

Mapping Grasps from the Human Hand to the DEXMART Hand by Means of Postural Synergies and Vision

Ficuciello Fanny, Gianluca Palli, Claudio Melchiorri, Bruno Siciliano

Abstract This work aims at defining a suitable postural synergies subspace for the DEXMART Hand from observation of human hand grasping postures. Previous works were carried out on a preliminary prototype (the UB Hand IV), without neither proprioceptive integrated sensors nor external sensors, by means of a joint-to-joint mapping technique. Using an RGB camera and depth sensor for 3D motion capture, the human hand palm pose and fingertip positions have been measured for a reference set of grasping postures. The proposed method for the determination of the synergies subspace is based on the kinematics mapping from the human hand to the robotic hand using data from experiments involving five subjects. The subjects' hand configurations have been mapped to the robotic hand by matching the hand pose and fingertip positions and applying a closed-loop inverse kinematic algorithm. Suitable scaling factors have been used to adapt the DEXMART Hand kinematics to the subjects' hand dimension. By means of Principal Component Analysis (PCA), the kinematic patterns of the first three predominant synergies have been computed and a brief comparison with the previous method and kinematics is reported. Finally, a synergy-based control strategy has been used for testing the efficiency of the grasp synthesis method.

1 Introduction

Recent studies on neuroscience and robotics have shown that imitating human prehension is a promising way to simplify and improve grasp planning and control

Fanny Ficuciello and Bruno Siciliano
DIS - University of Naples Federico II, Via Claudio, 21, 80125 Napoli, Italy
e-mail: fanny.ficuciello@unina.it, bruno.siciliano@unina.it

Gianluca Palli and Claudio Melchiorri
DEIS - University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy
e-mail: gianluca.palli@unibo.it, claudio.melchiorri@unibo.it

issues related to high multiple Degree-of-Freedom (DoF) devices such as anthropomorphic robotic hands. In [22], the authors measure a set of static human hand postures by recording 15 joint angles and, by means of the PCA, they show 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. 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 [12]. 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 [11] 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. Recently, Kinect technology is increasingly used for hand tracking, since it interprets 3D scenes thanks to the depth sensor, consisting of an infrared laser projector, combined with an RGB camera. In [16] a model-based method for recovering and tracking the 3D position, the orientation and the full articulation of a human hand has been proposed from marker-less visual observations. In [10] a heuristic hand tracker has been developed for the animation of the hand avatar in the virtual reality and for the implementation of the force rendering in wearable haptics. In this work we propose a model-based method to map grasps from the human to the DEXMART Hand by means of vision. The Kinect sensor is used for 3D human hand fingertips detection and a closed-loop inverse kinematic algorithm is used for human grasp mapping. A reference set of grasps have been selected and five subjects have been involved in the experiments. The inverse kinematic algorithm is based on the DEXMART Hand kinematics that is linearly scaled according to the subjects' hand dimensions.

2 Technical Approach and Motivation

According to recent grasp taxonomy literature [21], in [8] and [9] a set of 36 human hand grasp configurations was selected and adopted for experiments carried out on a preliminary prototype of the DEXMART Hand [18], the UB Hand IV [2]. The mapping of the human grasps to the robotic hand was obtained by means of a joint-to-joint mapping technique, i.e. the fingers' joint position of the DEXMART Hand prototype were manually adjusted in order to imitate as much as possible the human hand desired configuration. Obviously, this method strongly depends on the interpretation of the reference grasp by the operator and on his/her ability to reproduce the grasp with the robotic hand.

