Mapping synergies from human to robotic hands with dissimilar kinematics: an object based approach

G. Gioioso, G. Salvietti, M. Malvezzi and D. Prattichizzo

***Abstract*— Robotic hands differ in kinematics, dynamics, programming, control and sensing frameworks. Their common character is redundancy, which undoubtedly represents a key feature for dexterity and flexibility, but it is also a drawback for integrated automation since it typically requires additional efforts to seamlessly integrate devices, particularly robotic hands, in industrial scenario. This paper focuses on the mapping between hands with dissimilar kinematics. It is based on the argument that the reflected optimality of the pattern of grasping forces emerging from human hand synergies should be matched, in some sense, by the sought for postural synergies of robotic hands. As a natural consequence of the proposed approach, postural synergies for different kinematic structures could look entirely different in geometric shape. This difference should be a consequence of aspects such as different dimensions, kinematic structures, number of fingers, compliance, contact properties which cannot come into play if a gross geometric mapping is applied. The proposed mapping is based on the use of a virtual sphere and will be mediated by a model of an anthropomorphic robotic hand able to capture the idea of synergies in human hands.**

I. INTRODUCTION

Robotic hands share with the human hand, some of the fundamental primitives of motion, grasping, and manipulation. A deeper understanding of the human way to move their hands could suggest an approach to programming hands that allows users to more easily control the different devices that may be used in a robotic system, by encapsulating the hand hardware in functional modules, and ignoring the implementation-specific details.

Recent results on the organization of the human hand in grasping and manipulation [18] have demonstrated that, notwithstanding the complexity of the human hand, a few variables are able to account for most of the variance in the patterns of human hands configuration and movement. These conclusions were based on the results of experimental tests in which subjects were asked to perform grasping actions on a wide variety of objects. Data were recorded by means of data gloves and were analysed with principal component analysis (PCA) techniques. The results showed that the first two principal components account for most of the variability in the data, more than 80% of the variance in the hand postures. In this context the principal components were referred to *synergies* to capture the concept that, in the sensorimotor system of the human hand, combined actions are favoured over individual component actions, with advantages in terms of simplification and efficiency of the overall system.

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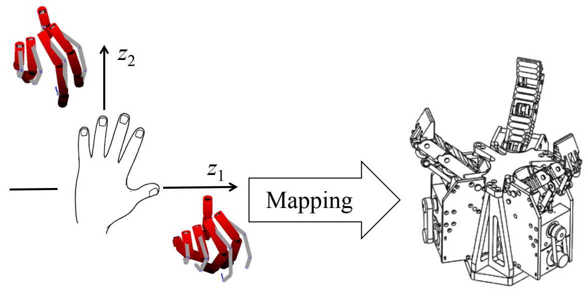

Fig. 1. Mapping between human synergies and robotic hands.

This reduced subspace allows to design more easily and intuitively robotic hand control algorithms, due to the lower number of DoF that has to be addressed. Anyway, this approach can be pursued only if there exists a mapping method that allows to replicate the actions defined in the synergistic subspace. This mapping leads to an interesting scenario, where control algorithms are designed considering a paradigmatic hand model, and without referring to the kinematic of the specific robotic hand.

This paper focuses on the mapping of human synergies on robotic hands by using a virtual object method as in Fig. 1.

The target is to reproduce deformations and movements exerted by the paradigmatic human-like hand on a virtual sphere computed as the minimum sphere containing the hand fingertips. This allows to work directly on the task space avoiding a specific projection between different kinematics.

II. RELATED RESEARCH WORK

In the literature there are several examples in which a mapping between human hand and a robotic hand is required. Basically, we can identify two different categories: tele-manipulation and learning by demonstration. In the former case, datagloves are typically used to collect human hand motion data to move the robotic hands. In [6], for example, a DLR Hand is controlled using a CyberGlove as controller. In the latter, human data are used to improve the grasping performance by teaching to the robot the correct posture to obtain stable grasps. In [5], authors evaluated and modelled human grasps during the arm transportation sequence in order to learn and represent grasp strategies for different robotic hands.

As the kinematics and configuration spaces of a human-like hand and an artificial robotic hand are generally different, the fingertip positions of the robotic hand cannot correspond exactly to the fingertip positions of the human-like hand (especially when fingertip grasps are considered). Generally, the mapping between human and robotic hands can be defined in the joint space and in the cartesian space.

