objects which are not modelled with this approach. The sphere represents the simplest solution. Increasing the number of parameters in the virtual object and virtual displacement definition allows to replicate more complex hand movements, but, at the same time, increases the mapping complexity while decreasing robustness.

In the following, possible human hand motions are represented considering a paradigmatic hand model which is a kinematic model inspired by the human hand. One of the advantages of this solution is that postural synergies for this hand are well defined [13], [14].

Refer to the left side of Fig. 1 and let the paradigmatic hand be described by the joint variable vector $q_h \in \Re^{n_{qh}}$. Assume that the subspace of all configurations can be represented by a lower dimensional input vector $z \in \Re^{n_z}$ (with $n_z \leq n_{qh}$) which parametrizes the motion of the joint variables along the synergies $q_h = S_h z$ being $S_h \in \Re^{n_{qh} \times n_z}$ the synergy matrix as defined in [6]. In terms of velocities one gets

$$\dot{q}_h = S_h \dot{z}.$$

A set of reference points $p_h = [p_{1h}^{\mathrm{T}}, \cdots, p_{ih}^{\mathrm{T}}, \cdots]^{\mathrm{T}}$ are chosen on the paradigmatic hand to define a possible way to represent its motion. In the rest of the paper the fingertip points will be considered as reference points. The velocity of the fingertips is related to the velocity of the hand joints through the Jacobian matrix J_h such that $\dot{p}_h = J_h \dot{q}_h$ (see [15] for more details). However, other choices for reference point positions are possible as for example the intermediate phalanges or the hand palm, and furthermore the number of reference points can be arbitrary fixed [6]. The virtual sphere object is computed as the minimum volume sphere containing the reference points p_h (left side of Fig. 1). Note that these points in general do not lie on the sphere surface. Let us parametrize the virtual sphere by its center o_h and radius r_h. A movement imposed to the hand moves also the reference points determining a motion of the sphere and a variation of its radius. A modification of the hand configuration due to synergies activation could be described using a large set of parameters. In this algorithm we simplify the problem assuming the following transformation for the virtual sphere:

- a *rigid-body* motion, defined by the linear and angular velocities of the sphere center $\dot{o}_h$ and ω_h, respectively;
- a *non-rigid* strain represented by the radius variation $\dot{r}$ of the sphere.

Representing the motion of the hand through the virtual object, a position variation of the generic reference point p_{ih} can be expressed as

$$\dot{p}_{ih} = \dot{o}_h + \omega_h \times (p_{ih} - o_h) + \dot{r}_h (p_{ih} - o_h).$$

Grouping all the reference point motions, one gets

$$\dot{p}_h = A_h \begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix}, \tag{1}$$

where matrix $A_h \in \Re^{n_{ch} \times 7}$ is defined as follows

$$A_h = \begin{bmatrix} I & -S(p_{1h} - o_h) & (p_{1h} - o_h) \\ \cdots & \cdots & \cdots \\ I & -S(p_{ih} - o_h) & (p_{ih} - o_h) \\ \cdots & \cdots & \cdots \end{bmatrix}, \tag{2}$$

with $S()$ acting as the skew operator. From these equations we can evaluate the virtual sphere motion and deformation as a function of the synergy vector velocity $\dot{z}$ of the paradigmatic hand

$$\begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix} = A_h^{\#} \dot{p}_h = A_h^{\#} J_h S_h \dot{z}, \tag{3}$$

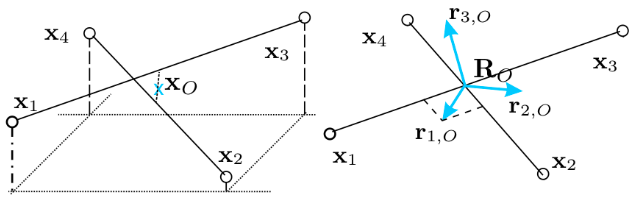


Fig. 2. Virtual object frame with four fingers, from [9].

where $A_h^{\#}$ denotes the pseudo-inverse of matrix A_h.