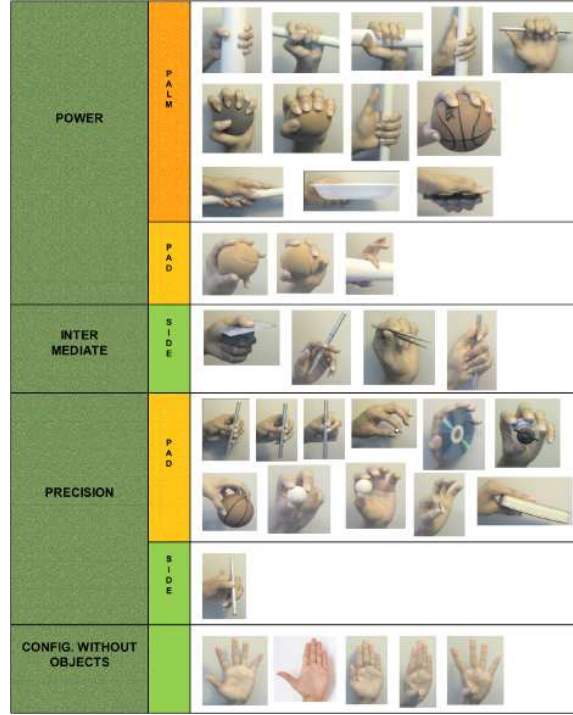


Fig. 1 Reference set of comprehensive human grasps and open-hand configurations used for PCA.

In this work, the same reference set of 36 human hand grasps, represented in Fig. 1, has been considered. Notwithstanding, a new method, based on fingertip mapping from human hand grasps to the robotic hand, has been adopted using measures in 3D space of the fingertip positions and inverse kinematics. A computer vision system, able to detect the position in 3D real world coordinates of each point in the scene, has been adopted in order to make the method independent of the characteristics and skills of the operator. As a matter of fact, the robotic hand grasping postures used for PCA are obtained from measurements performed directly on the hand of several subjects while they execute the grasps of the reference set. A commercial low-cost RGB+Depth (RGBD) camera, such as the Kinect from Microsoft Corp., has been adopted since this device achieves suitable 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). Moreover, a large number of open-source software for both the use of the Kinect sensor and computer vision applications are freely available. Therefore, we produced very easily and quickly a customized application for the execution of the required measures. Instead, capturing the motion of all the phalanges and the position of the joints during a grasp by means of a single camera is a very challenging task because of evident occlusion problems. Moreover, the reconstruction of the human hand joint angular positions implies the knowledge

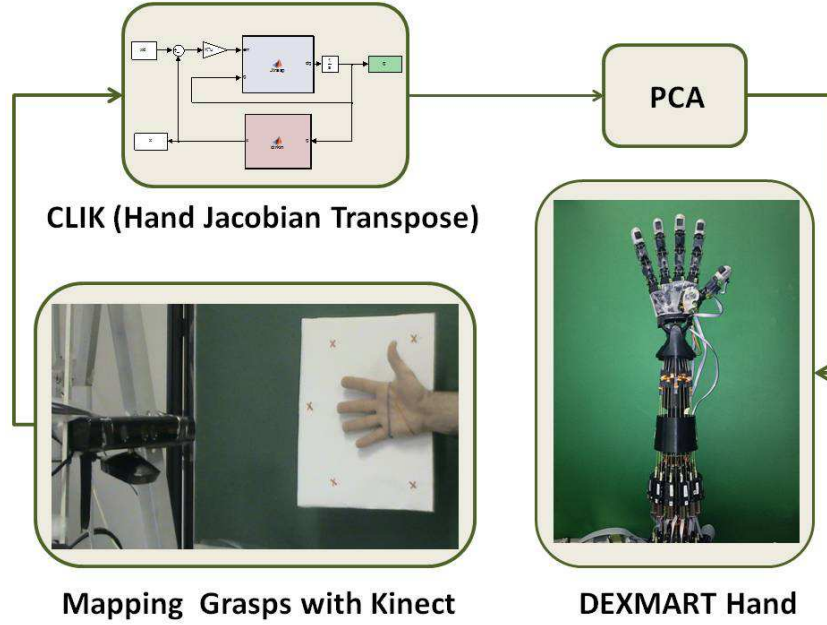


Fig. 2 Diagram of the methodological approach.

of its kinematics, not completely consistent in anatomical literature [13, 7], and may cause problems when the acquired information must be mapped on a different kinematic structure.

The DEXMART Hand is designed with a human-like kinematics and a total amount of $h = 15$ joint angles describes the whole robot hand configuration. Therefore we directly map the human fingertip position measured in the palm frame to the robot hand kinematics by means of a suitable scaling of the robot hand dimensions. The fingertip positions and 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 robotic hand by means of kinematic inversion. An inverse closed-loop kinematic algorithm has been adopted also to minimize the errors that affect the measures of the fingertip and palm positions, performed by the Kinect, due to noise and limited precision. Since significant differences exist in both the size and the kinematics of the human hands [15], the method has been applied to 5 different subjects. For each of the 36 grasps in the table (Fig.1), 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 PCA. Finally, the grasps in the reference set have then been performed with the DEXMART Hand by controlling the whole motion during reach to grasp using a linear combination of the selected synergies. A schematic representation of the whole procedure for postural synergies subspace computation is represented in Fig. 2.

