

A Model-based Strategy for Mapping Human Grasps to Robotic Hands Using Synergies

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Abstract—The aim of this paper is to derive the synergies subspace of an anthropomorphic robotic hand using the human hand as a master. A set of grasping postures performed by five subjects in grasping commonly used objects has been mapped to a robotic hand assuming its own kinematics as a simplified model of the human hand. Using an RGB camera and depth sensor for 3D motion capture, the human hand palm pose and fingertip positions have been measured for the reference set of grasping. From the measured fingertip positions a closed-loop inverse kinematics algorithm has been applied to reproduce the joint space configuration of the robotic hand relying on its kinematics, scaled using the human and robotic fingers length ratio. Once the set of grasping has been mapped on the robotic hand, the synergies subspace has been computed applying principal component analysis on the joint configurations. The obtained subspace is tested with experiments on the DEXMART Hand by performing reach to grasp actions on selected objects using the first three predominant synergies. The analysis of these synergies and a comparison with the results on the human hand available in the literature are performed by means of graphical and numerical tools.

I. INTRODUCTION

The use of the principal components, also called postural synergies, holds great potential for robotic hands control, implying a substantial reduction of the grasp synthesis problem dimension. Transferring human hand motion to a robotic hand is a quite challenging problem due to the complexity and variety of hand kinematics and the dissimilarity with the robotic hand. Indeed, in order to obtain a thorough human hand posture estimation, a reliable kinematic hand model and high-accurate motion tracking instrumentation are required. A synergies mapping from the human hand to the robotic hand has been addressed in [1]. The proposed mapping strategy between the synergies of a paradigmatic human hand and a robotic hand is carried out in the task space and it is based on the use of a virtual sphere. In [2] three synergies have been extracted from data on human grasping experiments and mapped to a robotic hand. Thus, a neural network with the features of the objects and the coefficients of the synergies has been trained and employed to control robot grasping. In [3], postural synergies of the UB Hand IV, the first prototype of the DEXMART Hand,

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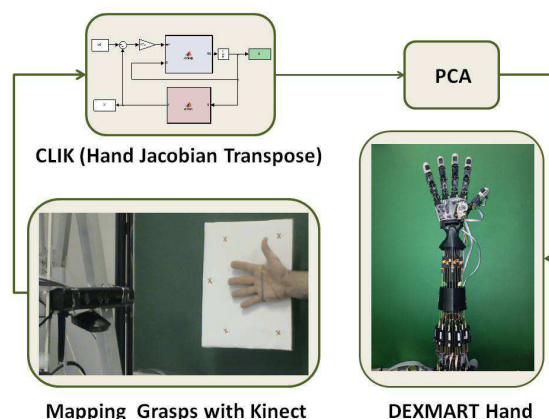


Fig. 1. Diagram of the methodological approach.

have been used for human-inspired control solutions. In [4], neural networks have been integrated to allow synergy-based grasp planning relying only on object geometric features and task requirements; the experiments were conducted on the last prototype of the DEXMART Hand. In this work, we propose a new model-based method to map grasps from the human to the DEXMART Hand [5]. The core idea of the mapping method is to dramatically simplify the detection of the human hand posture by measuring strategic points using a low cost camera and using the robotic hand kinematics as a paradigmatic model of the human hand for inverse kinematic computation. The Kinect sensor is used for 3D human hand fingertips detection and a Closed-Loop Inverse Kinematics Algorithm (CLIK) [6] is used for human grasp mapping and is based on the subjects' hand dimensions. The paper is organized as follows: Section II describes the DEXMART Hand kinematics. Section III explains the technical approach on the whole, from human hand detection to synergies derivation. Section IV illustrates the mapping procedure based on measures acquired with the Kinect. In Section V the computation of synergies subspace and the experimental results obtained using an open-loop control strategy based on the first three predominant synergies are reported. In Section VI the first three predominant synergies of the DEXMART Hand are analyzed by means of graphical and numerical tools. Evaluation of the method efficiency is made on the basis of the analysis performed in [7] on the human hand and taking into account the results of the mapping obtained on the UB Hand IV using the same reference postures. Finally, Section VII provides the conclusion.