In the mapping algorithm proposed in [6] a set of reference points p_r is chosen also on the robotic hand and a virtual sphere is thus defined in a similar way. The same motion of the two spheres is imposed, apart of a scaling factor K_c, through

$$\begin{bmatrix} \dot{o}_r \\ \omega_r \\ \dot{r}_r \end{bmatrix} = K_c \begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix}, \tag{4}$$

with o_r and ω_r being the center coordinates and the angular velocity of the sphere defined in the robot hand respectively, and the r_r the radius. Replicating eq. (1) for the robotic hand and considering eq. (3) and (4) the mapped joint velocities for the robotic hand can be computed as

$$\dot{q}_r = J_r^{\#} A_r K_c A_h^{\#} J_h S_h \dot{z}, \tag{5}$$

with J_r as its Jacobian matrix and A_r defined as in eq. (2).

In this work the robotic joint values obtained in eq. (5) are not used directly. Instead, the parameters describing the sphere motion in eq. (3) are used as reference input for the s-IPC as it will be described in details in Sec. IV.

III. The static Intrinsically Passive Controller

The majority of robot hand control algorithms proposed in literature require robust contact detection/tracking and switching controllers. Stramigioli presented in [16] a different approach involving a virtual object connected via spatial spring with the fingertip and with a virtual position of the hand, the Intrinsically Passive Controller (IPC). Wimböck et al. proposed in [9] a novel virtual object frame based on the robot hand configuration. The basis for this control was the virtual object frame which was defined by the positions of the fingertips. This control approach has been later defined as static-Intrinsically Passive Controller (s-IPC) in [10] to remark that the dynamic introduced by the virtual object in the IPC controller is not considered in this case.

In this work the s-IPC has been considered as a possible low level controller for the robotic hand. In the following, the main equations necessary for the s-IPC definition are reported. Further details can be found in [9] and [10].

Let us consider a robot hand with n fingers and 3 DoFs per finger. The equation of motion can be written, according to [1], as

$$M(\theta)\ddot{\theta} + C(\dot{\theta}, \theta)\dot{\theta} + g(\theta) = \tau + \tau_{ext},$$

where θ are the joint angles, τ and τ_{ext} are the joint torques and the external torques respectively, $M(\theta)$ is the joint level inertia matrix, $C(\dot{\theta}, \theta)$ contains the Coriolis and centrifugal forces and $g(\theta)$ represents the gravity effect.

The object coordinating the finger motions considered in the s-IPC is defined only by the position of fingertips. To describe its motion a frame is attached to the center of the fingertip positions (Fig. 2)

$$x_O = \frac{\sum_{i=1}^{n} x_i(\theta)}{n}, \tag{6}$$

where $x_i(\theta) \in \Re^3$ represents the Cartesian fingertip position for finger i w.r.t the base (frame O). For simplicity dependence on θ is omitted in the following. The orientation $R_O = [r_{1,O}, r_{2,O}, r_{3,O}]$ (right side of Fig. 2) for four fingers can be computed considering the unitary vector $r_{1,O}$ defined in the plane spanned by the vectors being defined by the connections between fingers 1 and 3 and between fingers 2 and 4, that is

$$\mathbf{r}_{1,O} = \frac{x_1 - x_3}{\|x_1 - x_3\|} + \frac{x_2 - x_4}{\|x_2 - x_4\|}, \qquad r_{1,O} = \frac{\mathbf{r}_{1,O}}{\|r_{1,O}\|}. \tag{7}$$

The unitary vector $r_{3,O}$ is defined perpendicular to this plane and $r_{2,O}$ is defined such that $R_O \in SO(3)$.

The virtual object frame H_{ho} can be defined as $H_{ho} = [R_O, x_O] \in SE(3)$. Note that this representation has singularities if $x_j - x_{j+2} = 0$ for $j = 1 \vee j = 2$ or if $(x_1 - x_3) \parallel (x_2 - x_4)$. For common convex objects like boxes, cylinders or spheres these singularities pose no problem. The extension to more than four fingers can be done imposing that all elements of H_{ho} are a function of all fingertip positions. The virtual-object frame is related to the real-object frame assuming that the relative contact points between the fingertips and the object do not change (neglecting rolling effects).

