

Experimental evaluation of Postural Synergies during Reach to Grasp with the UB Hand IV

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Abstract—In this paper, the postural synergies configuration subspace given by the fundamental eigengrasps of the UB Hand IV (University of Bologna Hand, version IV) is derived through experiments. This study is based on the kinematic structure of the robotic hand and on the taxonomy of the grasps of common objects. Experimental results show that it is possible to obtain grasp synthesis for a large set of objects both in the case of precision or power grasps by using only a very limited set of dominant eigengrasps. The tasks here presented are planned with an initial hold of the hand followed by reach and grasp phases, that are unique for each object/grasp combination, during which the robotic hand posture evolves continuously within a subset of the hand configuration space given by the two predominant eigenpostures. The paper reports the method adopted to define from experiments the postural synergies for the UB Hand IV and the results of the grasp tasks performed adopting the defined synergies.

I. INTRODUCTION

One of the greatest challenges of humanoid robotics is to provide robotic systems with autonomous and dextrous skills. Since the next generation of robots will interact with people directly, the robot of the future must be thought of heaving human excellence. Therefore, the interest on replicating the human manipulation abilities is growing among researchers.

To reproduce human-like grasping and manipulation abilities, complex dextrous hands with advanced sensorimotor skills and human-like kinematics are needed. Moreover, the implementation of control algorithms for anthropomorphic robotic hands able to reproduce human-like manipulation abilities is actually an hard problem. Therefore, the research is going towards the reproduction of human grasping capabilities not only by means of anthropomorphic design but also by adopting human-inspired control strategies.

The studies on grasp taxonomy carried out by scientists as Napier [1], Cutkosky [2] and Iberall [3] aim to define which fingers (and which parts of the fingers) are used by humans to generate forces on the grasped object. According to this criterion, the hand configuration during grasp operations can be decomposed in a limited set of basic postures. Nevertheless, recent advances in neuroscience have shown

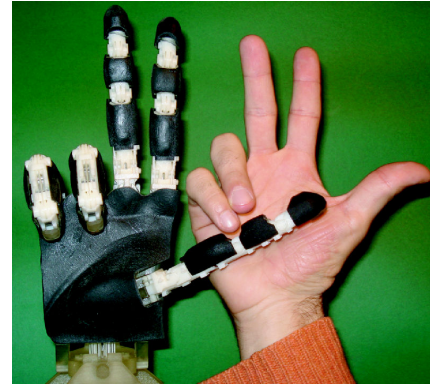


Fig. 1. The UB Hand IV prototype.

that the control of human hand during grasp is dominated by movements in a continuous configuration space of highly reduced dimensionality with respect to number of degrees of freedom of the human hand. In [4] the principal component analysis (PCA) has been used to calculate the postural synergies from real-world data collected on a variety of human hand postures. Moreover, the authors show that a wide set of hand postures during grasp operations evolves continuously within a linear space spanned by few postural synergies that account for most of the hand configurations variance, without distinguishing between power and precision grasps. The combination of tendon coupling and muscle activation patterns exhibited by humans lead to significant joint coupling and inter-finger coordination, or, in other words, to postural synergies, that are evidence of simplified control schemes occurring at neurological level for the organization of the hand movements.

In [5] it is shown that even if higher principal components account for a small percentage of the variance, they give critical details not only for the static grasp when the hand adapts to the object shape, but also for the act of preshaping during the grasp. In [6], [7], [8] the authors extend the concept of postural synergies to robotic hands showing how a similar dimensionality reduction can be used to derive comprehensive planning and controlling algorithms that produce stable grasps for a number of different complex hand models. Other applications has been made in order to simplify the design and the analysis of robotic hand structures [9]. In [10] the authors investigate how the number and types of synergies are related to the possibility of controlling the contact forces and the object motion in grasping and manipulation tasks. In [11], using the definition of force-closure for underactuated

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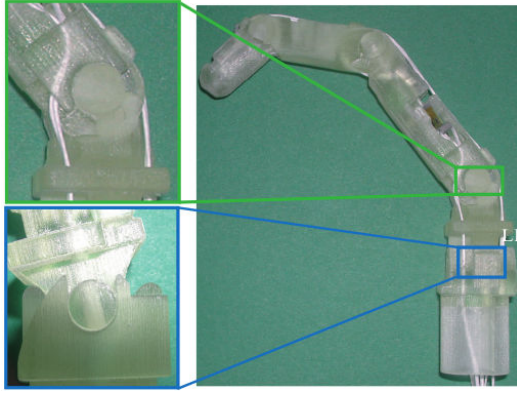


Fig. 2. UB Hand IV finger with pin joints integrated into the phalanx.

hands and the definition of grasping force optimization, the authors investigate the role of different postural synergies in the ability of obtaining force closure grasps and in the quality of the grasps in two case study addressing a precision and a power grasp.

