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A grasp synthesis algorithm based on postural synergies for an anthropomorphic arm-hand robotic system

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***Abstract*— In this paper development, implementation and experimental validation of a grasp synthesis algorithm for an anthropomorphic robotic arm-hand system in a low dimensional posture subspace is proposed. The algorithm has been developed on the basis of the analysis of human hand postural synergies. Drawing inspiration from neuroscientific studies, a database of grasps has been created through the observation and the analysis of the human finger posture during reaching and grasping tasks of several objects. The optimal hand configuration and wrist pose have been determined by applying an optimization procedure grounded on a stochastic method. The grasp synthesis algorithm has been validated in simulation and on a real arm-hand robotic platform consisting of the KUKA LWR 4+ robot arm and the DLR-HIT Hand II. The experimental results have validated the hypothesis made during algorithm implementation and have shown that the arm-hand robotic platform is able to perform the hand preshaping configurations predicted by the grasp synthesis algorithm.**

I. INTRODUCTION

Over the last decades, robotics research has produced significant advancements in the field of object grasping and manipulation. They mainly regard the design of novel robotic systems aimed at mimicking human hand morphology and behavior, as well as software improvements, e.g. the development of sophisticated grasp synthesis algorithms. This has led to an increase of potential dexterity but, also, to an increase of hardware and software complexity with, correspondingly, an increased difficulty in identification and control of stable grasping configurations. Several synthesis approaches for 3-D object grasping have been proposed in the literature [1] and are used to determine position and forces of each hand joint in order to apply a control strategy satisfying grasping properties such as dexterity, equilibrium, stability and dynamic behavior. Moreover, as shown in [2], synthesis algorithms have also to consider the task to be performed and the physical characteristics of the object to be manipulated, in order to ensure stability.

Grasping synthesis algorithms can be grouped into three main categories: analytical, heuristical, empirical. Analytical approaches [3] have high computational cost. Heuristical methods are proposed in [4] and [5]. Main limitations are the high dimension of the solution space for grasp optimization and the need of computing hand inverse kinematics in order to guarantee that the object contact points are physically reachable by the robotic hand. Empirical approaches are based on the imitation of human grasping strategies by choosing the hand configuration that fits the task constraints as well as the object characteristics [6]. In order to reduce the grasp space dimension and the hand control complexity, it has been investigated whether humans use a combination of basic grasp configurations for prehensile postures [7], [8]. This analysis has shown that a wide range of grasping tasks can be achieved through a reduced number of basic hand configurations [9]. In [10], a set of quantitative indicators have been defined for the description of the human hand behaviour and the development of a grasping algorithm able to replicate the same observed behaviour with a robotic hand. In [11], the authors have used linear combinations of *eigengrasps* (i.e. eigenvector basis which generates linear subspaces describing hand postures) to obtain a wide range of hand postures for grasping tasks. However, while the finger pose is automatically synthesized, the wrist pose is imposed by the human operator. Additionally, the database used to extract synergies for the algorithm is made of data taken from humans using objects of real life [9]. Therefore they can hardly be applied to the robotic hands that cannot handle such objects.

The main purpose of this work is to extend the approach in [11] to the wrist by using a more suitable database for extracting synergies and determining finger and wrist pose of an anthropomorphic robotic hand. A new grasping database has been specifically created for the robotic hand by selecting grasps that can be performed and objects that can be grasped by the adopted robotic hand. The proposed algorithm has been experimentally validated on a real anthropomorphic arm-hand robotic system made of the Kuka/LWR 4+ and the DLR-HIT-Hand II.

The paper is structured as follows: in Section II, the grasp synthesis algorithm is described; Section III is focused on the algorithm implementation on the anthropomorphic robotic platform. Experimental results in simulation and on the real robot are illustrated in Section IV. Finally, Section V reports conclusions and future work.