II. THE DEXMART HAND

The DEXMART Hand [5] is an innovative anthropomorphic hand developed within the DEXMART project [8] and based on a previous prototype, the so-called UB Hand IV (University of Bologna Hand, version IV) [9]. The new design aims at an improved human-like manipulation capability and mobility. Indeed, the kinematics is designed to improve the functionality, allowing the opposition of the thumb with the other four fingers. For this purpose, the Denavit-Hartenberg (D-H) parameters, reported in Tab. I, are different for all the fingers in order to fit better with the human hand kinematics. Remotely located actuators with

TABLE I
DENAVIT-HARTENBERG PARAMETERS OF THE DEXMART HAND FINGERS.

Link (Thumb)	d [mm]	θ	a [mm]	α [deg]
1	-42.5	$\theta_1 + 85$	18	-90
2	-1.65	$\theta_2 - 80$	24.57	70.32
3	4.89	$\theta_3 + 10.62$	30	0
4	0	$\theta_4 - 3.61$	30	0
Link (Index)	d [mm]	θ	a [mm]	α [deg]
1	-2.91	θ_1	18	90
2	0	$\theta_2 - 20$	38	0
3	0	θ_3	28	0
4	0	θ_4	28.5	0
Link (middle)	d [mm]	θ	a [mm]	α [deg]
1	-4.91	θ_1	18	90
2	0	θ_2	40	0
3	0	θ_3	28	0
4	0	θ_4	28.5	0
Link (Ring)	d [mm]	θ	a [mm]	α [deg]
1	-1.93	θ_1	18	90
2	0	$\theta_2 - 5$	38	0
3	0	θ_3	28	0
4	0	θ_4	28.5	0
Link (Little)	d [mm]	θ	a [mm]	α [deg]
1	4.24	θ_1	18	90
2	0	$\theta_2 + 15$	35	0
3	0	θ_3	28	0
4	0	θ_4	28.5	0

tendon-based transmissions routed by sliding paths (*sliding tendons*) [10] have been adopted for the joints actuation. Taking inspiration from the biological model and in order to reduce the complexity of the hand control, an internal non-actuated (passive) tendon has been introduced to couple the movements of the last two joints of each finger, i.e. the medial and the distal joint. Hence, only three angles are considered for the index, the middle, the ring and the little finger, i.e. the base (adduction/abduction) angle θ_{1f} , the proximal angle θ_{2f} and the medial angle θ_{3f} . About the thumb, the angles are: the base (proximal) angle θ_{1t} , the adduction/abduction angle θ_{2t} and the medial angle θ_{3t} . Therefore, a total amount of $h = 15$ joint angles is needed to describe the robotic hand configuration.

III. TECHNICAL APPROACH

Motion capture of the human hand and the detection of phalange postures and joint positions of a grasp configuration is a very challenging task if it is performed by a single camera because of evident occlusion problems. Moreover,

the reconstruction of the human hand joint angular positions implies the knowledge of its kinematics, not completely consistent in the anatomical literature [11], [12]. To solve this issue, we focused the observation of the human grasping postures on the detection of the position of the fingertips with respect to the palm, since the kinematic properties of the DEXMART Hand allow the joint angles to be univocally reconstructed from these measurements. For this purpose, a commercial low-cost RGB+Depth (RGBD) camera, such as the Kinect from Microsoft Corp., has been used. This device, indeed, after the calibration [13], allows reconstructing the 3D real world coordinates (in meters) with respect to the camera frame with precision (about 1mm) for space and distance in the range of interest of our measurements (an area of about 0.6×0.6 m at a distance of about 0.5 m). This functionality is embedded in the OpenCV library that has been used for the Kinect image elaboration, whereas the *freenect* driver has been used for low-level communication with the RGBD camera. Since a large number of open-source softwares for both the use of the Kinect sensor and computer vision applications are freely available, we produced very easily and quickly a customized application for the execution of the required measures. The developed application allows collecting and saving the information coming from the Kinect. The points to be detected are selected by clicking with the mouse on the RGB image and by matching information from the RGB data and depth data. With the aim of mapping a given grasp of the human hand, the transfer of the measurements carried out on humans to the robotic hand is mainly based on mapping the fingertip positions with respect to the palm from the human hand to the robotic hand.