In this paper, the two fundamental eigengrasps for the UB Hand IV have been derived by taking into account a set of 36 hand grasps of different objects, considering both precision and power grasps, and by applying PCA. Experimental results show that the control of the UB Hand IV configuration performed by using the first two postural synergies allows not only to reproduce with a good level of fidelity the set of postures adopted to derive the eigengrasps, but also to perform a very wide set of both precision or power grasps of common objects with different shapes and dimensions. By means of a suitable tuning of the two eigenpostures weight, the hand is controlled continuously during reach to grasp in human-like way in a configuration space of highly reduced dimensions with respect to the degrees of freedom of the robotic hand. The paper is organized as follows: in Sec. II the UB Hand IV design characteristics and its kinematics are described; Sec. III provides the description of the method adopted for deriving the hand postural synergies and the temporal weights of the synergies; in Sec. IV experimental results are reported to validate the efficiency of the chosen synergies in realizing grasps of common objects; finally, Sec. V provides conclusions and sketches the future work.

II. THE UB HAND IV MODELLING

An innovative robotic hand, called UB Hand IV (University of Bologna Hand, version IV) [12], has been developed within the DEXMART project [13], see Fig. 1 where the first prototype of this device is shown. Aiming at the maximum design simplification, the following driving issues have been considered during the development of the UB Hand IV:

- Endoskeletal structures articulated by means of pin joints integrated into the phalanx body simply consisting in a plastic shaft which slides on a cylindrical surface, see Fig. 2, have been adopted [14], [15], [12];
- The joints actuation is based on remotely located actuators with tendon-based transmissions routed by sliding

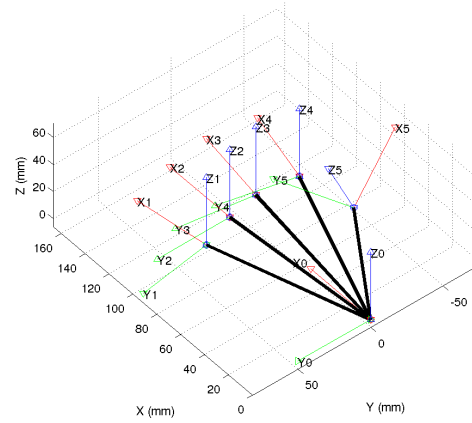


Fig. 3. Positions of the finger base reference frames with respect to the wrist center in the UB Hand IV.

paths (*sliding tendons*) [16], [17];

- Surface compliance is introduced through a purposely designed soft cover mimicking the human skin [18], [19], [20];
- Manufacturing and assembly complexity have been reduced by systematic parts integration adopting proper advanced materials and technologies. (e.g. polymers and additive manufacturing technologies like Fused Deposition Manufacturing or Stereo-Lithography).

As a matter of fact, current technology does not allow to arrange twenty or more actuators in a robot hand with dimensions similar to the human's one and with suitable requirements in terms of speed and forces. For this reason, it is necessary to place the actuators remotely, and use tendons for motion/force transmission. An $N+1$ tendon configuration has been adopted in the UB Hand IV, that means the joints are actuated by a tendon net composed by a number of tendons equal to the number of joints plus one. This tendon configuration allows the use of the minimum number of actuators and, at the same time, to avoid the use of pretension mechanisms. Moreover, this configuration allows both the independent regulation of the joints torques and the regulation of the internal tendon forces. A detailed view of the tendon network of the UB Hand IV is presented in Fig. 4, refer to [21] for a complete description of the UB Hand IV finger kinematics and tendon network characteristics.