The first one makes the two hand poses look similar. This is of interest for, e.g., enveloping or power grasps. This method is used for example by Ciocarlie and Allen in [4] to reproduce human synergies with different robotic hands. The human hand joint values were directly mapped into the joints of the anthropomorphic hands, while some empirical solutions were adopted with non-anthropomorphic ones. For example abduction movement of the human hand was mapped onto the spread angle of the Barrett hand. Although it represents the simplest way to map movements between hands, it has to be redefined according to the kinematic characteristics of the hands and moreover its performance notably decrease with non-anthropomorphic structures. Cartesian Space mappings focus on the relation between the two different workspace. This solution is more suitable for representing the fingertip positions and it is a natural approach when, for example, precision grasps are considered. In [15] a point-to-point mapping algorithm is presented for a multi-fingered telemanipulation system where fingertip motion of the human hand is reproduced with a three-finger robotic gripper. In [12] authors used a virtual finger solution to map movements of the human hand onto a four-fingered robotic hand. However these solutions are still not enough general to guarantee a correct mapping in terms of forces and movements exerted by the robotic hand on a grasped object.

Besides the above mentioned methods, combinations of them and some original solutions are also present in literature. For example in [10] the mapping is divided in three different steps. Initially, a local functional mapping is performed using a virtual finger approach to reduce the number of fingers. Then, an adjustable or gross physical mapping is carried out using the outcome of the local functional mapping to get an approximate grasp of the object which is geometrically feasible. Finally, a fine-tuning or local adjustment of grasp is performed.

In [9] the authors proposed a virtual object based mapping. The object based scheme assumes that a virtual sphere is held between the user's thumb and index finger. Important parameters of the virtual object (the size, position and orientation) are scaled independently and non-linearly to create a transformed virtual object in the robotic hand workspace. This modified virtual object is then used to compute the robotic fingertip locations that in this case is a simple two-finger four dof gripper. Our approach is inspired by the method proposed in this paper.

III. Synergy background

In this section we summarize main equations necessary to study hands controlled by synergies. A more detailed

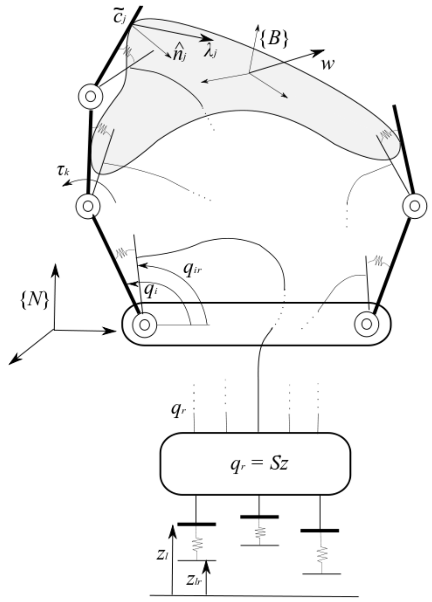

Fig. 2. The soft synergy actuated hand, from [16].

presentation of the problem is described in [16], further details on grasp theory can be found in [14], [17].

Consider a generic robotic hand grasping an object, Fig. 2. The force and moment balance for the object can be described by the equation:

$$w = -G\lambda \tag{1}$$

where $w \in \Re^6$ is the external load wrench applied to the object, $\lambda \in \Re^{n_c}$ is the contact force vector, $G \in \Re^{6\times n_c}$ is the grasp matrix. For a complete definition of the grasp matrix G, the reader is referred to [17]. The grasp matrix transpose relates velocities $\dot{p}$ of the contact points on the object to the object twist $\nu^o = [\dot{o}^{\mathrm{T}} \;\; \omega^{\mathrm{T}}]^{\mathrm{T}}$:

$$\dot{p} = G^{\mathrm{T}}\nu^o. \tag{2}$$

Solving eq. (1) for the contact forces introduces the definition of *internal forces*, i.e. the contact forces included in the nullspace of matrix G. Internal forces play a key role in grasp control: in force-closure grasps, a convenient control of internal forces guarantees that the whole vector of contact forces complies with contact friction constraints notwithstanding disturbances acting on the manipulated object. Not all the internal forces can be arbitrarily controlled by the hand, in order to define the subset of controllable internal forces the hand actuation has to be considered. The relationship between hand joint torques $\tau \in \Re^{n_q}$, where n_q is the number of actuated joints, and contact forces is:

$$\tau = J^{\mathrm{T}}\lambda \tag{3}$$

where $J \in \Re^{n_c \times nq}$ is the hand Jacobian matrix. The hand Jacobian relates the contact point velocities to the joint velocities $\dot{q}$:

$$\dot{p} = J\dot{q}. \tag{4}$$

For further details on its definition and computation, the reader is referred to [17]. We observe that in general the problem is not invertible and thus the contact forces λ cannot be arbitrarily controlled acting on joint torques τ.