The DEXMART Hand is designed with a human-like kinematics and a total amount of $h = 15$ joint angles describes the whole robotic hand configuration. Thus, from the fingertip measurements of the hand in a certain grasp configuration, by scaling the robotic hand link dimensions to fit with the human subject and by inverting the robotic hand kinematics through a CLIK algorithm, we reconstruct the joint positions corresponding to the grasp. This implies that the robotic hand kinematics is used as reference model for the measurement performed on the human hand. As we will explain deeply in the next section, the fingertip positions, the palm pose in the Cartesian space and the fingers length of the human hand are all the measurements we need to compute the 15 joint angles of the scaled robotic hand by means of kinematic inversion. Since significant differences exists in both the size and the kinematics of the human hands [14], the method has been applied to 5 different subjects for mapping generalization. For each of the 36 grasps in the table (Fig. 2), mapped from the five subjects to the robotic hand, the mean value has been computed and utilized for deriving the postural synergies by means of principal component analysis (PCA). Finally, the grasps in the reference set has then been performed with the DEXMART Hand by controlling the whole motion during reach to grasp using a linear combination of the three predominant selected synergies. A schematic representation

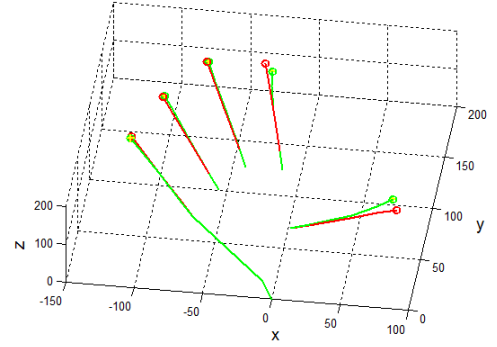


Fig. 2. Reference set of comprehensive human grasps and open-hand configurations used for PCA.

of the whole procedure for postural synergies subspace computation is represented in Fig. 1, where the DEXMART Hand has been considered inside the mapping algorithm.

IV. MAPPING THE HUMAN HAND GRASPS

The hand posture of the 5 subjects has been acquired through the Kinect RGBD camera. Since we are interested in measuring the fingertip positions with respect to the hand reference frame (the palm frame), the hand position and orientation (the palm pose) with respect to the RGBD camera must be reconstructed. As a matter of fact, the measures provided by the sensor are represented in the camera frame, thus, for inverse kinematic computation, the homogeneous transformation between the camera frame and the palm frame has to be known. The goal has been achieved by measuring a set of five reference points on a rigid panel fixed to the opisthenar (the back of the hand). Thus, before starting the mapping procedure, each subject was instructed first in wearing the rigid support and then in assuming an open-hand posture (corresponding to the configuration when all the joint angles are zero in the DEXMART Hand). The distance of the fingertips from the palm base in the open-hand configuration was measured with the aim of defining suitable scaling factors between the subject hand and the robotic hand size. The finger lengths of the 5 subjects are reported in Table II. In Fig. 3, the mapped open-hand configuration of one subject



(a) DEXMART Hand.

Fig. 3. The open-hand configuration of Subject 5, mapped on the robotic hand is represented by the green stylized hand. The red hand represents the robotic hands open configuration.