3 The DEXMART Hand

The DEXMART Hand [18] is an innovative anthropomorphic hand developed within the DEXMART project [1]. Based on a previous prototype, the so-called UB Hand IV (University of Bologna Hand, version IV) [2], the DEXMART Hand has been designed with an improved thumb kinematics. The new design aims at a human-like manipulation capabilities and mobility, allowing the opposition of the thumb with the other four fingers. For this purpose, the thumb kinematics has been differentiated with respect to the other fingers and provided of different joint limits. In particular, the adduction/abduction base joint and the first flexion joint have been inverted in the kinematic chain order. Furthermore, the Denavit-Hartenberg (D-H) parameters, reported in Tab. 1, are different for all the fingers in order to fit better with the human hand kinematics. The DEXMART Hand is also equipped with a wide set of sensors which comprise joint position sensors, tendon force sensors [20] and fingertip tactile sensors [6]. Moreover, the twisted string actuation concept [19] has been adopted for driving this robotic hand. As in the previous version, the maximum design simplification and reduction of the device's cost production and development has been held. To this end, the DEXMART Hand has been conceived by taking into account the following driving issues:

- The hand mechanics is based on an endoskeletal structure articulated by means of pin joints integrated into the phalanx body simply consisting in a plastic shaft which slides on a cylindrical surface [2, 5, 14].
- Remotely located actuators with tendon-based transmissions routed by sliding paths (*sliding tendons*) [17] have been adopted for the joints actuation.
- A purposefully designed soft cover mimicking the human skin [4, 3] has been introduced for improving the grasping capabilities of the hand.
- The mechanical structure of the hand has been manufactured adopting additive technologies (Fused Deposition Manufacturing).

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 progressively: the base (proximal angle) 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. The joint angles ranges for each finger are mechanically constrained by stroke limiters within the intervals:

$$\theta_{1f} \in [-10, 10], \quad \theta_{2f} \in [0, 90], \quad \theta_{3f} \in [0, 110] \quad [\text{deg}] \quad (1)$$

and for the thumb within the intervals:

$$\theta_{1t} \in [0, 90], \quad \theta_{2t} \in [0, 60], \quad \theta_{3t} \in [0, 90] \quad [\text{deg}]. \quad (2)$$

Table 1 Denavit-Hartenberg parameters of the DEXMART Hand fingers.

Link (Thumb)	d [mm]	θ	a [mm]	α [deg]
1	7.53	$\theta_1 + 85$	19.64	-110
2	-42.5	$\theta_2 - 80$	18	-90
3	-1.65	$\theta_3 + 10.62$	24.57	70.32
4	4.89	$\theta_4 - 3.61$	30	0
5	0	θ_4	30	0

Link(Index)	d [mm]	θ	a [mm]	α [deg]	Link (middle)	d [mm]	θ	a [mm]	α [deg]
1	40.75	θ_1	82	-95	1	14.34	θ_1	86	-86
2	-2.91	$\theta_2 - 20$	18	90	2	-4.91	θ_2	18	90
3	0	θ_3	38	0	3	0	θ_3	40	0
4	0	θ_4	28	0	4	0	θ_4	28	0
5	0	θ_4	28.5	0	5	0	θ_4	28.5	0

Link (Ring)	d [mm]	θ	a [mm]	α [deg]	Link (Little)	d [mm]	θ	a [mm]	α [deg]
1	-11.16	θ_1	82	-80	1	-36.1	θ_1	68	-75
2	-1.93	$\theta_2 - 5$	18	90	2	4.24	$\theta_2 + 15$	18	90
3	0	θ_3	38	0	3	0	θ_3	35	0
4	0	θ_4	28	0	4	0	θ_4	28	0
5	0	θ_4	28.5	0	5	0	θ_4	28.5	0

4 Mapping the Human Hand Grasps

The Kinect RGBD camera has been used to provide the RGB color image and the corresponding depth image of the hand for 3D fingertip positions and palm pose detection. After the calibration [24], it is possible to reconstruct the 3D real world coordinates (in meters) with respect to the camera frame. 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. For the purpose of this work, we developed an application that 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. To obtain 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 has to be known. 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. This goal is reached by measuring a set of points fixed to the palm. Since the palm can be hidden by the grasped object, a rigid panel with five reference points has been attached 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 DEXMART Hand configuration of zero joint angles. 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 robot hand size. The finger lengths of the 5 subjects are reported in Table 2.