We suppose that the hand is actuated using a number of inputs whose dimension is lower than the number of hand joints. These inputs are then collected in a vector $z \in \Re^{n_z}$ and parameterize the hand motions along the synergies.

In this paper we define the postural synergies as a joint displacement aggregation corresponding to a reduced dimension representation of hand movements according to a compliant model of joint torques. In other terms, the reference vector $q_{ref} \in \Re^{n_q}$ for joint variables is a linear combination of postural synergies $z \in \Re^{n_z}$ with $n_z \leq n_q$

$$q_{ref} = Sz \tag{5}$$

through the *synergy matrix* $S \in \Re^{n_q \times n_z}$, whose columns describes the shapes, or directions, of each synergy in the joint space.

This approach differs from other works, like for example those described in [2], [3], where the synergies are considered perfectly stiff and the *actual* joint variables are a linear combination of synergies. The problem of computing internal force distribution and object movements that can be controlled acting on synergies has been studied in [16].

In the following section a mapping procedure between the synergies of a *paradigmatic* human hand and a *robotic* hand will be presented. This procedure is based on a kinematic approach, without the need of a real grasp model, and consequently without using contact forces. The direct consequence of this kinematic approach is that there will be no difference between *reference* and *actual* joint variables and thus eq. (5) will be used in the form $q = Sz$ for both human and robotic hands.

IV. Description of the Mapping Method

The objective of this study is to define a way to map a set of synergies defined on a reference human hand, henceforth the paradigmatic hand, onto a generic robotic hand with a dissimilar kinematic structure. We have focused on kinematic analysis considering recent works on synergies for human hands as discussed in Section I. For this reason the paradigmatic hand mimics the human hand with postural synergies. The kinematic analysis of the paradigmatic hand with postural synergies is reported in [7] and is here briefly summarized.

The hand fingers are modelled as kinematic chains sharing their origin in the hand wrist. Fig. 3 shows a scheme of bones linkage. The bone lengths have been chosen according to the anatomy of the real hand skeleton [11]. The *metacarpophalangeal* (MCP) joint of the index, middle, ring and pinky fingers have two DoFs each (one for adduction/abduction and another flexion/extension). The *proximal interphalangeal* (PIP) and *distal interphalangeal* (DIP) joints of the other fingers have one DoF each. The thumb has 4 DoF: 2 DoF

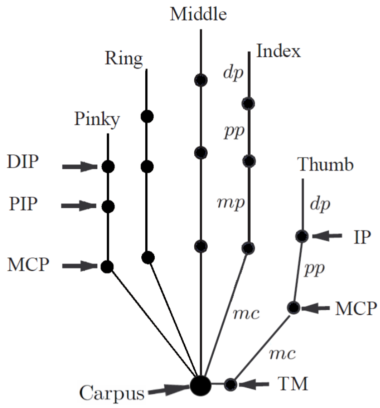

Fig. 3. Scheme of the *paradigmatic* hand highlighting the joints and the links.

in *trapeziometacarpal* (TM) joint, 1 DoF in *metacarpophalangeal* (MP) joint, and 1 DoF in *interphalangeal* (IP) joint.

Let the paradigmatic hand be described by the joint variable vector $q_h \in \Re^{n_{qh}}$ and 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. In terms of velocities one gets

$$\dot{q}_h = S_h \dot{z}. \tag{6}$$

The ultimate goal of this work is to find a way of controlling the reference joint variables $\dot{q}_r \in \Re^{n_{qr}}$ of the robotic hand in a synergistic way using the vector of synergies z of the paradigmatic hand. In other terms we want to design a map S_r to steer the robotic joint reference variables as follows

$$\dot{q}_r = S_r \dot{z} \tag{7}$$

where map S_r depends on synergy matrix S_h and other variables as explained in the following.

To the best of our knowledge all previous synergy mapping strategies [3], [8] do not explicitly take into account the task to be performed by the robotic hand. In this work, we propose a method of projecting synergies from paradigmatic to robotic hands which explicitly takes into account the task space.

One of the main advantages of designing a mapping strategy in the task space is that results can be used for robotic hands with very dissimilar kinematics. The idea is to replicate the task performed with the paradigmatic hand using the robotic hand with projected synergies.

To define the mapping we assume that both the paradigmatic and the robotic hands are in given configurations q_{0h} and q_{0r}.

Given the configuration q_{0h}, 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. In this work we will chose the fingertip points as reference points. It is worth noting that reference points can also be arbitrary considered on the palm or on the links of the hand according to the task to be performed. The virtual sphere object is then computed as the minimum sphere containing the reference points in p_h. Note that these points in general do not lie on the sphere surface. Let us parameterize the virtual sphere by its center o_h and radius r_h. The motion imposed to the hand reference points moves the sphere and changes its radius.