The hand controller has been developed in the Matlab/Simulink environment and it is based on the RTAI-Linux realtime operating system, and the Matlab Realtime Workshop toolbox has been used for the automatic generation of the realtime application that implements the UB Hand IV controller. The user interface to the realtime application has been implemented by means of the Simulink External Mode capabilities, for which the RTAI-Linux support has been purposely developed.

The UB Hand IV presents a total amount of 20 DOFs, 4 DOFs for each of the 5 identical fingers. The Denavit-

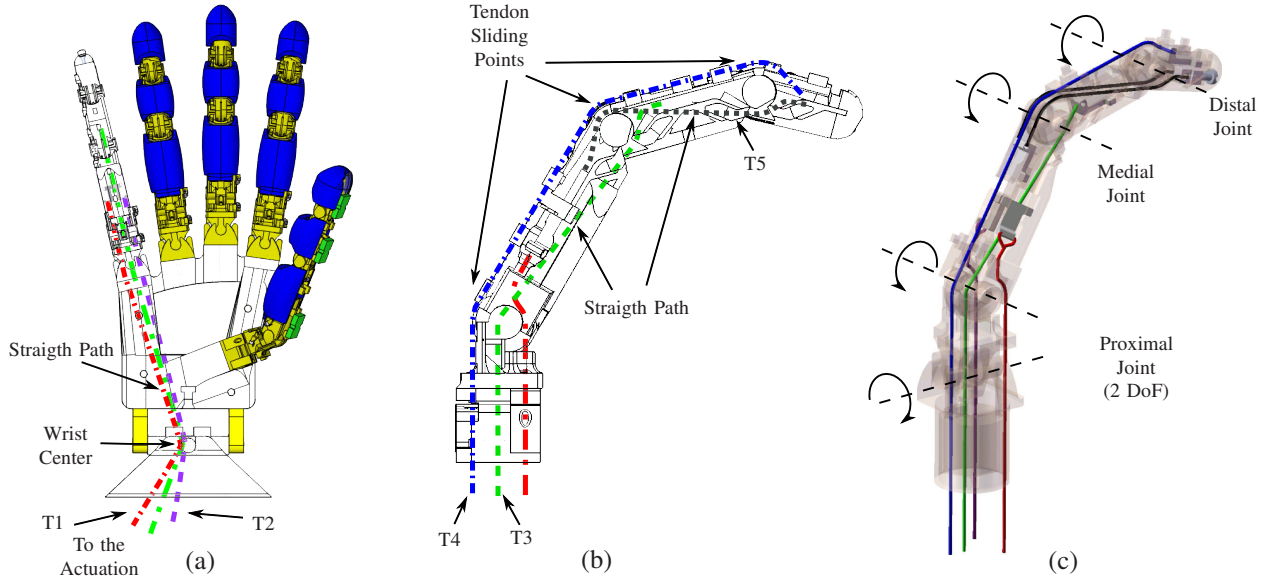


Fig. 4. UB Hand IV: Details of the tendon network.

Hartenberg parameters of each finger are reported in Tab. I. Inspired to the biological model and to reduce the complexity of the hand control, the two last finger's joints, the medial and the distal joint, have been coupled by means of an internal tendon in such a way that $\theta_3 = \theta_4$. For this reason, only three angles for each finger are considered, the base (adduction/abduction) angle θ_1 , the proximal angle θ_2 and the medial angle θ_3 . Then, a total amount of $h = 15$ joint angles are used to represent the robotic hand configuration. The joint angle ranges of each finger are mechanically constrained by stroke limiters to the intervals:

$$\theta_1 \in [-\pi/18, \pi/18], \quad \theta_{\{2,3,4\}} \in [0, \pi/2] \quad [\text{rad}] \quad (1)$$

The locations of the reference frames of each finger base with respect of the center of the wrist are reported in Fig. 3.