II. GRASP SYNTHESIS ALGORITHM

A. Algorithm Formulation

It has been demonstrated in [9] that grasping hand configurations are distributed in a multidimensional continuum, whose dimension can be reduced thanks to synergies (i.e. patterns of human motor coordination during reaching and

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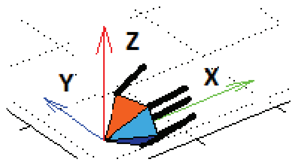


Fig. 1. Algorithm reference frame centred in the wrist. X-axis is parallel to the reaching direction, Y-axis is perpendicular to the hand plane and Z-axis is defined with the right hand rule.

grasping tasks). In particular, the usage of postural synergies implies a reduction of the control space dimension via Principal Component Analysis (PCA) on joint angle values extracted during grasping. Different grasping postures are gradually reached in the multidimensional continuum space as linear combination of a reduced number of principal components. The approach proposed in [11], and grounded on the concept of postural synergies, defines a grasp planner for determining finger posture of a robotic hand; on the other hand the wrist pose is manually specified by the human user.

The grasp synthesis problem is regarded as an optimization problem based on the same quality function proposed in [11]. Benefiting from the extracted synergies, it can be expressed as a function of the amplitude of two eigengrasps and the six variables of the wrist pose, as

$$Q = f(a, w), \quad a \in \mathbb{R}^b, \ w \in \mathbb{R}^6 \tag{1}$$

where a is the vector of the eigengrasp amplitudes (it has been demonstrated that a high number of grasping configurations is described by varying eigengrasp amplitudes), b is the eigengrasp number used for expressing the hand posture and w describes the wrist pose. Once a set of contact points have been chosen on the hand fingers and palm (in this work they are located as explained in Sect. III), the minimization of the quality function leads to the hand configurations that make the chosen contact points as close as possible to the object to be grasped. Therefore, it is possible to conclude that the quality function, for each hand posture, is a function of the distance between hand contact points and the object surface, as demonstrated also in [10] for power grasps. Afterwards, the quality function can be written as

$$Q = \sum_{i=1}^{n} \delta_i = \sum_{i=1}^{n} \frac{|o_i|}{\alpha} + \left(1 - \frac{\widehat{n_i} \cdot o_i}{|o_i|}\right). \tag{2}$$

where n is the number of desired contact points, δ_i is the distance between a contact point and the object surface, o_i is the minimum distance of the i-th contact point from the object surface, $\widehat{n_i}$ is the normal to the surface in the neighborhood of the contact point and α is a scaling factor needed to uniform the two addends.

The system reference frame has the origin in the wrist and is oriented as shown in Fig. 1. With respect to this reference frame, the unit vector applied to the contact point and normal to the object surface is defined as follows

$$\widehat{n} = p_{contact} + \widehat{z} \times \widehat{link} \tag{3}$$

where $\widehat{z}$ is the unit vector of the rotation axis perpendicular to the link the contact point belongs to and $\widehat{link}$ is the finger link unit vector the contact point belongs to. The optimization procedure relies on the *Simulated Annealing* method [12]. The synergies extracted from a database of reference grasps (explained in Sect II-B), the initial pose of the wrist and the position and shape of the object to be grasped are required for algorithm implementation. A synergy matrix (i.e. the relation between joint variables and postural synergies) is extracted from the database through the PCA; the first two eigengrasps of the synergy matrix represent the finger pose. It can be expressed as

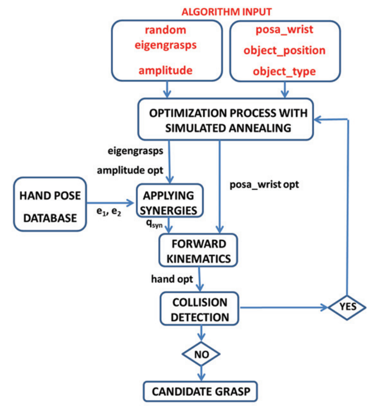


Fig. 2. Flowchart of the grasping synthesis algorithm.