(the number 5) is represented. The comparison between the mapped human hand configuration (green hand in Fig. 3) and the corresponding configuration of the robotic hand (red hand) demonstrate that the entire mapping process ensures that the human hand palm pose matches very well the robotic hand palm pose and that the robotic hand kinematics matches satisfactory the human hand kinematics. As shown in Fig. 4, ten points have been detected in the open configuration by the vertices of the cyan line: the fingertips and the five points on the support attached to the palm. The obtained fingertip positions, expressed in the camera frame, have been then matched with the ones of the robotic hand (whose kinematics has been scaled by the ratio between the human and the robotic fingers length) expressed in the robotic hand reference frame (the palm frame), obtaining in this way the affine transformation T_i between the camera and the hand reference frame for the i -th subject. The position of the panel reference points $p_{i,j_{ref}}$, $j = 1, \dots, 5$ with respect to the hand frame has been then computed on the basis of the transformation T_i . Once T_i and $p_{i,j_{ref}}$ have been determined, each subject has been asked to achieve each of the 36 reference postures using the right hand and following the approach depicted in Fig. 2. The fingertip position and the position of the panel reference points have been acquired as shown in Fig. 5. By matching the position of the panel reference points measured by the Kinect with $p_{i,j_{ref}}$, the new affine transformation $T_{i,k}$, $k = 1, \dots, 36$ between the camera and the hand reference frame during the execution of each grasp can be computed together with the position of the subject fingertips $p_{i,j}$ expressed in the hand frame.

The mapping from the human hand fingertip positions $p_{i,j}$ and the robotic hand joint positions is then performed inverting the robotic hand kinematics.

For each subject, the robotic hand kinematics is differently scaled for each finger by multiplying the linear D-H parameters (a and d in Tab. I) for the ratio between the human finger length and the corresponding robotic finger length, see Tab. II. The CLIK algorithm [6], based on the transpose of the robotic hand Jacobian matrix, has then been

TABLE II
FINGER LENGTHS (IN MM) OF THE FIVE SUBJECTS, OF THE DEXMART HAND AND OF THE UB HAND IV.

Finger	S. 1	S. 2	S. 3	S. 4	S. 5	D. Hand	UB Hand
Thumb	115	120	130	125	140	126	170
Index	165	170	173	180	190	217	247
Middle	170	175	180	185	200	216	249
Ring	160	165	173	175	185	210	240
Little	140	140	155	150	165	198	234

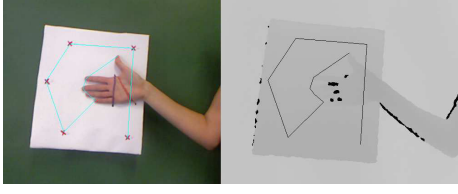


Fig. 4. Open-hand configuration corresponding to the DEXMART Hand joint angles set to zero.

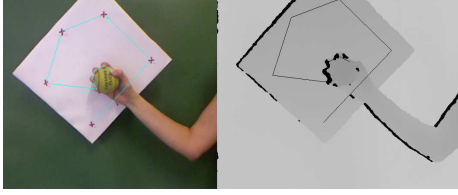


Fig. 5. RGB and depth image from Kinect.

implemented in order to map the subject fingertip position to the scaled robotic hand joint configuration. For each grasp of the reference set (Fig. 2), the average of the five robotic hand configurations $\mathbf{c}_i \in \mathbb{R}^{15}$ mapped from the five subjects performance has been computed and stored in a configuration matrix $\mathbf{C}$.

V. COMPUTATION OF THE SYNERGIES SUBSPACE

At this point, the matrix $\mathbf{C} = \{\mathbf{c}_i \mid i = 1, \dots, 36\}$ of the mapped configurations has been built. Each of the 36 joint configurations represents the average of the mapped posture from the five subjects. Thus, the vector $\bar{\mathbf{c}}$ representing the mean hand position in the grasp configurations space (the zero-offset position) and the matrix $\mathbf{F} = \{\mathbf{c}_i - \bar{\mathbf{c}} \mid i = 1, \dots, 36\}$ of the grasp offsets with respect to the mean configuration have been computed. The PCA has then been performed on the matrix $\mathbf{F}$ and a base matrix $\mathbf{E} = \{\mathbf{e}_1 \mathbf{e}_2 \mathbf{e}_3\}$ of the postural synergies subspace has been found selecting the three predominant components from the PCA, see [15] for additional details on the procedure. We refer to the

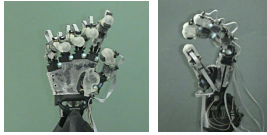


Fig. 6. Mean position of the DEXMART Hand configuration.