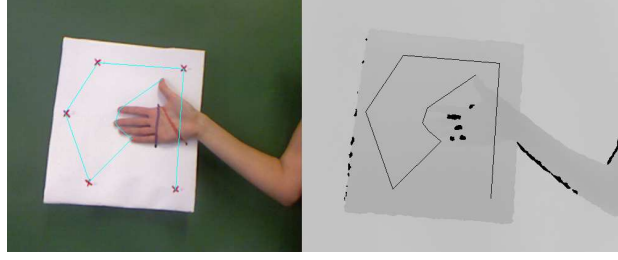


Fig. 3 Open Hand Configuration corresponding to the DEXMART Hand joint angles set to zero.

Table 2 Finger lengths (in mm) of the five subjects and of the DEXMART Hand.

Finger	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	DEXMART Hand
Thumb	115	120	130	125	140	126
Index	165	170	173	180	190	217
Middle	170	175	180	185	200	216
Ring	160	165	173	175	185	210
Little	140	140	155	150	165	198

As shown in Fig. 3, ten points have been detected in the open configuration: the fingertips and the five points on the support. The obtained fingertip positions, expressed in the camera frame, have been then matched with the ones of scaled version of the robot hand kinematics expressed in the robot 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 $p_{i,j_{\text{ref}}}$, $j = 1, \dots, 5$ with respect to the hand frame has been then computed on the basis of the transformation T_i .

Once T_i and $p_{i,j_{\text{ref}}}$ 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. 1. The fingertip position and the position of the panel reference points have been acquired as shown in Fig. 4. By matching the position of the panel reference points measured by the Kinect with $p_{i,j_{\text{ref}}}$ 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 by scaling the robot hand link dimensions to fit with the human subject and by inverting the robot hand kinematics through a closed-loop algorithm. For each subject, the DEXMART Hand kinematics is differently scaled for each finger by multiplying the linear D-H parameters (Tab. 1) for the ratio between the human finger length and the corresponding robotic finger length (Tab. 2). A closed-loop inverse kinematic (CLIK) algorithm [23], based on the transpose of the DEXMART Hand Jacobian matrix, has then been implemented in order to map the subject fingertip position to the robotic hand joint configuration. For each grasp of the reference set (Fig. 1), the average of the five robotic hand configurations

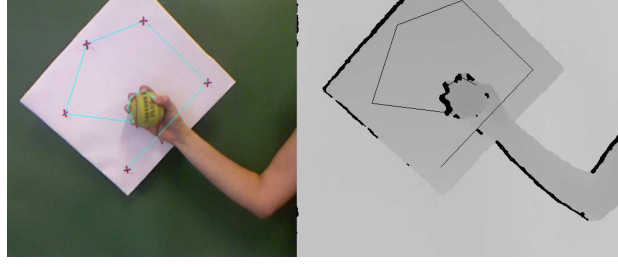


Fig. 4 RGB and depth image from Kinect.

$\mathbf{c}_i \in \mathbb{R}^{15}$ mapped from the five subjects performance has been computed and stored in a configuration matrix $\mathbf{C}$. Once the mapping procedure has been completed, the PCA analysis has been computed on the obtained DEXMART Hand configuration matrix.

5 Postural Synergies Subspace of the DEXMART Hand

The procedure reported in [9] has been adopted for deriving the postural synergies of the DEXMART Hand on the basis of the data obtained by mapping human hand grasps to the robot hand kinematics, as reported in the previous section. Once the matrix $\mathbf{C} = \{\mathbf{c}_i \mid i = 1, \dots, 36\}$ of the DEXMART Hand configurations has been built, 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. In the following, the three synergies are described, with further considerations about the differences with respect to the previous results obtained with the previous prototype reported in [9], especially for the motion of the thumb.