III. POSTURAL SYNERGIES OF THE UB HAND IV

Postural synergies describe patterns occurring at the joint displacement level. In [4], the authors measured a set of static human hand postures by recording 15 joint angles and, by means of PCA, they showed that the first two principal components account for $>80\%$ of the hand postures. Thus the use of the principal components, also called postural synergies, holds great potential for robot hands control, implying a substantial reduction of the grasp synthesis problem dimension with respect to the case of considering the entire number of robotic hand DOFs. Drawing inspiration from the studies on the human hand motion, we have found the

Link	d	θ	a [m]	α [rad]
4	0	θ_1	$a_1 = 20.2 \cdot 10^{-3}$	$\pi/2$
5	0	θ_2	$a_2 = 45.0 \cdot 10^{-3}$	0
6	0	θ_3	$a_3 = 29.9 \cdot 10^{-3}$	0
7	0	θ_4	$a_4 = 21.8 \cdot 10^{-3}$	0

TABLE I

DENAVIT-HARTENBERG PARAMETERS OF THE UB HAND IV FINGERS.

two principal components of the UB Hand IV configuration space.

A. PCA Analysis

The UB Hand IV kinematics is quite close to the human's one, therefore, aim at deriving the PCA, a set of grasps similar to the ones in [22] have been considered. The choice of the reference set of postures has been made by taking into account all the most common human grasps considered in the grasp taxonomy literature [2]. This set is composed by grasps of objects such as spheres of different dimensions involving different number of fingers in both power and precise grasp configuration. Cylindrical grasps has been considered as well, distinguishing also between different positions of the thumb. Moreover, several configurations for precise grasps with index and thumb opposition as well as grasps with lateral opposition of the thumb have been included. A total amount of $n = 36$ hand configurations, have been evaluated to derive the fundamental eigenpostures. Each grasp configuration of the postures reference set has been experimentally reproduced with UB Hand IV as close as possible to a natural human-like grasps, and the vector $\mathbf{c}_h^i$ of the joint angle values corresponding to each reproduced grasp has been measured. Once the set of UB Hand IV configurations matrix $\mathbf{C} = \{\mathbf{c}_h^i \mid i = 1 \dots n\}$ has been built, the vector $\bar{\mathbf{c}}_h$ representing the mean hand position in the grasp configurations space and the matrix $\mathbf{F} = \{\mathbf{c}_h^i - \bar{\mathbf{c}}_h \mid i = 1 \dots n\}$ of the grasp offsets with respect to the mean configuration have been computed. The PCA has been then performed on $\mathbf{F}$ and the base matrix $\mathbf{E}$ of the postural synergies has been found. The PCA can be performed by diagonalizing the covariance matrix of $\mathbf{F}$ as:

$$\mathbf{F} \mathbf{F}^T = \mathbf{E} \mathbf{S}^2 \mathbf{E}^T. \quad (2)$$

The $h \times h$ orthonormal matrix $\mathbf{E}$ gives the directions of variance of the data, and the diagonal matrix $\mathbf{S}^2$ is the variance in each direction sorted in decreasing magnitude.

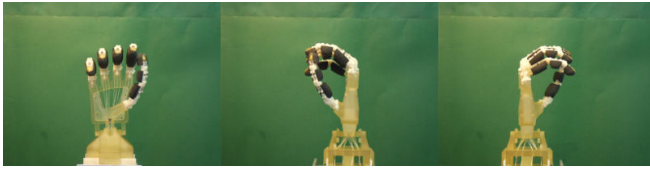


Fig. 5. Zero-offset configuration $\bar{\mathbf{c}}_h$ of the UB Hand IV.

Since the first two principal components account for $>80\%$ of the postures, the posture matrix $\mathbf{C}$ can be reconstructed with reasonable accuracy by adopting the matrix

$$\hat{\mathbf{E}} = [\mathbf{e}_1 \ \mathbf{e}_2] \quad (3)$$

composed by the first two principal components of $\mathbf{E}$ as a base of the robotic hand configuration space, thus allowing the control of the robotic hand motion in a configuration space of highly reduced dimensions with respect to the degrees of freedom of the hand itself.

In the following, the two fundamental synergies derived for the UB Hand IV, i.e. the robotic hand motions spanned by $\mathbf{e}_1$ and $\mathbf{e}_2$ respectively, are briefly described, referring to the minimum and maximum configuration of each synergy as the hand configuration obtained by means of, respectively, the minimum and maximum value of the corresponding synergy weight without violating the joint limits reported in (1). When the weights of the synergies are zero, the hand posture corresponds to the zero-offset position shown in Fig. 5. The vectors of the two eigengrasps and of the zero offset of the UB Hand IV postural synergies subspace are reported in Tab. II.