The motion of the hand due to synergies could be described using a large set of parameters, in this paper 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. Let $\dot{r}$ be the radius derivative that the sphere would have if its radius length was one.

Although, the virtual sphere does not represent an object grasped by the paradigmatic hand, it can be easily shown that with a suitable model of joint compliance and contact compliance, the rigid-body motion of the virtual sphere corresponds to the motion of a grasped spherical object and that the non-rigid motion accounts for the normal components of the contact forces for a spherical object grasp.

Having represented the motion of the hand trough the virtual object, the motion of the generic reference point p_{ih} can be expressed as

$$\dot{p}_{ih} = \dot{o}_h + \omega_h \times (p_{ih} - o_h) + \dot{r}_h (p_{ih} - o_h) \quad (8)$$

Grouping all the reference point motions one gets

$$\dot{p}_h = A_h \begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix}, \quad (9)$$

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

$$A_h = \begin{bmatrix} I & -S(p_{1h} - o_h) & (p_{1h} - o_h) \\ \cdots & \cdots & \cdots \\ I & -S(p_{ih} - o_h) & (p_{ih} - o_h) \\ \cdots & \cdots & \cdots \end{bmatrix} \quad (10)$$

Matrix A_h depends on the type of motion that we decide to reproduce on the robotic hand and then it depends on the task. From (4), (6) and (9) we can *evaluate* the virtual sphere motion and deformation as a function of the synergy vector velocity $\dot{z}$ of the paradigmatic hand

$$\begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix} = A_h^{\#} \dot{p}_h = A_h^{\#} J_h S_h \dot{z}, \quad (11)$$

where $A_h^{\#}$ denote the pseudo-inverse of matrix A_h. We now need to map these motions and deformations on the robotic hand. The robotic hand is in a given configuration $q_{0r} \in \Re^{n_{qr}}$ with resulting reference point location vector $p_r \in \Re^{n_{cr}}$. Note that no hypothesis were imposed on the number of reference points on the paradigmatic human and robotic hands, in general we can consider $n_{ch} \neq n_{cr}$, neither on their locations, and neither on the initial configuration of the two hands. The same use of the virtual sphere is applied here: find the minimum sphere enclosing the reference points and indicate with o_r its center coordinates and with r_r its radius. Let us thus define the *virtual object scaling factor* as the ratio between the sphere radii $k_{sc} = \frac{r_r}{r_h}$. This factor is necessary to scale the velocities from the paradigmatic to the robotic hand wokspaces. Note that the scaling factor depends on the hand dimensions, but also on their configuration.

Then, the motion and deformation of the virtual sphere generated by the paradigmatic hand are scaled and tracked by the virtual sphere referred to the robotic hand:

$$\begin{bmatrix} \dot{o}_r \\ \omega_r \\ \dot{r}_r \end{bmatrix} = K_c \begin{bmatrix} \dot{o}_h \\ \omega_h \\ \dot{r}_h \end{bmatrix} \quad (12)$$

where the scale matrix $K_c \in \Re^{7 \times 7}$ is defined as:

$$K_c = \begin{bmatrix} k_{sc} I_{3,3} & 0_{3,3} & 0_{3,1} \\ 0_{3,3} & I_{3,3} & 0_{3,1} \\ 0_{1,3} & 0_{1,3} & 1 \end{bmatrix} \quad (13)$$

According to eq. (9) and (10), the corresponding robot reference point velocity is given by

$$\dot{p}_r = A_r \begin{bmatrix} \dot{o}_r \\ \omega_r \\ \dot{r}_r \end{bmatrix}, \quad (14)$$

where matrix $A_r \in \Re^{n_{cr} \times 7}$ is defined as follows:

$$A_r = \begin{bmatrix} I & -S(p_{1r} - o_r) & (p_{1r} - o_r) \\ \cdots & \cdots & \cdots \\ I & -S(p_{ir} - o_r) & (p_{ir} - o_r) \\ \cdots & \cdots & \cdots \end{bmatrix} \quad (15)$$

Recalling eq. (11) and (12) we can express the robotic hand reference point velocities $\dot{p}_r$ as a function of the synergy velocities $\dot{z}$:

$$\dot{p}_r = A_r K_c A_h^{\#} J_h S_h \dot{z} \quad (16)$$

and, considering the robot hand differential kinematics $\dot{p}_r = J_r \dot{q}_r$, where $J_r \in \Re^{n_{cr} \times n_{qr}}$ is its Jacobian matrix, the following relationship between robot hand joint velocities and synergy velocities is defined:

$$\dot{q}_r = J_r^{\#} A_r K_c A_h^{\#} J_h S_h \dot{z} \quad (17)$$

Then the synergy mapping S_r in (7) for the robotic hand is defined as

$$S_r = J_r^{\#} A_r K_c A_h^{\#} J_h S_h \quad (18)$$

Remark 1: The paradigmatic hand synergy matrix S_h is mapped to the synergy matrix for the robotic hand S_r through matrix $J_r^{\#} A_r S_c A_h^{\#} J_h$ which is function of

- paradigmatic and robotic hand configurations q_{0h} and q_{rh}
- location of the reference points for the paradigmatic and robotic hands, p_h and p_r.