Once the virtual object is defined, a possible control law can be derived. Let us consider

$$\tau = -D(\theta)\dot{\theta} - \left(\frac{\partial V_d}{\partial \theta}\right)^T + g(\theta). \tag{8}$$

with $D(\theta)$ being a positive damping matrix and V_d being the desired potential function.

In addition to an impedance related to the object pose, impedances to realize grasping forces are added. These impedances connect each fingertip position x_i with the virtual-object frame (see right side of Fig. 1). The potential is chosen to be spherical for each fingertip:

$$V_{hc}(\theta, K_{hc}) = \frac{1}{2}\sum_{i=1}^{n} K_{hc,i}[\|\Delta x_i\| - l_{i,des}]^2$$

with $\Delta x_i = x_i - x_O$ as the distance from the fingertip i to the virtual object frame x_O, and $K_{hc,i} > 0$ the corresponding connecting stiffness. The value $l_{i,des}$ corresponds to the rest length of the connecting stiffness. We summarize $K_{hc,i}$ and $l_{i,des}$ for $i = 1, ..., n$ in K_{hc}. This means that the grasping forces can be parametrized so that they point toward the virtual frame. The desired potential for the object-level control law is composed of the potentials used to derive the spatial object stiffness and the connecting stiffness, and, thus, is given by

$$V_d(\theta) = V_s(H_{ho}(\theta), H_{ho,des}, K_{ho}) + V_{hc}(\theta, K_{hc}),$$

with $V_s()$ defined as in [10]. By inserting this potential into eq. (8), a control law is obtained, which generates the control torques for the hand. The differential mapping from the hand motion to the object motion and the change of distance between the fingertips and the object center is given by

$$\underbrace{\begin{bmatrix} \dot{x}_O \\ \dot{x}_i \end{bmatrix}}_{\overline{x}} = \underbrace{\begin{bmatrix} \frac{\delta x_O}{\delta \theta} \\ \frac{\delta \mathbf{x}_i}{\delta \theta} \end{bmatrix}}_{J_{tot}} \dot{\theta} \tag{9, 10}$$

where $\overline{x} \in \Re^{6+n}$ represents the generalized coordinate of the task and $\mathbf{x}_i = \|\Delta x_i\|$.

The stacked Jacobian J_{tot} is useful for a compact derivation of the damping parameters. Details on the derivation of the damping term $D(\theta)$ can be found in [10]. In conclusion, the input for the s-IPC controller can be considered the desired position of the object frame $H_{ho,des}$ and the desired contact stiffness defined by $l_{i,des}$.

IV. Integration with the virtual sphere algorithm

In the virtual sphere mapping motions of the paradigmatic hand are described through motions and deformation of a virtual object defined considering opportune reference points. This solution dramatically reduces the number of parameters necessary to describe the hand configuration (from 20 to 7). In the s-IPC controller a similar reduction is considered introducing a relation between fingertip positions. Although the s-IPC guarantees grasp stability even in presence of contact lost or contact slippery, the way a task can be specified for the robotic hand through the virtual object is not intuitive when non trivial motions have to be considered. On the other hand, the virtual sphere mapping can be easily used to describe a task in the paradigmatic hand, but cannot guarantee grasp maintenance when the motions imposed to the robotic hand lead to loosing contact due to the specific kinematic of the robotic hands. Summarising, the main advantages in integrating the s-IPC and virtual sphere mapping are

- a direct and intuitive solution to generate suitable trajectory for the s-IPC object obtained considering the parameters that describe the virtual sphere motion and deformation on the paradigmatic hand;
- the stability of the grasp of real object is guarantee by the s-IPC.