5.1 Kinematics Assessment and Comparison

We refer to the minimum and maximum configuration of each synergy as the robot hand configurations spanned by $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ by means of, respectively, the minimum and maximum value of the corresponding synergy weights without violating the joint limits reported in (2) and (1). When the weights of the synergies are zero, the hand posture corresponds to the zero-offset position (mean position) $\bar{\mathbf{c}}$, see Fig. 5 where a frontal and a lateral view of the robot 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. The vectors of the three synergies and the zero-offset vector are reported in Tab. 3. The synergies sub-

Table 3 First three eigenpostures and zero offset (data in degrees) vectors of the DEXMART Hand postural synergies subspace.

		$\mathbf{e}_1$	$\mathbf{e}_2$	$\mathbf{e}_3$	$\mathbf{c}$ [deg]
Thumb	adduction/abduction	0.1270	0.1078	-0.3166	18.7185
	proximal	-0.0224	-0.1410	0.4633	35.2796
	medial	0.0363	0.0086	0.6401	38.4707
Index	adduction/abduction	-0.0190	-0.0037	-0.1267	-1.1206
	proximal	0.1610	-0.0471	0.1775	20.6411
	medial	0.2960	0.2785	0.3858	45.6014
Middle	adduction/abduction	0.0428	0.0272	-0.0714	-1.9326
	proximal	0.5254	-0.1617	-0.0477	49.3695
	medial	0.1751	0.4205	0.1212	29.1440
Ring	adduction/abduction	0.0599	0.0283	-0.0978	-1.4200
	proximal	0.5674	-0.2750	-0.1368	56.5125
	medial	0.1724	0.5216	-0.0366	26.2536
Little	adduction/abduction	0.0345	-0.0105	-0.0794	-3.8122
	proximal	0.3789	-0.3453	0.0410	44.4781
	medial	0.2440	0.4659	-0.1390	31.0406

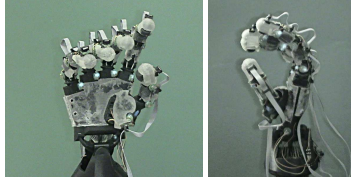


Fig. 5 Mean position of the DEXMART Hand configuration.

space derived in [9] on the basis the previous robot hand prototype by means of the joint-to-joint mapping is now compared with the results obtained with the DEXMART Hand kinematics and the mapping method reported in this paper by means of appropriate graphical tools. The circular graphs in Fig. 6 are a graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ reported in Tab. 3 and identify the joints whose rotations are more involved in each synergy. From left to right, the joint position variation is represented for the first, the second and the third synergy respectively. On the top of the figures, the graphs corresponding to the DEXMART Hand are reported, whereas on the bottom the ones corresponding to the UB Hand IV prototype are shown for comparison. The three fundamental synergies derived for the DEXMART Hand are here briefly described.

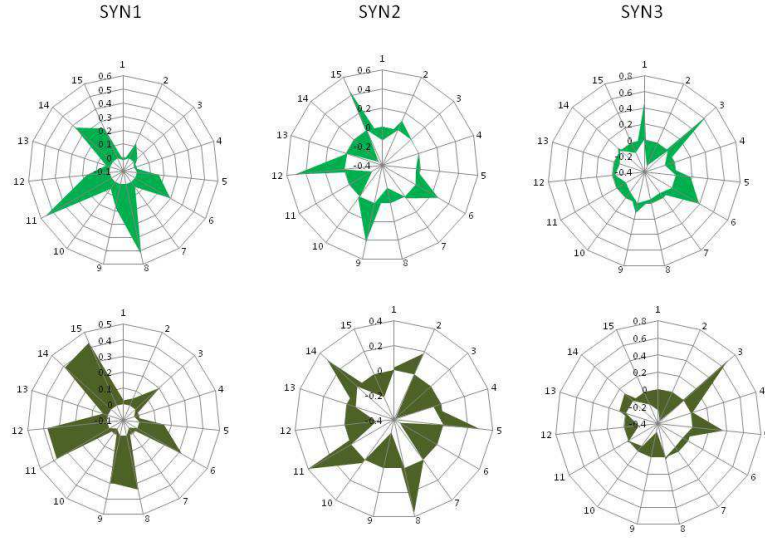


Fig. 6 Graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$. The adduction/abduction, proximal and medial flexion joints are indicated from 1 to 3 for the thumb, from 4 to 6 for the index finger, from 7 to 9 for the middle finger, from 10 to 12 for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

First Synergy

With reference to the first postural synergy (column $\mathbf{e}_1$ in Tab. 3, Fig. 7), 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.