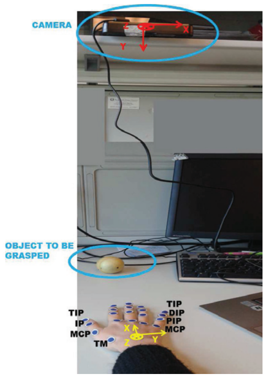
$$p = p_m + \sum_{i=1}^{b} a_i e_i \tag{4}$$

where p_m is the mean hand pose describing the origin of the eigengrasp subspace, $e_i \in \mathbb{R}^d$ is the i-th eigengrasp vector and d is the number of hand DoFs. The i-th eigengrasp is the i-th column of the synergy matrix.

In Fig. 2 a flowchart describing the grasping synthesis algorithm steps is shown. The synthesis algorithm takes in input variables a and w and, iteratively, uses them for obtaining the optimized configuration for wrist and finger by applying the forward kinematics, taking into account possible collisions and interpenetration. If no collisions occur, the quality function value associated with the current status of the eight variables to be optimized is compared with the optimal quality function value obtained in previous iterations. If the current value is lower than the previous one, it is saved (by replacing the previous one) as it indicates a new feasible optimal grasping configuration. The optimized variables are then used in the forward kinematic function to obtain the grasping configuration in the reduced dimension space of the hand postural synergies. It is important to note that the grasp planning in the eigengrasp subspace generates a hand preshaping configuration rather than a grasping configuration: the hand contact points are not actually in contact with the object surface. Therefore, it is necessary to introduce a *closing finger command* that moves the finger until they reach the object surface. This implies that the hand posture moves away from the eigengrasp space in order to mold the target object surface.

B. Grasp Database

The grasping algorithm receives in input postural synergies extracted from a database including hand joint angles during grasping tasks and the corresponding wrist orientation. In this work the database composed of data from [9] was used to verify the functioning of the synthesis algorithm. Data in [9] are related to finger pose and to wrist pitch and yaw angles during the grasping of 57 commonly used objects performed by one healthy subject (the roll angle is fixed during grasping since the hand is semi-pronated on the plane). Since this database has been created for extracting postural synergies for the human hand, it is not appropriate for robotic hands, which have different motion capabilities. Therefore, a new database has been created and is still being completed specifically focused on objects graspable by the robotic hand. It is made of data related to a higher number of healthy subjects (i.e. 10), but with a more limited set of objects. Due to the higher number of subjects a higher level of generalization to also robotic hands is expected. The new database is composed of wrist and fingers pose acquired by the Asus Xtion Prolive motion sensing device and reconstructed by the hand pose estimation approach proposed in [13], i.e. a marker-based approach grounded on the Unscented Kalman Filter (UKF) where the hand kinematics is used to enclose geometrical constraints in the estimation process. In brief, in order to estimate the hand pose, 21 markers made of blue paper are placed on the subject hand, as shown in Fig. 3(a), and a fast detector based on color histogram and a connected component labeling algorithm have been implemented [14]. The Asus Xtion



(a) Setup

Object type	Size	Grasping type
Ball 	radius = 3 cm	tripod
Glue stick 	radius = 2.8 cm height = 11.3 cm	pinch
Stack of glasses 	radius = 3 cm height = 18 cm	Power grasp

(b) Objects

Fig. 3. (a) Protocol used for marker positioning and joint reference frames in the hand starting position. The system reference frame (in yellow) is positioned on the hand wrist [13]. The camera frame is outlined in red. (b) Object to be grasped with corresponding physical characteristics and the corresponding grasp configuration.