In this work, the proposed integration is obtained considering the virtual sphere mapping to generate suitable reference signals for the object frame $H_{ho,des}$ and the contact stiffness defined for the s-IPC. In eq. (10) $\overline{x}$ was defined as the generalized coordinate of the task, where both the position and orientation of the object frame and the stiffness behaviour were considered. So that, the virtual mapping has to generate the $\overline{x}_{des}$ for the s-IPC. In Fig. 3 a block diagram of the integrated controller is reported.

Let consider the paradigmatic and the robotic hand in a given starting position. There is no constraints on the choice of the starting position apart the singularity condition for the s-IPC object described in the previous section. A virtual sphere can be defined on the paradigmatic hand as the minimum volume sphere containing all the reference points defined in the paradigmatic hand. Also in this case there are no constraints for the number of reference points and the locations. In the robotic hand, the object coordinating the finger motion is computed using eq. (6) and (7). Let us denote the initial position of the frame as H_0.

When the joints of the paradigmatic hand are moved, for instance due to a synergies activation, the motion of the reference points is described by the virtual sphere using the vector of parameters defined in eq. (1) containing the linear and angular velocity of the center and the radius variation. The first six components of the vector of parameters describe the twist applied to the virtual sphere. At each time step, this twist is used to update the desired position and orientation $H_{ho,des}$ of the frame attached to the object defined for the s-IPC. Considering

$$H_{ho,des} = \begin{bmatrix} R_{ho} & p_{ho} \end{bmatrix},$$

where $R_{ho} \in \Re^{3\times3}$ and $p_{ho} \in \Re^3$ represent the orientation and the position of the frame respectively, the new orientation is computed via quaternion integration using the angular velocity ω_h and the new position is computed integrating the linear velocity $\dot{o}_h$. The variation of the sphere radius is instead related to the rest length of the connecting stiffness $l_{i,des}$. By imposing

$$l_{i,des} = \alpha\, \dot{r}\, l_{\text{off}} \tag{11}$$

where l_{off} is a fixed initial offset for the connecting spring and α is used to mitigate the difference in the workspace with a similar meaning of K_c (eq. (4)) for the virtual object mapping, it is possible to related the radial deformation of the sphere to the connecting force. Intuitively both these parameters, the connection spring length and the sphere radius, are related to grasping forces.

The adopted solution allows to move the robotic hand according to the motion imposed by the paradigmatic hand, but enforcing the grasp thanks to the low level s-IPC controller. The motion of the real grasped object depends on the desired reference inputs

$$\overline{x}_{des} = \begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r} \end{bmatrix}, \tag{12}$$

but also on the compliance of the s-IPC system and the compliance of the robot hand joints. So that, the imposed and the obtained trajectories could differ. In the proposed approach, however, the grasp maintenance is considered with an higher priority with respect to the accuracy of the trajectories.

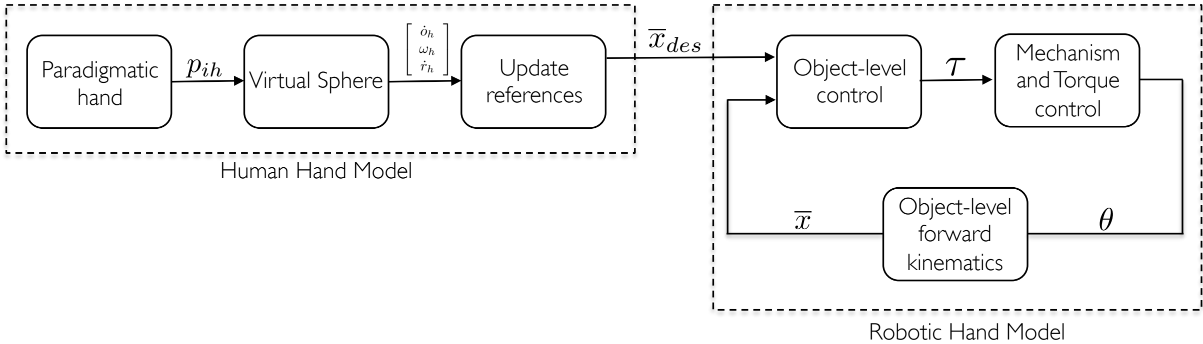


Fig. 3. Block diagram of the virtual sphere mapping plus the s-IPC. The task is performed by the paradigmatic hand model and reference signals are computed for the low level controller of the robotic hand, the s-IPC.