Second Synergy

The second postural synergy (column $\mathbf{e}_2$ in Tab. 3, Fig. 8) 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.

Third Synergy

In the third postural synergy (column $\mathbf{e}_3$ in Tab. 3, Fig. 9) 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 char-

acteristic is important for correct index/thumb opposition that allows increasing the grasp accuracy, and thus achieving more stable grasps.

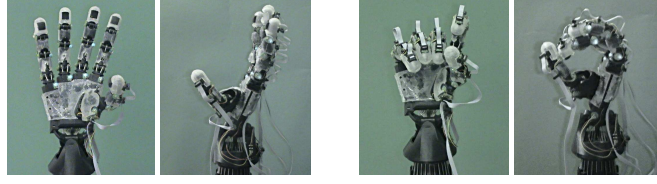


Fig. 7 From left to right, front and lateral view of the first postural synergy in the minimum and the maximum configuration.

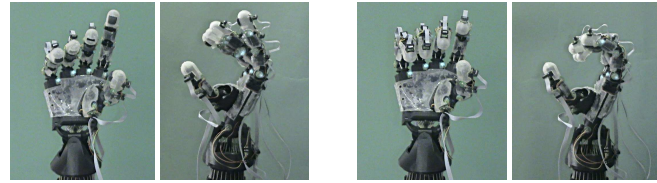


Fig. 8 From left to right, front and lateral view of the second postural synergy in the minimum and the maximum configuration.

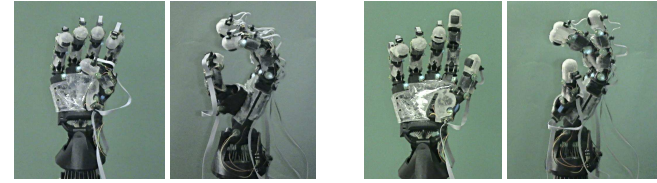


Fig. 9 From left to right, front and lateral view of the third postural synergy in the minimum and the maximum configuration.

By observing the circular graphs it emerges that the basic characteristics of the three synergies are quite similar for both the kinematics and methods. Nevertheless, with reference to the kinematics of the DEXMART Hand, even if the excursion of the thumb motion is greater in the third synergy, the differences with the previous two synergies are less evident if compared to the results on the previous robot hand prototype. Since the three predominant postural synergies derived for the DEXMART Hand account for $>86\%$ of the hand postures, i.e. the percentage of the total variance of the data described by the first 3 principal components of the $\mathbf{F}$ covariance matrix, it is expected that a control strategy that uses these synergies for robot hand motion allows obtaining very good grasping performance in a configuration space of highly reduced dimensions with respect to the DoFs of the robot hand itself.

5.2 Control with postural synergies

As in our previous work [9], the first three postural synergies have been used to control the hand in order to perform selected grasps from the reference set. 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

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

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

$$\begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix} = \mathbf{E}^\dagger (\mathbf{c}_i - \bar{\mathbf{c}}) \quad (4)$$

where $\mathbf{E}^\dagger$ is the Moore-Penrose pseudo-inverse of the base matrix $\mathbf{E}$. The temporal value of the weights $\alpha_1, \alpha_2, \alpha_3$ 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 (4) 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 (4) 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 $\{\bar{\mathbf{c}}, \hat{\mathbf{c}}_0, \hat{\mathbf{c}}_i\}$.

6 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 (4). 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.

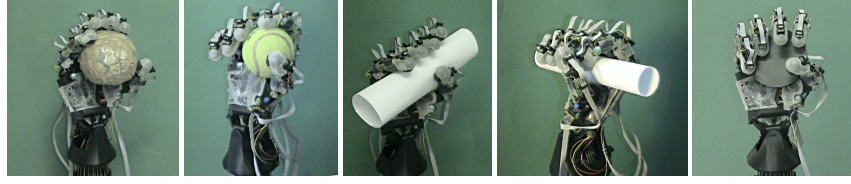


Fig. 10 Reproduced power grasps from the reference set of postures using the first three synergies.