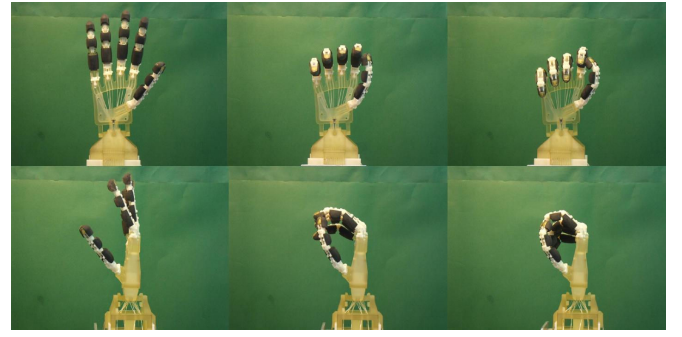
B. First Synergy

With reference to the first postural synergy, in the minimum configuration the proximal and medial flexion joint angles of all the fingers are all almost zero and increase their value during the motion toward the maximum configuration. The abduction/adduction movements are involved in this synergy especially for the thumb, causing the opposition with

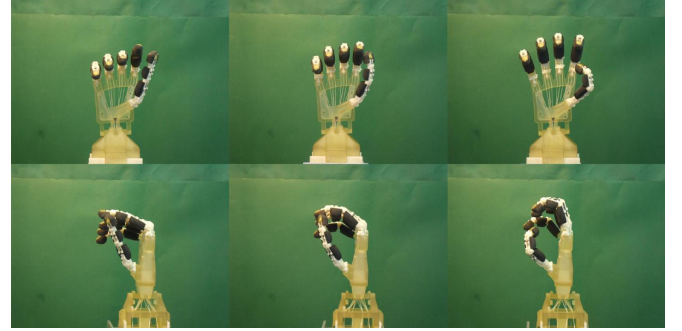
		$\mathbf{e}_1$	$\mathbf{e}_2$	$\bar{\mathbf{c}}_h$
Thumb	adduction/abduction	0.0247	0.0235	-0.833
	proximal	0.0498	0.1873	20.5
	medial	0.2023	-0.3849	34.7
Index	adduction/abduction	-0.0301	-0.0648	2.92
	proximal	0.152	0.2896	34.9
	medial	0.3178	-0.3488	50.5
Middle	adduction/abduction	-0.0419	0.0068	-0.694
	proximal	0.3422	0.3801	41.4
	medial	0.2971	-0.2943	42.2
Ring	adduction/abduction	-0.0352	0.0343	-1.11
	proximal	0.3792	0.3985	45.5
	medial	0.3754	-0.2561	49.2
Little	adduction/abduction	0.0338	-0.0738	0.694
	proximal	0.3905	0.3221	48.7
	medial	0.4292	-0.2016	51.7

TABLE II

FIRST TWO EIGENPOSTURES AND ZERO OFFSET VECTORS OF THE UB HAND IV POSTURAL SYNERGIES SUBSPACE.



(a) First postural synergy.



(b) Second postural synergy.

Fig. 6. Representation of the UB Hand IV postural synergies. On the top of each figure, from left to right, a sequence of hand postures going from the minimum to the maximum configuration, is represented. On the bottom the lateral view are represented.

the index in the closing phase. In Fig. 6(a) the minimum, zero offset and maximum configuration in frontal and lateral view of the first postural synergy are represented.

C. Second Synergy

The second postural synergy is characterized by a movement in opposite directions of the proximal and medial flexion joints during the motion of the hand. In this synergy, the abduction/adduction movements of all the fingers are involved, especially for the index finger. In Fig. 6(b) the most significant configurations of the second postural synergy are depicted in frontal and lateral view.