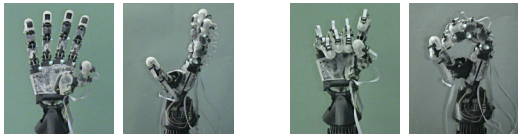


Fig. 7. From left to right, front and lateral view of the first postural synergy in the minimum and the maximum configuration.

minimum and maximum configuration of each synergy as the robotic hand configurations spanned by $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ by

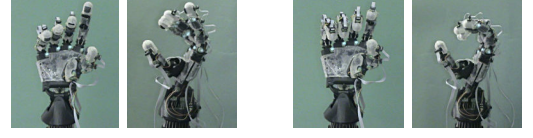


Fig. 8. From left to right, front and lateral view of the second postural synergy in the minimum and the maximum configuration.

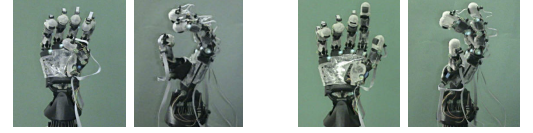


Fig. 9. From left to right, front and lateral view of the third postural synergy in the minimum and the maximum configuration.

means of, respectively, the minimum and maximum value of the corresponding synergy weights without violating the joint limits. When the weights of the synergies are zero, the hand posture corresponds to the zero-offset position (mean position) $\bar{\mathbf{c}}$, see Fig. 6 where a frontal and a lateral view of the robotic hand mean position are shown. In Figs. 7, 8 and 9 the minimum and maximum configurations in frontal and lateral views of the three postural synergies are represented.

A. Control with postural synergies

The synergy-based control relies on the fact that each hand grasp posture $\mathbf{c}_i$ can be approximated, by a suitable selection of the postural synergy weights $[\alpha_1 \ \alpha_2 \ \alpha_3]^T \in \mathbb{R}^3$, as the projection $\hat{\mathbf{c}}_i$ on the postural synergies subspace

$$\hat{\mathbf{c}}_i = \bar{\mathbf{c}} + \mathbf{E} \begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix}. \quad (1)$$

Thus, the value of the three eigenpostures weights $[\alpha_1 \ \alpha_2 \ \alpha_3]^T$ are computed from the desired grasp posture as

$$\begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix} = \mathbf{E}^\dagger (\mathbf{c}_i - \bar{\mathbf{c}}) \quad (2)$$

where $\mathbf{E}^\dagger$ is the Moore-Penrose pseudo-inverse of the base matrix $\mathbf{E}$. The temporal value of the weights α_1 , α_2 , α_3 during grasp operations has to be chosen in such a way that, starting from the zero-offset position $\bar{\mathbf{c}}$ (i.e. $\alpha_1 = \alpha_2 = \alpha_3 = 0$), the hand opens during the reach in preparation for object grasp, and then closes reaching a suitable shape determined from (2) and depending on the original grasp configuration $\mathbf{c}_i$. In the open-hand configuration, namely $\mathbf{c}_0$, all the flexion joint angles are close to zero, and the corresponding values of α_1 , α_2 and α_3 can be determined from (2) by posing $\mathbf{c}_i = \mathbf{c}_0$.

The intermediate values of the synergy weights have been determined by assuming a suitable time interval for the grasp operation (six seconds for the whole reach to grasp phase, three seconds for both the opening and closing phases) and by linear interpolation of the α_1 , α_2 and α_3 values in the three reference configurations $\{\bar{\mathbf{c}}, \hat{\mathbf{c}}_0, \hat{\mathbf{c}}_i\}$.