The proposed method then allows to define a *non-linear* mapping between the paradigmatic human-like hand and the robotic hand. The obtained synergy matrix is not constant and depends on hands configurations.

V. Simulations

A. Performance analysis

The proposed mapping of synergies between hand with dissimilar kinematics was validated on a fully-actuated three fingered robotic hand. In order to validate the mapping algorithm, joint-to-joint mapping [4] and the fingertip-mapping [15] methods were compared with the proposed algorithm. The grasp of two different objects is considered: a sphere and a cube. Algorithm performances are evaluated comparing the grasp quality and the motion of the grasped objects. Grasp quality evaluation was performed using both qualitative and quantitative metrics in order to evaluate the force-closure properties of the grasp as described in [1]. The qualitative metric returns a boolean value that shows if the obtained grasp is *force-closure*. The quantitative aspect of the grasp quality is expressed using a penalty function. The resulting index represents the inverse of the *distance* of the grasp from violating contact constraints. All details of the used indexes can be found in [1].

In the first simulation, the spherical object is considered. The paradigmatic and the robotic hands have the following reference joint configurations (rad), according to the Denavit-Hartenberg notation:

$$q_{0h} = \begin{bmatrix} -0.43 \\ 0.47 \\ -0.09 \\ 1.76 \\ 0.22 \\ 0.50 \\ 1.06 \\ 0.71 \\ 0 \\ 0.59 \\ 1.27 \\ 0.85 \\ -0.31 \\ 0.84 \\ 1.15 \\ 0.77 \\ -0.57 \\ 1.06 \\ 0.45 \\ 0.30 \end{bmatrix} \quad q_{0r} = \begin{bmatrix} 0.80 \\ 1.50 \\ 1.80 \\ 0.80 \\ 1.20 \\ -1.80 \\ 0.80 \\ 1.20 \end{bmatrix}$$

The reference points for the human and robotic hand are chosen on their fingertips, three for the robotic hand and five for the paradigmatic human-like hand (mm):

$$\begin{bmatrix} p_{1h} & p_{2h} & p_{3h} & p_{4h} & p_{5h} \end{bmatrix} = \begin{bmatrix} -26.45 & -23.84 & -8.00 & 3.81 & 25.79 \\ 77.45 & 68.79 & 51.78 & 48.03 & 75.45 \\ -24.15 & -56.30 & -45.27 & -35.95 & -60.59 \end{bmatrix}$$

$$\begin{bmatrix} p_{1r} & p_{2r} & p_{3r} \end{bmatrix} = \begin{bmatrix} -37.00 & -74.63 & 0.63 \\ 23.48 & 126.80 & 126.80 \\ -73.15 & -81.33 & -81.33 \end{bmatrix}$$

These vectors are expressed with respect to a reference frame fixed at the wrist of the robotic and paradigmatic hands.

For these joint configurations and reference points, the first three synergies for the paradigmatic human-like hand are [7], [18]

$$S_{h,1-3} = \begin{bmatrix} -0.18 & 0.13 & 0.08 \\ 0.23 & 0.23 & 0.05 \\ -0.06 & 0.07 & 0.04 \\ -0.26 & 0.07 & -0.02 \\ -0.19 & -0.07 & 0.31 \\ 0.32 & 0.23 & 0.03 \\ 0.21 & -0.22 & -0.20 \\ 0.14 & -0.15 & -0.13 \\ 0 & 0 & 0 \\ 0.37 & 0.32 & 0.28 \\ 0.31 & -0.17 & -0.19 \\ 0.21 & -0.11 & -0.13 \\ 0.14 & 0.14 & -0.17 \\ 0.34 & 0.37 & 0.44 \\ 0.43 & -0.26 & -0.26 \\ 0.29 & 0.78 & -0.74 \\ 0.24 & -0.17 & -0.17 \\ -0.12 & -0.15 & 0.31 \\ -0.08 & -0.10 & 0.20 \end{bmatrix}$$

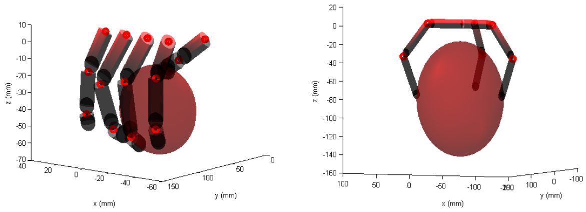

Fig. 4. The human-like hand (left) and the robotic hand (right) grasping a sphere with three contacts.

