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Experimental Evaluation of Synergy-Based In-Hand Manipulation

Gianluca Palli * **Fanny Ficuciello** ** **Umberto Scarcia** *
Claudio Melchiorri * **Bruno Siciliano** **

* *DEI - Department of Electrical, Electronic and Information Engineering - University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy*
** *DIETI - Dipartimento di Informatica e Sistemistica, Università degli Studi di Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy*

Abstract: In this paper, the problem of in-hand dexterous manipulation has been addressed on the base of postural synergies analysis. The computation of the synergies subspace able to represent grasp and manipulation tasks as trajectories connecting suitable configuration sets is based on the observation of the human hand behavior. Five subjects are required to reproduce the most natural grasping configuration belonging to the considered grasping taxonomy and the boundary configurations for those grasps that admit internal manipulation. The measurements on the human hand and the reconstruction of the human grasp configurations are obtained using a vision-based mapping method that assume the kinematics of the robotic hand, used for the experiments, as a simplified model of the human hand. The analysis to determine the most suitable set of synergies able to reproduce the selected grasps and the relative allowed internal manipulation has been carried out. The grasping and in-hand manipulation tasks have been reproduced by means of linear interpolation of the boundary configurations in the selected synergies subspace and the results have been experimentally tested on the UB Hand IV.

Keywords: Dexterous Manipulation, Postural Synergies, Robotic Hands, Grasping.

1. INTRODUCTION

Solving the problem of robotic grasping and manipulation involves many complex issues, and the theoretical approach based on the research of optimal solutions results too complex to be implemented in practice with the actual technologies (sensors and computational capability) and poorly reliable due to the simplified modeling of the real system behavior. On the other hand, neuroscience studies point out the natural ability of humans to unconsciously find sub-optimal solutions to those problems. Moreover, the observation of human behavior shows the presence of coordinated motions among the degrees of freedom of the fingers in common to many different grasping postures [Santello et al., 1998, Mason and Salisbury, 1985]. The applications of postural synergies to dexterous robotic hands reported in literature regard essentially problems of hand preshaping during grasping actions and grasp synthesis using the first order synergies, see Ciocarlie and Allen [2009], Wimboeck et al. [2011], Villani et al. [2012]. A synergy-based grasp planning approach relying only on object geometric features and task requirements have being also investigated in literature [Vilaplana and Coronado, 2006, Ficuciello et al., 2012b]. For synergies computation, the Principal Component Analysis (PCA) method has been preferred in several work since it is fast and allows finding global optima with good performance in representing new grasps and, due to its linearity, it allows planning the movements of the robot hand by means of a simple linear interpolation of the synergies [Sun et al., 2010, Wimboeck et al., 2011, Matrone et al., 2010]. At present, the role of synergies in fine manipulation are quite unexplored and the problem of transferring human hand motion to a robotic hand is quite challenging due to the complexity and variety of hand kinematics and the dissimilarity with the robotic hand [Gioioso et al., 2011, Geng et al., 2011]. In this work, we explore the role of synergies in fine manipulation by extending the previous results on grasping. In Ficuciello et al. [2012a] a method based on the acquisition of contact points related to a set of 36 human grasping tasks performed by different test subjects has been described. Since data were collected from subjects with hands that have different kinematics, it was necessary to adopt a normalization procedure to a common kinematic structure which in our case is the UB Hand IV (University of Bologna Hand, version IV) kinematics. Then through kinematic inversion the scaled data were transformed from the Cartesian space to the robotic hand joint space. Finally, the measures have been elaborated by using PCA and the three predominant synergies extracted from the data have been exploited to implement a grasp planner based on defining a trajectory within the synergy subspace. In this work, this previous result is extended in order to represent not only grasps but also manipulation tasks as trajectories connecting suitable configuration sets in the synergy subspace. The basic idea comes out from the observation that there are grasp postures, mainly the precision grasps, that admit internal manipulation (an example is depicted in Fig. 1). Then, starting from the basic reference grasp set, we have enlarged the database of postures by adding the hand configurations that

Fig. 1. Representation of an internal manipulation task starting from a basic grasp posture: from left to right, counterclockwise rotation, basic grasp and clockwise rotation.

represents the maximum and minimum bounds for those grasps that admit internal manipulation without loosing the contact between fingertips and the object. To preserve the characteristic and the properties of the previously defined synergy-based grasp synthesis, the in-hand manipulation tasks are represented as deviations from a reference grasp and are obtained by adding so-called manipulation synergies defined in an orthogonal configuration subspace. Preliminary simulations and experimental results are reported to validate the proposed approach.

The paper is organized as follows: Section 2 describes the experimental setup made of 3D vision system for data acquisition and the UB Hand IV. Section 3 describes the method adopted to derive grasp postural synergies and the extension of the synergy-based approach to the manipulation tasks. Section 4 reports the simulation and the experimental evaluation of the proposed synergy-based manipulation planning and, finally, Section 5 provides the conclusion.

2. EXPERIMENTAL SETUP AND DATA ACQUISITION

The kinematics of the UB Hand IV allow the joint angles to be univocally reconstructed from the measurements in 3D space of the fingertip positions. In order to simplify the detection of the human hand postures, a low cost RGBD camera sensor have been used to detect the position of the human fingertips with respect to the wrist. A software application that allows collecting and saving the information coming from the Kinect has been developed, and the data collected in this way have been used for the joint space pose reconstruction by means of an inverse kinematics algorithm. In this way, the occlusion problems that affect motion capture methods for the detection of the human hand postures and joint positions during grasps have been solved.

2.1 Data Acquisition System

The Kinect camera sensor from Microsoft Corp. has been used to provide the RGB color image and the corresponding depth image of the human hand for fingertip position measurements. After a suitable calibration of the device [Zhang and Zhang, 2011], it is possible to reconstruct the 3D real world coordinates (in meters) with respect to the camera frame of each point in the acquired image with precision of about 1.5mm 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. 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.

2.2 The UB Hand IV

The UB Hand IV [Berselli et al., 2009, Palli et al., 2012b] is an innovative anthropomorphic hand developed within the DEXMART project [DEX]. The hand design aims at an improved human-like manipulation capability and mobility. Indeed, the robotic hand is able to perform the opposition of the thumb with the other four fingers. The Denavit-Hartenberg (DH) parameters of the UB Hand IV are reported in Tab. 1: note that all

Table 1. Denavit-Hartenberg parameters of the UB Hand IV.

Link (Thumb)	d [mm]	θ	a [mm]	α [deg]
1	-42.5	θ_1+85	18	-90
2	-1.65	θ_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	θ_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	θ_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	θ_2+15	35	0
3	0	θ_3	28	0
4	0	θ_4	28.5	0

the fingers present different lengths of the links in order to fit better with the human hand kinematics.

Remotely located actuators with tendon-based transmissions routed by sliding paths [Palli et al., 2012a] 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.

3. GRASPS AND MANIPULATION ANALYSIS AND SYNTHESIS

In this section, the synergy-based grasp analysis and synthesis developed in previous works [Ficuciello et al., 2012a] is briefly summarized to provide an overview of the basic grasp planning and the extension of the synergy-based approach to in-hand manipulation tasks representation is reported.

3.1 Synergy-Based Grasp Analysis

The choice of the reference set of postures for grasp synthesis has been made by taking into account the most common human grasp taxonomy reported in literature [Feix et al., 2009, Romero et al., 2010]. The considered set is composed by grasps of objects such as spheres of different dimensions involving a different number of fingers in both power and precise grasp configuration. Cylindrical grasps have been considered as well, distinguishing also between different positions of the thumb. Moreover, several configurations for precise grasps with index