

Synergies Evaluation of the SCHUNK S5FH for Grasping Control

Fanny Ficuciello, Alba Federico, Vincenzo Lippiello, and Bruno Siciliano

Abstract In this work, a study on postural synergies has been conducted on an under-actuated anthropomorphic hand, the SCHUNK Five-Fingered Hand (S5FH). Human hand grasps are mapped on the robotic hand using fingertips measurements, obtained with an RGBD camera sensor, and inverse kinematics. Since the S5FH is under-actuated, an approximate solution can be obtained using the differential kinematics mapping between the motor space and the Cartesian space and a closed-loop inverse kinematics (CLIK), based on a high-rectangular hand Jacobian that takes into account the mechanical synergies of the hand. The so-computed motor synergies have been tested for hand control during grasping. The motor current measurements have been used to limit the grasping forces through a motor position control in the synergies subspace.

Key words: Grasping, Anthropomorphic Hands, Postural Synergies.

1 Introduction

Nowadays, in robotics and prosthetic applications, postural synergies have been widely recognized to be a powerful tool to plan grasps and control artificial hands using few parameters compared to the degrees of freedom (DOFs) of the hand itself [1]. Several methods have been proposed to compute the synergies subspace. In [2], [3], [4] the basis space of synergies is represented by a matrix of constant eigengrasps (basis of eigenvectors), while in [5] syn-

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ergies are mapped directly from human to robotic hands using non-constant eigengrasps.

The authors' previous work refers to fully actuated anthropomorphic hands [6], [7], [8], [9]. In these works, the experimental results highlight that,



Fig. 1 The Schunk Five-Fingered Hand.

despite the differences in kinematics and mapping methods, the first three synergies have some basic features that are preserved if the hand kinematics is anthropomorphic and if the grasps data set is suitably chosen to cover a large variety of human grasping postures [10], [11].

In this work, the method developed in [8] has been adapted and tested to evaluate the first three synergies on an under-actuated five-fingered hand suitable for service robot applications in the household domain, the S5FH depicted in Fig. 1. The hand possesses 20 degrees of mobility and it is designed with “mechanical synergies” that regulate the kinematic couplings between the finger joints while decreasing the number of motors from 20 to 9.

One of the main problems of under-actuation is that the inverse kinematics problem that maps fingertips Cartesian space onto joints motor space does not necessarily have a closed-form solution, but in some cases only an approximate solution that minimizes the norm of the error can be obtained. Moreover, the human hand grasps cannot be accurately mapped onto the robotic hand since some information is unavoidably lost due to mechanical couplings between the joints.

A valuable possibility to obtain a solution to the inverse kinematics problem is to use the differential kinematics mapping between the motor space and the Cartesian space and a closed-loop inverse kinematics (CLIK) algo-

rithm based on the high-rectangular hand Jacobian that takes into account the mechanical synergies of the hand.

In this work, a data set of grasps, measured on five human subjects and available from the authors' previous work, is used to evaluate the grasping capabilities of the robot hand in a synergy-based framework. For this purpose, a synergies Jacobian can be computed and suitably used in the CLIK algorithm to map the grasps from the human hand to the robotic hand. The details of the grasping data and mapping method can be found in [2, 8].

The results demonstrate that the computed synergies are suitable to control the hand in a three-dimensional subspace and the evaluated features of the first three synergies confirm the results obtained in [12], i.e. the grasping capabilities are very similar to those of the fully actuated anthropomorphic hands.

The paper is structured as follows: in Sect. 2 the hand kinematics and the mechanical synergies are described, while in Sect. 3 the method for synergies computation is briefly described and the computed synergies are analyzed. Section 4 reports the experimental results obtained using the synergy-based control for grasping actions and grasping forces regulations. Finally, Section 5 provides the conclusions and sketches future work.

2 The Schunk S5FH

The Schunk S5FH has an anthropomorphic structure very similar to the human hand for shape, size and overall for the cosmetic appearance. Indeed, the dimensions are of 1 : 1 ratio with the human hand and the weight is of 1.3 kg. The control and power electronics are integrated in the wrist allowing an easy connection with market-standard industrial and lightweight robots. The current technology, however, does not allow arranging twenty or more motors within a mechanical structure with dimensions similar to those of the human hand while ensuring appropriate requirements of speed and strength. As a matter of fact, the S5FH has 20 joints and 9 DOFs led by servo motors. The reader can find the whole technical data, hardware and software specifications in [13] and [14].

Hence, the number of motors is significantly lower than the number of joints and suitable motion couplings are obtained by means of mechanical synergies defined via mechanical transmissions.