Prolive works at $30fps$ and is made of an InfraRed (IR) laser emitter, an IR camera for measuring depth information and a RGB camera with a resolution of 640×480 pixels. The pose estimation algorithm is a stochastic optimization approach whose output is made of the pose parameters – position $T(t)$ and orientation $R(t)$ – of the wrist with respect to its initial pose, together with the kinematics of the 17 finger joints. Two participants were required to grasp three objects with three different grasp configurations, as shown in Fig. 3(b). Each grasping type was designated for one object and was repeated 4 times. They were seated in front of a table on which the objects were located in a a-priori known position. In the hand starting configuration, the wrist was pronated, the four long fingers were fully extended and the thumb was adducted. The starting configuration allows evaluating Denavit-Hartenberg parameters for each subjects and, hence, make the algorithm valid for different hand sizes. After grasping, the subject held the object for a while, until an auditory cue announced the acquisition end. Before starting the data acquisition, each participant was asked to grasp the object five times, in order to get familiar with the grasping action.

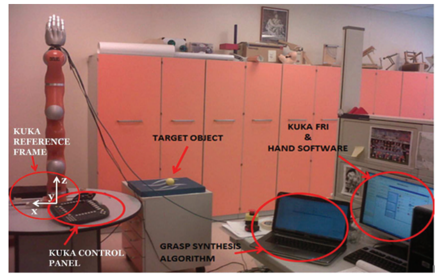


Fig. 4. Experimental Setup adopted for validating the grasping synthesis algorithm. The KUKA reference frame is outlined in white.

III. Algorithm Implementation on the Arm-Hand Robotic System

The grasping synthesis algorithm has been designed for planning the reach-and-grasp action of an anthropomorphic arm-hand robotic system. The robotic platform (left side of Fig. 4) is composed of the KUKA-LWR 4+ [15], which acts as the arm responsible for the reaching task, and an anthropomorphic robotic hand (i.e. the DLR-HIT Hand II [16]) mounted on the KUKA-LWR end effector and responsible for preshaping and grasping. The KUKA-LWR is a 7 DoFs anthropomorphic robotic arm, which communicates with a remote PC through the Fast Research Interface (FRI) Library. It runs on a remote PC node connected to the KUKA Robot Controller via an UDP communication protocol that guarantees high dependability for real-time operations.

During reaching, the arm moves with a minimum jerk trajectory until the final position (provided by the synthesis algorithm) is reached. A position control in the joint space has been chosen in order to obtain an accurate motion (position errors in the Cartesian space are of the order of hundredths of a mm). Since the planning phase is in the Cartesian space, a kinematic inversion procedure [17] is used to generate reference values for the joint variables. The reaching movement lasts 20 seconds, with low velocity for security reasons. Once the reaching phase is completed, the preshaping phase takes place and the hand fingers are closed in order to maximize the contact area with the object. A third degree polynomial function has been used to plan the joint motion up to the final reference value and a PD torque control in the joint space enabled reaching the desired final angles. Eleven contact points are located on the robotic hand (i.e. the DLR-HIT-Hand II). In particular, two contact points are considered for each finger: one is located in the middle of the link connecting MCP and PIP joints, the other is located in the middle of the link connecting the DIP joint and the fingertip. The last one is on the hand palm. The grasp synthesis algorithm produces as output the optimized wrist pose referred to the hand base frame (Fig. 1); a transformation of reference system has been performed to move the wrist pose in the KUKA reference frame.

IV. Experimental Results

The grasp synthesis algorithm has been validated on the arm-hand robotic system in simulation and on the real system. The objective of the validation procedure in simulation is to find the best set of input parameters for the simulated annealing algorithm in order to achieve a compromise between the goodness of the grasping configuration and the computational cost. On the other hand, the experimental tests are aimed to verify if the platform can replicate the grasping configuration obtained in simulation and if the proposed configuration is stable.

A. Algorithm Validation in Simulation

The grasping synthesis algorithm has been tested in simulation by using the database in [9] enriched with the data of the database described in Sect. II-B. In order to find the optimal set of input parameters for the simulated annealing approach, five tests have been carried out using the same object. In particular, the following parameters have been tuned:

1) distance between the object and the hand along the reaching direction;
2) constraints for searching the optimal solution;
3) temperature (i.e. the system control variable in the simulated annealing method; it defines the state space region explored by the algorithm in a particular phase);
4) initial condition for searching the optimal solution;
5) iteration number.