It maps onto the first three columns of the synergy matrix S_r for the robotic hand (eq. 18):

$$S_{r,1-3} = \begin{bmatrix} -0.59 & 0.00 & -0.23 \\ 1.16 & -0.03 & -0.10 \\ -0.34 & -0.28 & 0.03 \\ 0.93 & 0.34 & 0.03 \\ -1.00 & -0.69 & -0.16 \\ -0.01 & -0.28 & 0.24 \\ 0.97 & 0.17 & 0.01 \\ -1.07 & -0.33 & -0.01 \end{bmatrix}$$

It is worth highlighting that the map S_r is not a constant map and that the value reported above is the map evaluated at this given configuration.

The resulting synergy mapping on the robotic hand has been tested in a grasping configuration similar to those imagined to design the mapping. In particular the robotic hand is assumed to grasp the sphere with contacts at the fingertips which in this case correspond to the reference points of the mapping.

Note that choosing reference points as contact points is not mandatory but it is highly recommended when possible.

To test the validity of the mapping we compared the grasp quality and the object motion between the robotic hand grasping a sphere and the paradigmatic hand grasping a sphere with the fingertips of the thumb, index and ring fingers. The *paradigmatic* and robot hand grasps that were analysed are shown in Fig. 4

The obtained results are summarized in the first two columns of table I. Each row corresponds to the case of controlling hands with one synergy or combinations of synergies. This analysis was carried out considering the first three synergies and their combinations. Values of the synergy activation were obtained as result of an optimization problem that computes the best activation vector in terms of force-closure properties, given the grasp configuration.

The second column shows the grasp quality indexes for the human-like hand controlled with synergies, while the third one reports those of the robotic hand controlled with the synergies obtained with the proposed virtual-sphere mapping. The fourth and the fifth columns refer to the joint-to-joint mapping and to the fingertip mapping [4], [15].

The performance is expressed by a couple of values x/y where x is the value of the cost function measuring the grasp quality (lower values are better) while y is 1 or 0 if the grasp is force closure or not, respectively.

The same quality indexes were evaluated considering the grasp of a different shape object: a cube, the obtained results

TABLE I
GRASP QUALITY EVALUATION FOR THE SPHERICAL OBJECT

Synergies	Human H	Virtual Sphere	Joint-to-joint	Fingertip
Syn 1	0.2/1	0.12/1	26.48/1	0.37/1
Syn 2	−/0	−/0	0.09/1	−/0
Syn 3	−/0	0.36/1	−/0	−/0
Syn [1-2]	0.14/1	0.08/1	0.09/1	0.11/1
Syn [1-3]	0.09/1	0.08/1	0.08/1	0.07/1

are summarized in table II.

TABLE II
GRASP QUALITY EVALUATION FOR THE CUBIC OBJECT

Synergies	Human H	Virtual Sphere	Joint-to-joint	Fingertip
Syn 1	0.2/1	0.12/1	26.48/1	−/0
Syn 2	−/0	−/0	0.10/1	−/0
Syn 3	−/0	0.37/1	−/0	−/0
Syn [1-2]	0.20/1	0.08/1	0.09/1	−/0
Syn [1-3]	0.14/1	0.08/1	0.08/1	0.08/1

In both cases, when only the first synergy is considered, the joint-to-joint approach achieves a force-closure grasp but it exhibits a very high value of the cost function when compared to the virtual sphere mapping proposed in this paper.

Concerning the fingertip mapping, we observe that it reaches satisfying performances in the case of sphere manipulation, but with the cubic object it guarantees force closure when a combination of the three synergies is considered.

We can conclude that, concerning the grasp quality index, the virtual-sphere mapping for both the spherical and cubic objects gets closer to the human-like grasp behaviour in all cases.

Then we analyzed the object motion obtained controlling the robotic hand with mapped synergies according to the three above described methods. Object *rigid-body* motion was considered in our simulations, it was evaluated according to [16]. The performance index in this case was evaluated as the angle between motion directions obtained by the human and the robotic hands controlled with the three different mappings. In this case the hands are controlled using the first four synergies, otherwise, according to the results presented in [16], no objet rigid-body motion is possible neither for the paradigmatic, nor for the driven hands. Tables III and IV show the results for linear and rotational components of the object velocities.