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. Table 4 reports the first three synergy weights computed by

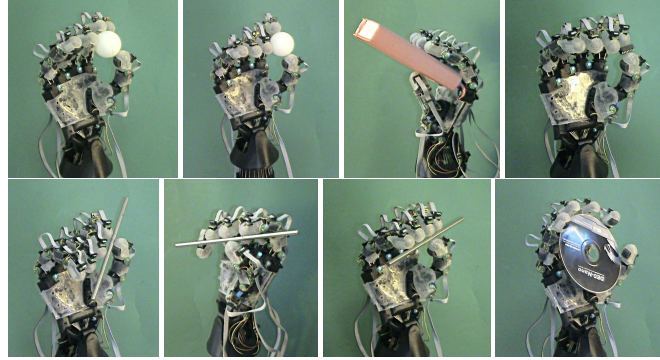


Fig. 11 Reproduced precision grasps from the reference set of postures using the first three synergies.

projection of the reference set of postures in the synergies subspace, and indicates the contribution rate of each synergy to achieve the final configuration.

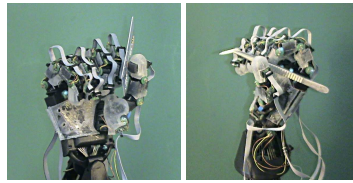


Fig. 12 Reproduced intermediate side grasps from the reference set of postures using the first three synergies.

Table 4 Synergy weights of the grasps from the reference set of postures.

Conf.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
α_1	6.853	46.23	49.31	59.63	25.91	-22.48	23.33	46.92	-15.63	29.30	40.92	53.38
α_2	-38.23	-9.027	-27.78	-16.81	89.32	94.38	-38.39	34.18	-31.73	-3.989	-21.40	-22.79
α_3	9.587	13.77	13.45	-13.61	-1.344	38.53	21.57	-18.98	13.45	-23.41	-26.13	-12.12
Conf.	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
α_1	0.379	23.39	-63.11	63.99	23.05	51.46	64.84	10.45	24.91	37.85	-0.793	-71.15
α_2	-13.23	11.83	1.973	26.72	-0.912	10.02	29.73	-3.443	-5.238	6.500	-3.208	9.748
α_3	6.449	-2.747	23.69	-5.729	-26.83	-3.781	-14.49	10.40	3.79	-4.464	9.452	11.09
Conf.	C25	C26	C27	C28	C29	C30	C31	C32	C33	C34	C35	C36
α_1	0.552	-31.042	12.68	-2.231	-37.17	6.858	49.08	106.4	-102.5	-94.19	-100.9	-103.6
α_2	-30.58	-3.642	-1.075	-7.637	8.701	-50.77	8.869	-5.661	3.314	10.97	-2.110	-8.587
α_3	-6.857	18.39	4.446	8.478	25.41	12.38	-6.857	-32.20	-33.54	-32.88	2.810	1.624

7 Conclusion

In this work, 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 RGB+Depth (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. A comparison with the synergies corresponding to the UB Hand IV prototype, obtained using a joint-to-joint mapping, reveals that the basic characteristics of the three synergies are quite similar for both the kinematics and methods. 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 on grasping various objects throughout a complete taxonomy.

References

1. DEXMART Project website. <http://www.dexmart.eu/>
2. Berselli, G., Borghesan, G., Brandi, M., Melchiorri, C., Natale, C., Palli, G., Pirozzi, S., Vassura, G.: Integrated mechatronic design for a new generation of robotic hands. In: Proc. IFAC Symposium on Robot Control. Gifu, Japan (2009)
3. Berselli, G., Piccinini, M., Palli, G., Vassura, G.: Engineering Design of Fluid-Filled Soft Covers for Robotic Contact Interfaces: Guidelines, Nonlinear Modeling, and Experimental Validation. IEEE Trans. on Robotics **27**(3), 436–449 (2011)
4. Berselli, G., Vassura, G.: Differentiated layer design to modify the compliance of soft pads for robotic limbs. In: Proc. IEEE Int. Conf. on Robotics and Automation, pp. 1285–1290. Kobe, Japan (2009)
5. Biagiotti, L., Lotti, F., Melchiorri, C., Palli, G., Tiezzi, P., Vassura, G.: Development of UB Hand 3: Early results. In: Proc. IEEE Int. Conf. on Robotics and Automation, pp. 4488–4493. Barcelona, Spain (2005)