V. Experimental validation

In this section, two experiments are presented to validate the use of virtual sphere mapping combined with the s-IPC. The activation of the two first synergies were considered on the paradigmatic hand. This choice is related to the capability of the first two synergies to describe a great amount of hand motions. However, the method can be extended to different movements. In the first experiment a ball is grasped using only the first synergy on the paradigmatic hand to generate the input signals for the s-IPC. In the second experiment a combination of the first two synergies is used to firmly grasp a ball while moving it along a predefined direction. The robotic hand used was the DLR II Hand, while the control approach is described in Sec IV. The control law was implemented using the Real-time Workshop of MATLAB/SIMULINK. The code generated from the SIMULINK model runs on QNX on a Pentium IV with 3 GHz with a controller sample time of 1 ms.

In Fig. 4 the first two mapped synergies using the virtual sphere algorithm to generate the inputs for the s-IPC are shown. The mapped synergies are obtained moving the paradigmatic hand along the first two synergies and using the control law presented in Sec. III.

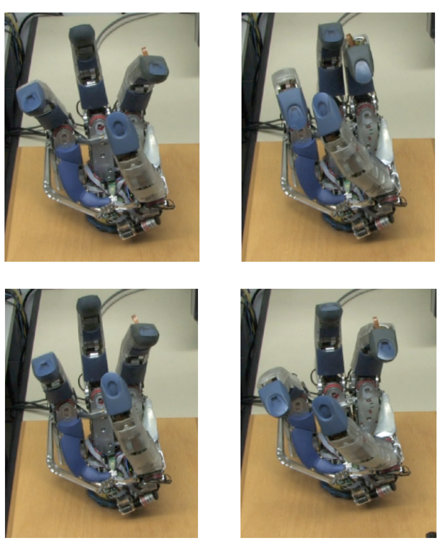


Fig. 4. In the first row (left initial position, right final position) the first synergy mapped onto the DLR II hand using the s-IPC controller. In the second row the second mapped synergy.

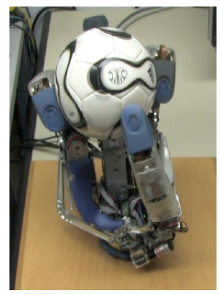
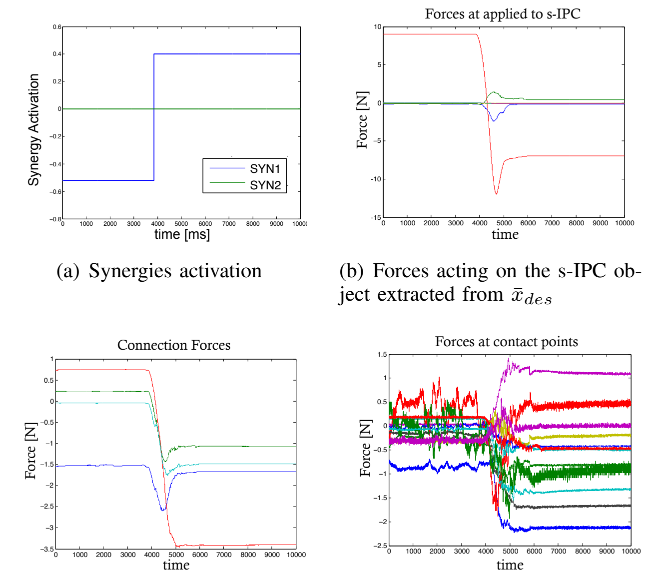


Fig. 5. Grasping and manipulating object with s-IPC: the setup for the DLR II hand.