B. Experimental Evaluation of the Synergy-based Grasp Control

In the experiments, starting from the zero-offset position, the hand moves continuously in the synergies configuration subspace and goes in an open-hand configuration. Then, it closes reaching a configuration that depends on the particular grasp to be performed. During the closing phase, the weights of the three postural synergies are obtained by linear interpolation from those corresponding to the open-hand configuration to those suitable values unique for each object and computed using (2). The linear combination of the three synergies allows a power grasp of both cylinders and spheres of different dimensions by means of suitable opposition of the thumb, see Fig. 10.

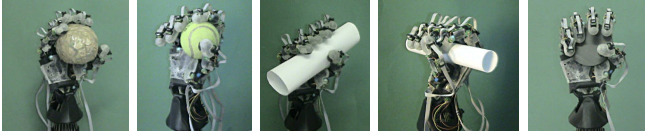


Fig. 10. Reproduced power grasps from the reference set of postures.

In Fig. 11, the performance corresponding to precise grasp operations are reported considering both prismatic and circular objects and grasps involving from two to five fingers.

The reproduced intermediate side grasps from the reference set of postures is depicted in Fig. 12.

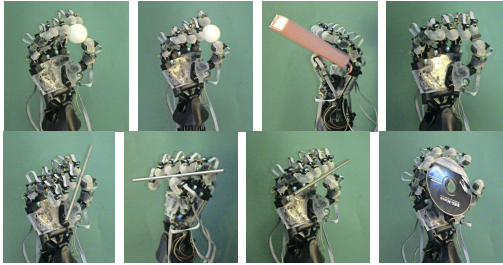


Fig. 11. Reproduced precision grasps from the reference set of postures.

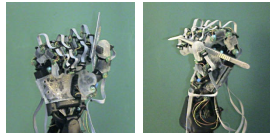


Fig. 12. Reproduced intermediate side grasps from the reference set of postures.

VI. SYNERGIES ASSESSMENTS AND COMPARISON BETWEEN THE ROBOTIC AND HUMAN HAND

In [16], using the definition of force-closure for underactuated hands and the definition of grasping force optimization, the authors demonstrate that the first few synergies are sufficient to establish force-closure. Further, investigating the role of different postural synergies in the quality of the grasps, no improvement has been observed beyond the first three synergies in the precision grasp case, while continuous but

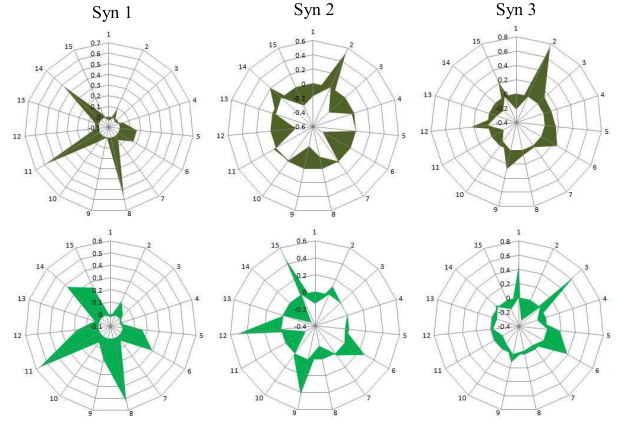


Fig. 13. Graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$. The adduction/abduction, proximal and medial flexion joints are indicated from 1 to 3 for the thumb, from 4 to 6 for the index finger, from 7 to 9 for the middle finger, from 10 to 12 for the ring finger and finally from 13 to 15 for the little finger. On the top of the figure the graphs are referred to the UB Hand IV, on the bottom to the DEXMART Hand.