D. Control with postural synergies

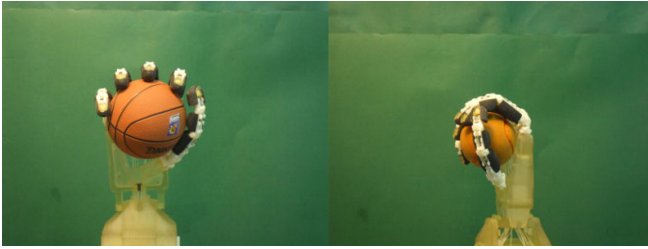
By choosing as a base of the robotic hand configuration space the matrix $\hat{\mathbf{E}}$ composed by the two principal components of $\mathbf{F}$, see eq. (3), each hand grasp postures $\mathbf{c}_h^i$ can be obtained by a suitable selection of the weights of the postural synergies. In order to perform the desired grasp, the value of the two eigenpostures weights $[\alpha_1 \ \alpha_2]^T$ are computed by projection of the desired grasp posture in the synergies subspace:

$$\begin{bmatrix} \alpha_1^i \\ \alpha_2^i \end{bmatrix} = \hat{\mathbf{E}}^\dagger (\mathbf{c}_h^i - \bar{\mathbf{c}}_h) \quad (4)$$

where $\hat{\mathbf{E}}^\dagger$ means the pseudo-inverse of the base matrix $\hat{\mathbf{E}}$. Therefore, the projection $\hat{\mathbf{c}}_h^i$ of each robotic hand configuration $\mathbf{c}_h^i$ on the postural synergies subspace can be evaluated

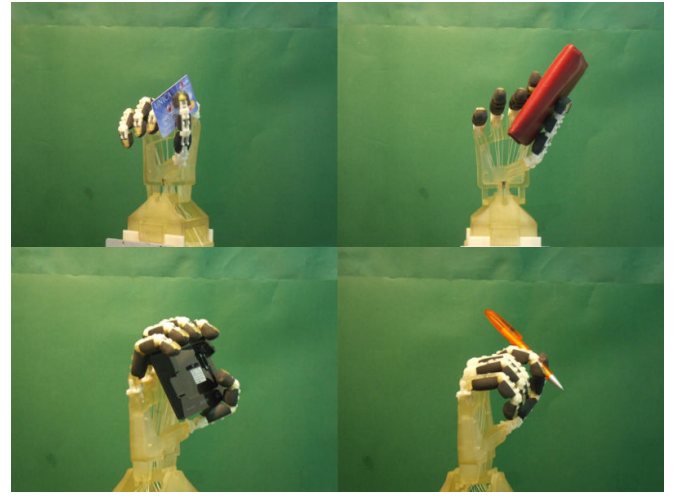


(a) Power grasps of prismatic objects.

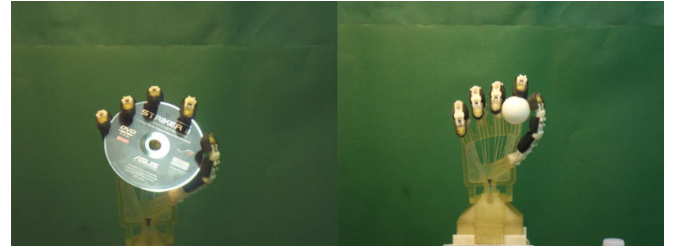


(b) Power grasps of circular objects.

Fig. 7. Experimental evaluation of power grasps.



(a) Precise grasps of prismatic objects.



(b) Precise grasps of circular objects.

Fig. 8. Experimental evaluation of precise grasps.

as:

$$\hat{\mathbf{c}}_h^i = \bar{\mathbf{c}}_h + \hat{\mathbf{E}} \begin{bmatrix} \alpha_1^i \\ \alpha_2^i \end{bmatrix} \quad (5)$$

It is straightforward to note that the motions shown in Fig. 6(a) and 6(b) obtained by considering separately the two synergies are obtained from eq. (5) by assuming $\alpha_2 = 0$ for the first synergy and $\alpha_1 = 0$ for the second one.

The temporal value of the weights α_1 and α_2 during grasp operations are then chosen in such a way that, starting from the zero-offset position $\bar{\mathbf{c}}_h$ (i.e. $\alpha_1 = \alpha_2 = 0$), the hand opens during the reach in preparation for object grasp, and then closes reaching a suitable shape determined from (4) depending on the original grasp configuration $\mathbf{c}_h^i$ for the considered object. In the open-hand configuration, namely $\mathbf{c}_h^0$, all the joint angle values are close to zero, and the corresponding values of α_1 and α_2 can be determined from eq. (4) by posing $\mathbf{c}_h^i = \mathbf{c}_h^0$. The intermediate values of the synergies weights have been determined by assuming a suitable time interval for the grasp operation and by linear interpolation of the α_1 and α_2 values in the three reference configurations $\{\bar{\mathbf{c}}_h, \hat{\mathbf{c}}_h^0, \hat{\mathbf{c}}_h^i\}$.