Furthermore, the objective function behaviour during the optimization process is monitored and a comparison between the approach proposed in [11], with a manual imposition of the wrist pose, and the approach followed in this work, with the automatic estimation of the wrist pose, is also reported. The wrist/no wrist compared analysis will lead to identify the best approach in terms of computational cost and final grasping configuration.

1) Case 1: hand-object distance variation: Three different hand positions with respect to the object have been considered. The other parameters are set as follows. The starting temperature is given by

$$T_{in} = \frac{\frac{Q_{start}}{2} - Q_{start}}{ln(\frac{0.1}{0.9})} \qquad (5)$$

where Q_{start} is the starting value of the quality function. It has been supposed that, at one half of Q_{start}, the probability of accepting the new state is equal to 90%. The

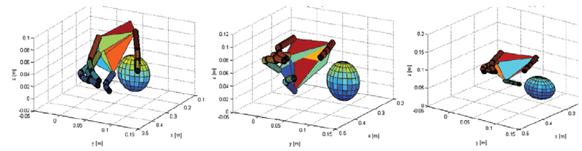


Fig. 5. Optimal grasping configuration obtained with the synthesis algorithm corresponding to the best hand initial position with respect to the object to be grasped with starting temperature given by eq. (5) (left), equal to 100 (center), corresponding to a vector of values (right).

iteration number is equal to 1000 and lower and upper limits for searching the optimal solutions have been chosen in order to have a human-like optimized grasping configuration. Therefore, eigengrasp amplitude limits have been chosen according to [11] and wrist position is enclosed in the object graspable region, i.e. the object portion in which the user will most probably perform the grasp. Joint RoMs have been also considered. In Table I lower and upper limits for each variable to be optimized are listed. In particular, the values are related to the case of grasping a ball. In Tab. I,

TABLE I

Lower and upper limits for the variables to be optimized

bound	a_1	a_2	w_x	w_y	w_z	ϕ	θ	ψ
lower	-2	-2	$obj_x - r - l_{hand}$	$obj_y - 1.5r$	$\frac{h_{hand}}{2}$	-15^o	-15^o	-90^o
upper	2	2	$obj_x + r$	$obj_y - \frac{r}{2}$	$obj_z + r$	30^o	30^o	0^o

obj_x,obj_y, obj_z are the object center coordinates, r is the object radius, l_{hand} and h_{hand} are hand lengths (from the base to the middle fingertip) and palm width, respectively. Running the simulation, the best initial position of the hand with respect to the object to be grasped has been obtained (left side of Fig. 6). In particular, the best distance is equal to $5cm$.

2) Case 2: constraints variations for searching the wrist orientation optimal solution: The range of values of wrist orientation, where the optimal solution is searched, is enlarged by considering the whole physiological RoM: $\phi = -70^o \div 65^o$, $\theta = -15^o \div 30^o$, $\psi = -90^o \div 90^o$.

3) Case 3: temperature variation: Three different starting temperature values have been considered: 1) the temperature obtained from eq. (5); 2) a temperature equal to 100; 3) a starting temperature chosen on the basis of the solution research interval amplitude (therefore, a vector of values is given in input to the algorithm). Results, shown in Fig. 5, have demonstrated that the best temperature starting value is given by eq. (5).

4) Case 4: starting wrist orientation variation: The grasping synthesis algorithm output is influenced by the wrist starting orientation. This is evident from Figure 6, where wrist orientation starting values are taken from the database in [9] for the left configuration while starting values from the new database are taken for the right configuration. The values in the two cases are reported in Table II. In the first case an enveloping grasp is obtained, whereas, in the second case, the lateral approach to the object and the finger preshaping corresponds to a tridigital grasp (i.e. the same executed during acquisitions with the motion analysis system). Therefore, it is possible to conclude that the starting

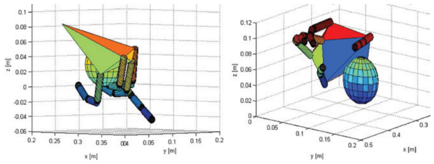


Fig. 6. Optimal grasping configuration obtained with the synthesis algorithm corresponding to two different starting conditions for the wrist orientation. The wrist orientation angles are obtained from the database in [9] (left) and from the new database (right).

conditions on the wrist orientation influence the grasp type synthesized by the algorithm. However, consider for example wrist orientation starting value equal to [8.87^o, 30^o, 0^o], the final wrist orientation is [29.35^o, 28.61^o, -57.24^o]. Hence, initial conditions are not so binding and the approach is quite generalizable.