small improvements are observed in the power grasp case. Moreover, considering that by applying the three predominant synergy-based control, the results of the experiments reveals that the DEXMART Hand succeeded in grasping various objects throughout a complete taxonomy, we evaluate only the three fundamental synergies. In order to validate the efficiency of the synergies subspace of our mapping method, we consider a qualitative comparison with the work of Santello [7]. As in [7], we have considered five subjects (3 males and two females) in order to obtain a comprehensive set of grasps to perform the PCA. Furthermore, Santello considers a paradigmatic model of the human hand of 15 degrees of freedom, indeed he collected real-world data on a variety of human hand postures by means of a data glove that measure 3 angles for each finger. Actually, in this work the same number of parameters are used to map the human hand grasps. Indeed, the fingertip measurements (3 parameters for each finger) are used in a CLIK algorithm to determine the 15 DoFs joint space configuration, relying on a scaled robotic hand kinematics to adapt to the human hand. The circular graphs on the bottom of Fig. 13 are a graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ and identify the joints whose rotations are more involved in each synergy. From left to right, the unitary variation of joints position, is represented for the first, the second and the third synergy respectively. By observing the circular graphs, it emerges that there are basic characteristics of the three synergies described in the follow.

1) *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 adduction/abduction movements of the four fingers are not very involved in this synergy.

2) *Second Synergy*: The second postural synergy is characterized by a movement in opposite directions of the proximal and medial flexion joints. The adduction/abduction movements of the four fingers are not very involved also in this synergy.

3) *Third Synergy*: In the third postural synergy the movement involves especially the index and the thumb. The movement of adduction/abduction of the thumb and of the index increases with respect to the first two synergies. This characteristic is important for correct index/thumb opposition that allows increasing the grasp accuracy, and thus achieving more stable grasps. The evaluations on circular graphs highlights that the kinematic patterns of the first three synergies are in accordance with the results of the studies conducted on the human hand in [7]. Moreover, the synergies subspace computed on the prototype of the DEXMART Hand, the UB Hand IV (on the top of Fig. 13), that presents a different kinematics, even though anthropomorphic, reveals very similar kinematic patterns for the first predominant synergies. This confirms the validity of the mapping method for computation of synergies for kinematics with anthropomorphic features. In Table III, the variance of the data for two and three predominant synergies obtained by Santello et al. on the human hand (H.H.) and obtained in this work on the UB Hand IV (UB H.) and DEXMART Hand (D.H.) are represented. Observing Table III, it is evident that the differences in the kinematics of the DEXMART Hand and UB Hand IV affect the data variance of the first two and three synergies. The variance computed for the DEXMART Hand decreases with respect to the old prototype. Indeed, the UB Hand IV has a simplest kinematics characterized by all the fingers with the same D-H parameters and the opposition of the thumb is not allowed with all the other four fingers. This means that more complex kinematics and closer to the humans, like the DEXMART Hand, require a wider set of grasps (57 different grasps are considered in [7]) for the PCA in order to compute suitable synergies subspace to transfer human grasping capabilities and allow grasp synthesis and control in a reduced dimension subspace ensuring human-like behavior.

TABLE III

VARIANCE OF THE DATA FOR THE FIRST TWO AND THREE SYNERGIES.

Syn	UB H.	D. H.	H. H.
two	87%	79%	84%
three	91%	86%	90%

VII. CONCLUSION

A model-based method for mapping grasps from the human hand to the DEXMART Hand has been presented. The method comprises fingertips detection, using a commercial low-cost RGBD camera such as the Kinect sensor, and a closed-loop inverse kinematics algorithm, that is based on the DEXMART Hand kinematics. The robotic hand kinematics is linearly scaled according to the hands dimension of five subjects involved in the experiments. The kinematic patterns

of the first three postural synergies of the DEXMART Hand are computed. Experimental evaluation of the computed synergies subspace has been performed testing the synergy-based control during reach to grasp. The results of the experiments reveals that hand succeeded in grasping various objects throughout a complete taxonomy. A comparison between the results obtained with the previous prototype (UB Hand IV) has been provided using the same grasps reference set. Synergies evaluation, provided by means of graphical and numerical tools, reveals that the basic characteristics of the three synergies are similar to the results of Santello et al. [7] studies on the human hand. The results are comparable since both works use a simplification of the human hand parameterized as a kinematic structure of 15 DoFs.

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