IV. EXPERIMENTAL EVALUATIONS

In this section, the experimental evaluation of both precise and power grasps performed by using only the two principal hand synergies discussed in the previous section are briefly presented and discussed, see Fig. 7 and 8 where the grasps obtained by means of the postural synergies are depicted.

During the experiments, starting from the zero-offset position, the hand moves continuously in the configuration space and goes in an open grasp configuration in which all the joints reach a value close to zero, then the hand closes more for smaller objects and less for bigger objects, see the video attached to the paper. During the hand opening phase, the temporal weight of the first synergy α_1 goes from zero (zero-offset configuration) to a negative values (toward the minimum configuration of the first synergy), while the weight of the second synergy α_2 goes from zero to negative values (toward the maximum configuration of second synergy). During the closing phase, the weights of the two postural synergies are obtained by linear interpolation from those corresponding to the open hand configuration to suitable values unique for each object and computed using eq. (4).

Experimental results reveal that it is enough to consider the first two postural synergies to control the hand motion in order to perform power grasp of common objects using all the fingers and the palm. The linear combination of the two synergies allows to grasp both cylinders and spheres of different dimensions by means of suitable opposition of the thumb, see Fig. 7(a) and 7(b).

In the case of precise grasps, by choosing suitable weights of the postural synergies, it is possible to perform reach and grasp operations considering different objects, achieving opposition of the thumb and the index as well as tripodal precise grasps for both prismatic and circular objects, as

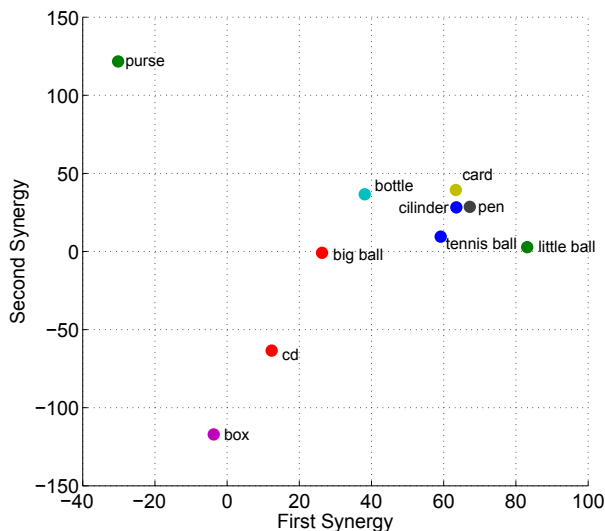


Fig. 9. Distribution of hand postures in the plane of the first two postural synergies.

depicted in Fig. 8(a) and 8(b).

In Fig. 9, the distribution of the synergy weights adopted during the experiments presented in Fig. 7 and 8 for grasping various object is reported in the plane of the two hand synergies. The weights of the first two principal components in the final grasp configuration are shown for each grasped object.

V. CONCLUSIONS AND FUTURE WORKS

In this paper the experimental evaluation of the UB Hand IV postural synergies has been presented, together with the verification of the grasp operations performed by using the computed postural synergies. Using PCA, the UB Hand IV eigenpostures have been found taking into account a suitable set of hand postures, and the two dominant hand synergies have been successfully used to reach and grasp common everyday objects during experiments by a properly choosing their weights. The defined postural synergies have been used not only for computing the hand configuration during the grasp, but also to control the hand motion during the whole pre-grasp and grasp phase.

In the future we intend to integrate the arm control and the hand control with synergies. The goal is to correlate the palm position and orientation with the postural synergy weights in order to coordinate the arm and the open hand movements during the reaching phase. Future work will focus on using also additional eigenpostures for fine manipulation through the integration of the contact force measurements. Force closure tests will be also used to determine the quality of the grasps and to properly choose the optimal weight of the synergies for each grasp and fine manipulation. The principle of postural synergies will be used also to improve the kinematics of UB Hand IV toward increasing its level of anthropomorphism.

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