TABLE II

ROLL-PITCH-YAW EULER ANGLES DESCRIBING WRIST ORIENTATION STARTING VALUES.

Wrist orientation	ϕ	θ	ψ
Santello database	8.87^o	30^o	0^o
motion analysis	-0.48^o	-45^o	0^o

5) Case 5: iteration number variation: Varying the iteration number shows that higher iteration numbers lead to a more effective minimization of the distance between hand contact points and the object and, consequently, a better grasp configuration. However, high iteration number implies a higher computational burden. An iteration number of 1000 represents a good compromise between accuracy of the synthesized grasping configuration and computational cost. In this condition, the algorithm can also be used for an on-line implementation on the robotic platform.

Given the optimal set of input parameters, the objective function behaviour during the optimization process has been studied. It is possible to note that the function reaches the minimum around iteration 180 and keeps this value until the end of iterations, i.e. 1000.

Finally, the comparison wrist/no-wrist is reported, thus comparing our case of automatic determination of optimal wrist pose with the case of manual imposition of wrist final pose. The two approaches are compared in terms of computational cost and final grasping configuration. The obtained results have shown that the computational time for the automatic wrist determination is around 300 sec, whereas in the no wrist case, it is equal to 220 sec. Although the computational time is slightly lower for the no wrist case, the difference between joint angles given by the optimization algorithm and the corresponding values measured after the finger closing command is higher than the wrist case. Therefore, the fully automatic method seemed the best compromise between computational cost and performance.

B. Algorithm Validation on the Robotic Platform

The grasping synthesis algorithm has been validated on the robotic platform with two different objects: a ball with a radius of $3cm$ and a cylinder with a radius of $4cm$ and height of $22cm$. For each object three different trials have

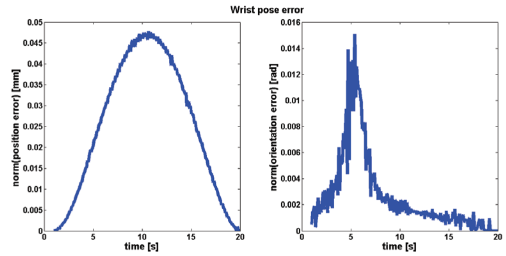
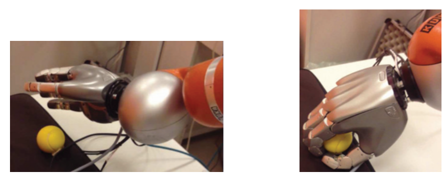


Fig. 7. Wrist pose error between the algorithm output and the pose actually reached by the KUKA end-effetor.

been performed. The pose of the KUKA end-effector and the robotic hand fingers configuration are given by the grasping synthesis algorithm. In particular, the KUKA end-effector corresponds to the wrist in the grasping algorithm. The error between the wrist position and orientation obtained with the optimization algorithm and those actually reached by the robot wrist, in the case of grasping a ball, are shown in Fig. 7. In figure 8, the reaching and grasping configurations of the robotic system performing the grasping of the ball are shown.



(a) reaching (b) grasping

Fig. 8. The reaching and grasping configurations performed by the robotic arm-hand system.