TABLE III
LINEAR VELOCITY ANGLE COMPARISON

Object	Virtual Sphere	Joint-to-joint	Fingertip
Sphere	33.66	118.29	131.92
Cube	32.32	126.05	132.82

TABLE IV
ROTATIONAL VELOCITY ANGLE COMPARISON

Object	Virtual Sphere	Joint-to-joint	Fingertip
Sphere	45.01	80.88	76.53
Cube	44.49	89.30	83.98

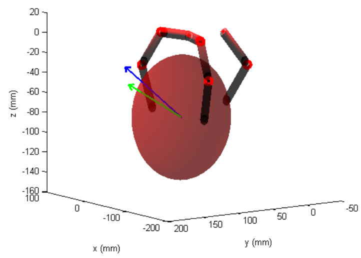

Fig. 5. The motion performance of the virtual sphere mapping

We observe that the virtual sphere method achieves the best performances in terms of controllable object motions. In Figure 5 the result obtained by our mapping, in the sphere manipulation task, is shown. The blue vector represents the motion direction obtained by the paradigmatic hand (desired direction) while the green one represents the direction obtained controlling the robotic grasp with the virtual sphere mapping.

In the case of spherical object we performed also a sensitivity analysis. As previously discussed, the mapping function defined in eq. (18) depends on joint variables of both the human and the robotic hand. Preliminary results on sensitivity show that changes on matrix S_r are not disregardable thus suggesting that this method needs an on line implementation.

VI. DISCUSSION

Robotic hands usually have very dissimilar kinematics (in terms of number of fingers, number and type of joints, etc.), and actuation systems (tendons, mechanical linkages, direct joint actuation etc.), and then their control system has to be very customized.

The proposed mapping strategy, based on mimicking behavior of human hand synergies, could be the basis of an interface between a higher level control, that defines the synergy reference values z, and the robotic hand. The high level can be thought as independent from the robotic hand structure (Fig. 6). The interface, based on the proposed mapping strategy, represents the low level control stage whereby the input synergies are translated into reference joint values which actually control the robotic hand.

The main advantage of this approach is that the high level control is substantially independent from the robotic hand and depends only on the specific operation to be performed. It could then be possible, for example, to use the same controller with different robotic hands, or simply substitute a

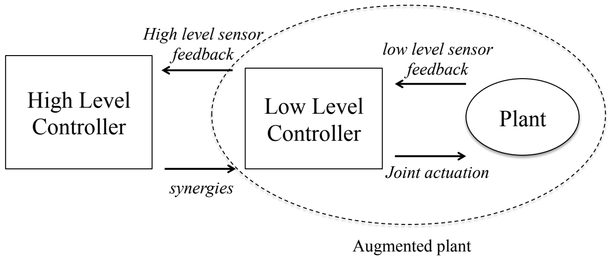

Fig. 6. Two stage controller for a robotic hand: the high level stage is low dimensional and independent from the controlled device, the low level transforms the synergy inputs into joint reference values.

device without changing the controller, thus realizing a sort of abstraction layer for robotic hand control based on postural synergies. Furthermore, the proposed virtual-sphere mapping focuses on the task to be performed rather than replicating the human hand motion at the fingertips or joint-by-joint.

This mapping has been tested in manipulation tasks. Work is in progress to validate the virtual-sphere mapping also for the approaching phase of grasps.

Simulation results are very interesting in terms of performances as shown in the previous section. However this approach presents some drawbacks.

The proposed mapping is based on a heuristic approach: we choose to reproduce a part of the hand motion, which practically corresponds to move and squeeze a spherical object. Although squeezing and moving an object explains a wide range of tasks, many other possibilities exist in manipulating objects which are not modeled with this mapping. Work is in progress to generalize the proposed method enriching the possible motions to be reproduced.

Differently from the joint-to-joint mapping, with respect to which the proposed method gets better performances, here S_r is not a constant matrix but it depends on both the human and robotic hand configurations and by the reference position points of the human and robotic hands which should be given in this work.

For a given object to grasp, different grasping planning algorithms [3] can be used to choose the contact points and the hand configurations to be used as parameters of the virtual-sphere mapping.