The setup for the grasping and manipulation experiments is reported in Fig. 5. In the grasping experiment only the first synergy was activated to obtain a stable grasp (Fig. 6-a). The forces applied to the s-IPC object by the controller (Fig. 6-b) are small excepting the force along the direction perpendicular to the hand palm (the red line in Fig. 6-b). This motion is related to the first synergy activation that moves the s-IPC object toward the palm. The arising connection forces related to the virtual sphere's radius variation are shown in Fig. 6-c. Note that the connection forces are related to the virtual spring connecting the fingertips with the virtual object frame. Varying the setpoints $l_{i,des}$ we act on the related connection forces. The scaling factor α introduced in eq. (11) was experimentally evaluated and set to 0.2. The arising forces measured at the contact points are reported in Fig. 6-d. Since the open-close motion induced by the first synergy significantly affects the variation of the virtual sphere radius, the resulting contact forces guarantee a stable grasp. The synergies activation for the manipulation experiment is reported in Fig. 7-a. The first synergy has a constant value for all the experiment to ensure a sufficient internal forces corresponding to a stable grasp. In the meanwhile the second synergy is activated to generate a motion of the object resulting in a variation of the forces acting on



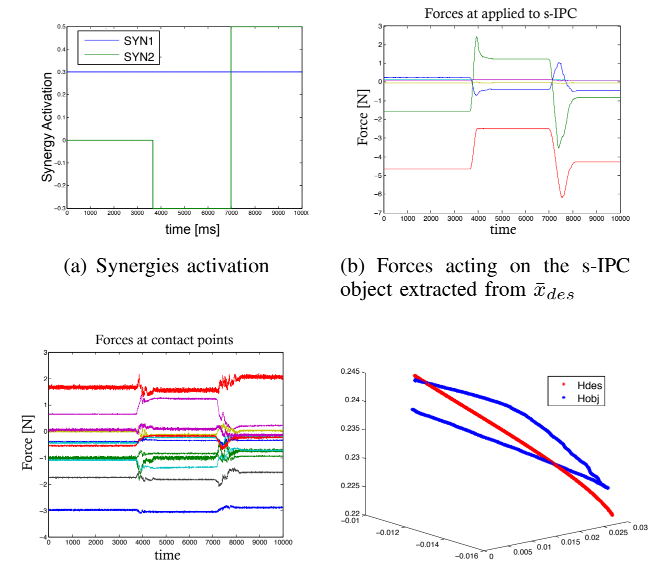
(a) Synergies activation

(b) Forces acting on the s-IPC object extracted from $\bar{x}_{des}$

(c) Connection forces extracted from $\bar{x}$

(d) Measured forces at contact points

Fig. 6. Grasping a ball using the first mapped synergy and the s-IPC controller.



(a) Synergies activation

(b) Forces acting on the s-IPC object extracted from $\bar{x}_{des}$

(c) Measured Forces at contact points

(d) Desired and actual trajectory of the grasped object in m

Fig. 7. The DLR II hand manipulating a ball using the s-IPC controller.

the s-IPC object (Fig. 7-b). The activation of the second synergy does not significantly affect the variation of the virtual sphere radius and consequently the contact forces (Fig. 7-c). In Fig. 7-d are reported the desired trajectory of the s-IPC object and the actual trajectory of the grasped object. The discrepancy of the two trajectories are due to unmodelled dynamics, in particular uncompensated friction and possible sliding effects. However, using only two DoFs represented by the first two synergies activation values, a simple on-hand manipulation task, where the stability of the grasp is guaranteed by the s-IPC, has been obtained. More complicated motions would require a higher number of involved synergies.

VI. Conclusion

This paper presents a novel approach to control robotic hands that merges the capabilities of the object-based mapping to efficiently describe the human hand motion and the stability properties of the s-IPC. In particular we demonstrated how the use of the s-IPC enhances the stability of the grasp when synergistic motion of a human hand model is mapped onto a robotic hand with different kinematics. We have tested the proposed approach performing a *grasping and a manipulation* task using the DLR Hand II. The input to the robot hand controller were generated using only the first two human postural synergies mapped using an object-based approach. As future work we are investigating the potentiality of this approach for a teleoperation framework.

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