The error between the angle values read from the robotic hand position sensors and averaged on the three trials, have been compared with the angles given by the synthesis algorithm. In Fig. 9 mean error ($\pm$ SD) values are listed. For the sake of brevity, only the results regarding the ball are shown. The results demonstrate that the difference between the two configurations is small (of the order of tenth of a degree). However, it is worth considering that, when the contact with the object takes place, the finger postures slightly deviate from the subspace described by the eigengrasps for adapting to the target object morphology. Therefore, joint angle values at the end of the preshaping phase have been compared to the corresponding values measured after the finger closing command. Their distance in norm has been evaluated but the values are not reported for the sake of brevity. Anyway, it

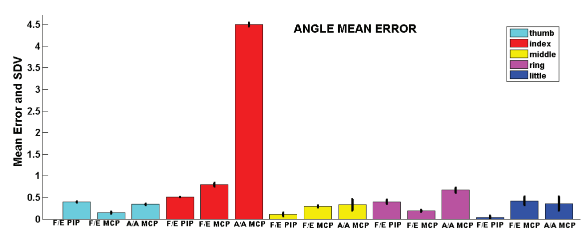


Fig. 9. Mean error ($\pm$ SD) between preshaping angles read from position sensors and given by the synthesis algorithm. Values are expressed in degrees.

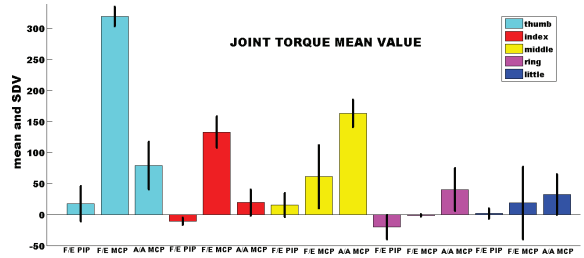


Fig. 10. Mean joint torque values (± SD). Values are expressed in mNm.

can be observed that a smaller distance implies that the joint is closer to the object during preshaping. As expected, due to the choice of the contact points in the synthesis algorithm, the difference is small for thumb MCP flexion/extension angle and for index flexion/extension angle, for both the objects. It means that, at the end of preshaping, the object is located between the thumb and the index finger in proximity of the palm, whereas the remaining fingers are farther from the object and need bigger closing angle values for touching it.

Joint torque values are also measured in order to verify the correspondence between the set of contact points imposed in the algorithm and those actually reached at the end of the finger closure on the object surface. In Fig. 10 the torque mean values (± SD) computed on the three trials are listed. Results,regarding only the ball case for the sake of brevity, show that higher torques are found for the thumb and the index finger. This reinforces the conclusion that such fingers are the nearest ones to the object, due to the contact point on the palm.

V. Conclusion

This paper has borrowed from [11] the formulation of a grasp synthesis algorithm based on postural synergies, and has extended it to the wrist. To this purpose, a new database of grasp data has been developed to extract the synergies, in order to have grasping tasks achievable with the robotic hand. The new database consists of wrist and fingers pose acquired by a motion sensing device and reconstructed by an ad hoc developed hand pose estimation approach. The optimization procedure for the synthesis algorithm is grounded on a stochastic optimization method, i.e. the simulated annealing, able to provide the optimal hand configuration that avoids finger collisions and respects joint RoMs. The obtained optimal hand configuration has been preliminary validated in simulation and then tested on a real arm-hand robotic platform consisting of the KUKA LWR 4+ robot arm and the DLR-HIT Hand II. The experimental results have shown that the robotic platform is able to perform the hand preshaping configurations predicted by the grasp synthesis algorithm confirming the hypothesis on the hand contact areas made during algorithm implementation. Higher performance is obtained for power grasps where, after closing the fingers, the contact area between hand and object is maximized, thus achieving a higher level of stability. Future works will concern the extension of the new database to more subjects and grasp tasks involving only objects that can be grasped by the adopted robotic hand. A more extensive study about the success rate of the robotic grasps in order to better demonstrate the robustness of the proposed grasp planning will be performed. Further an extension of the synthesis algorithm to the phase of contact with the objects is envisaged, thus accounting also for contact forces. An on-line implementation of the approach will be also carried on.

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