VII. Conclusion and Future Work

Designing synergy-based control strategies in the paradigmatic hand domain can dramatically reduce the dimensionality of the grasping and manipulation problems for robotic hands. However, an efficient mapping is needed to deal with robotic hands with dissimilar kinematics. We proposed a method for mapping synergy matrices that using a virtual object allows to specify the mappings directly in the task space thus avoiding the problem of dissimilar kinematics between human-like hand and robotic hands. We compared our solution to the most used solutions existing in literature and we evinced that the proposed method is more efficient in terms of mapped grasp quality and direction of motion. Our preliminary results seem to be very promising on a fully-actuated three fingered robotic hand. Further investigation on different robotic hands have been already planned. One of the main issue of our approach is that the mapping is not linear and that its implementation could a high computational burden. The ongoing research is evaluating the conditions whereby some simplification can be applied to get constant or slowly varying mapping. As future work, moreover, an integration with grasping simulator like Grasp-it! [13] is expected in order to use its grasp planner to determine initial position of the human and the robotic hand.

A synergy based mapping approach can be useful also in uncertain conditions. The human hand synergies are able to adapt to a wide range of tasks, and to work in uncertain environments, with an almost infinitely wide set of objects. The synergies are defined to synthesize the common components of all these tasks and then they represent an optimal tradeoff between simplicity and versatility. A synergy based mapping can take advantage of these properties and consequently can result to be a robust control solution also when the environment conditions and/or the planned tasks are uncertain.

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References

[1] A. Bicchi. On the closure properties of robotic grasping. *The Int. J. of Robotics Research*, 14(4):319–334, 1995.

[2] C.Y. Brown and H.H. Asada. Inter-finger coordination and postural synergies in robot hands via mechanical implementation of principal components analysis. In *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, pages 2877–2882. IEEE, 2007.

[3] M. Ciocarlie, C. Goldfeder, and P. Allen. Dimensionality reduction for hand-independent dexterous robotic grasping. In *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, pages 3270–3275, 2007.

[4] M. T. Ciocarlie and P. K. Allen. Hand posture subspaces for dexterous robotic grasping. *The International Journal of Robotics Research*, 28(7):851–867, July 2009.

[5] S. Ekvall and D. Kragic. Interactive grasp learning based on human demonstration. In *Robotics and Automation, 2004. Proceedings. ICRA '04. 2004 IEEE International Conference on*, volume 4, pages 3519–3524, May 2004.

[6] M. Fischer, P. Van der Smagt, and G. Hirzinger. Learning techniques in a dataglove based telemanipulation system for the dlr hand. In *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, volume 2, pages 1603–1608, May 1998.

[7] M. Gabiccini and A. Bicchi. On the Role of Hand Synergies in the Optimal Choice of Grasping Forces. In *Proceedings of Robotics: Science and Systems*, Zaragoza, Spain, June 2010.

[8] T. Geng, M. Lee, and M. Hulse. Transferring human grasping synergies to a robot. *Mechatronics*, 21(1):272 – 284, 2011.

[9] W.B. Griffin, R.P. Findley, M.L. Turner, and M.R. Cutkosky. Calibration and mapping of a human hand for dexterous telemanipulation. In *ASME IMECE 2000 Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, pages 1–8, 2000.

[10] S. B. Kang and K. Ikeuchi. Robot task programming by human demonstration: mapping human grasps to manipulator grasps. In *Intelligent Robots and Systems '94. 'Advanced Robotic Systems and the Real World', IROS '94. Proceedings of the IEEE/RSJ/GI International Conference on*, volume 1, pages 97–104, September 1994.

[11] K. Kim, Y. Youm, and WK Chung. Human kinematic factor for haptic manipulation: The wrist to thumb. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002. Proceedings. 10th Symposium on*, pages 319–326, 2002.

[12] J. Liu and Y. Zhang. Mapping human hand motion to dexterous robotic hand. *2007 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 829–834, December 2007.

[13] A.T. Miller and P.K. Allen. Graspit! a versatile simulator for robotic grasping. *Robotics & Automation Magazine, IEEE*, 11(4):110–122, 2005.

[14] R.M. Murray, Z. Li, and S.S. Sastry. *A mathematical introduction to robotic manipulation*. CRC, 1994.

[15] A. Peer, S. Einenkel, and M. Buss. Multi-fingered telemanipulation - mapping of a human hand to a three finger gripper. In *Robot and Human Interactive Communication, 2008. RO-MAN 2008. The 17th IEEE International Symposium on*, pages 465–470, August 2008.

[16] D. Prattichizzo, M. Malvezzi, and A. Bicchi. On motion and force controllability of grasping hands with postural synergies. In *Proceedings of Robotics: Science and Systems*, Zaragoza, Spain, June 2010.

[17] D. Prattichizzo and J. Trinkle. Grasping. In B. Siciliano and O. Kathib, editors, *Handbook on Robotics*, pages 671–700. Springer, 2008.

[18] M. Santello, M. Flanders, and J.F. Soechting. Postural hand synergies for tool use. *The Journal of Neuroscience*, 18(23):10105–10115, December 1998.