6. De Maria, G., Natale, C., Pirozzi, S.: Force/tactile sensor for robotic applications. *Sensors and Actuators A: Physical* (2012). DOI 10.1016/j.sna.2011.12.042
7. Drenckhahn, D., Benninghoff, A.: *Anatomie: Makroskopische Anatomie, Embryologie und Histologie des Menschen. Zellen-und Gewebelehre, Entwicklungsbiologie, Bewegungsapparat, Herz-Kreislauf-System, Immunsystem, Atem-und Verdauungsapparat. Anatomie: Makroskopische Anatomie, Embryologie und Histologie des Menschen.* Urban & Schwarzenberg (1994)
8. Ficuciello, F., Palli, G., Melchiorri, C., Siciliano, B.: Experimental evaluation of postural synergies during reach to grasp with the UB Hand IV. In: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 1775–1780. San Francisco (2011)
9. Ficuciello, F., Palli, G., Melchiorri, C., Siciliano, B.: Planning and control during reach to grasp using the three predominant ub hand iv postural synergies. In: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1775–1780. Saint Paul, MN (2012)
10. Frati, V., Prattichizzo, D.: Using kinect for hand tracking and rendering in wearable haptics. In: *IEEE World Haptics Conference*. Istanbul (2011)
11. Geng, T., Lee, M., Hulse, M.: Transferring human grasping synergies to a robot. *Mechatronics* **21**(1), 272–284 (2011)
12. Gioioso, G., Salvietti, G., Malvezzi, M., Prattichizzo, D.: Mapping synergies from human to robotic hands with dissimilar kinematics: An object based approach. In: *Proc. IEEE Int. Conf. on Robotics and Automation, Workshop on Manipulation Under Uncertainty*. Shanghai (2011)
13. Kapandji, I., Honoré, L.: *The Physiology of the Joints: The upper limb. The Physiology of the Joints.* Churchill Livingstone (2007)
14. Lotti, F., Vassura, G.: A novel approach to mechanical design of articulated finger for robotic hands. In: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robot and Systems*, vol. 2, pp. 1687–1692 (2002)
15. M. Grebenstein et al.: A method for hand kinematics designers 7 billion perfect hands. In: *Proc. of 1st International Conference on Applied Bionics and Biomechanics*. Venice, Italy (2010)
16. Oikonomidis, I., Kyriazis, N., Argyros, A.A.: Full dof tracking of a hand interacting with an object by modeling occlusions and physical constraints. In: *Proc. 13th International Conference on Computer Vision*, pp. 1260–1264. Barcelona (2011)
17. Palli, G., Borghesan, G., Melchiorri, C.: Modeling, identification and control of tendon-based actuation systems. *IEEE Trans. on Robotics* **28**(2), 277–290 (2012)
18. Palli, G., Melchiorri, C., Vassura, G., Berselli, G., Pirozzi, S., Natale, C., De Maria, G., May, C.: Innovative Technologies for the Next Generation of Robotic Hands, In: *Advanced Bimanual Manipulation*, B. Siciliano (Ed.), vol. 80, pp. 173–218. Springer Tracts in Advanced Robotics (STAR), Springer (2012)
19. Palli, G., Natale, C., May, C., Melchiorri, C., Wurtz, T.: Modeling and control of the twisted string actuation system. *IEEE/ASME Transactions on Mechatronics* **PP**(99), 1–10 (2012). DOI 10.1109/TMECH.2011.2181855
20. Palli, G., Pirozzi, S.: Miniaturized optical-based force sensors for tendon-driven robots. In: *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 5344–5349. Shanghai, China (2011)
21. Romero, J., Feix, T., Kjellstrom, H., Kragic, D.: Spatio-temporal modelling of grasping actions. In: *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2103–2108. Taipei (2010)
22. Santello, M., Flanders, M., Soechting, J.: Postural hand synergies for tool use. *Journal of Neuroscience* **18**(23), 10,105–10,115 (1998)
23. Siciliano, B., Khatib, O. (eds.): *Springer Handbook of Robotics*. Springer (2008)
24. Zhang, C., Zhang, Z.: Calibration between depth and color sensors for commodity depth cameras. In: *Proc. Int. Conf. on Multimedia and Expo*, pp. 1–6. Barcelona, Spain (2011)