Let $\mathbf{q}$ be the vector of the 20 joint angles describing the robotic hand configuration. The joint motions (Fig. 2) are coupled according to the mechanical synergies matrix, defined below. $\mathbf{m} \in \mathbb{R}^m$, with $m = 9$, is the vector of motor variables and $\mathbf{q}_0$ is an offset representing the vector of joint values when the motor positions are zero. In vector $\mathbf{q}$ the finger joints are pointed in progressive order from the thumb to the little finger using the subscripts t, i, m, r, l . Not all the fingers have the same number of joints and motors. About the

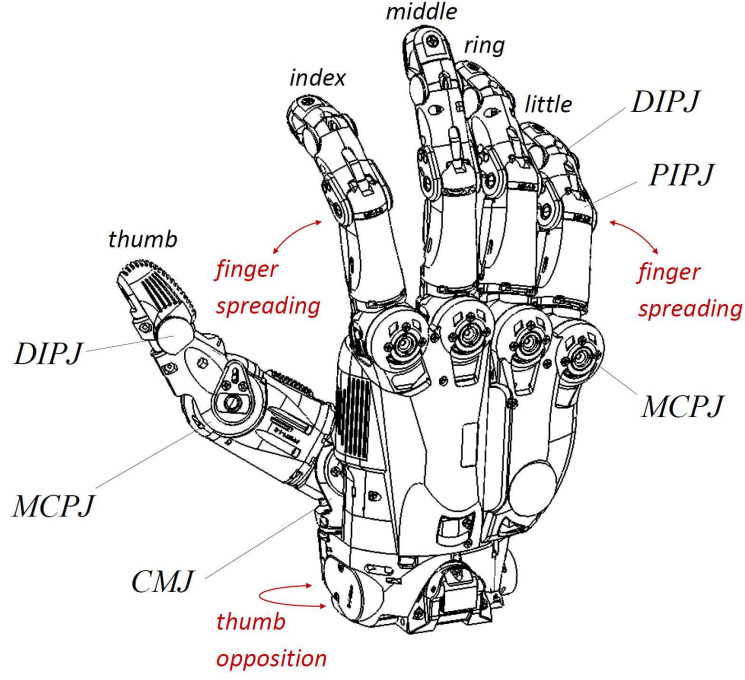


Fig. 2 The finger movements of the Schunk Five-Fingered Hand are illustrated.

thumb, the opposition joint q_{t_o} is coupled with the q_{p_o} joint allocated into the palm that moves only the ring and the little finger with respect to the palm frame. The carpometacarpal flexion joint $q_{t_{cm}}$, metacarpophalangeal flexion joint $q_{t_{mcp}}$, distal interphalangeal flexion joint $q_{t_{dip}}$ are clearly indicated in Fig. 2 as well as the metacarpophalangeal flexion joint (DIP), proximal interphalangeal joint (PIP) and distal interphalangeal flexion joint (MCP) for the other fingers. Finally, the index, ring and little fingers have also coupled spread motion $(q_{i_s}, q_{r_s}, q_{l_s})$.

$$\begin{aligned}
\underbrace{\begin{bmatrix} q_{t_o} \\ q_{t_{cm}} \\ q_{t_{mcp}} \\ q_{t_{dip}} \\ q_{i_s} \\ q_{i_{mcp}} \\ q_{i_{pip}} \\ q_{i_{dip}} \\ q_{m_{mcp}} \\ q_{m_{pip}} \\ q_{m_{dip}} \\ q_{p_o} \\ q_{r_s} \\ q_{r_{mcp}} \\ q_{r_{pip}} \\ q_{r_{dip}} \\ q_{l_s} \\ q_{l_{mcp}} \\ q_{l_{pip}} \\ q_{l_{dip}} \end{bmatrix}}_{\mathbf{q}} &= \underbrace{\begin{pmatrix} 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.29 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.29 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.42 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.25 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.49 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.51 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.49 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.51 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.26 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.36 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.38 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.26 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.36 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.38 & 0 \end{pmatrix}}_{\mathbf{S}_m} \underbrace{\begin{bmatrix} m_0 \\ m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \\ m_7 \\ m_8 \end{bmatrix}}_{\mathbf{m}} + \mathbf{q}_0, \quad (1)
\end{aligned}$$

3 Postural Synergies Computation

A data set of 36 grasping configurations, measured on five human hands, have been considered as in [8] and the same mapping method has been applied to the S5FH hand. The differential kinematics mapping between the mechanical synergies subspace and the Cartesian space, used in the CLIK algorithm, is represented by the following equation

$$\dot{\mathbf{x}} = \mathbf{J}_{h_m} \dot{\mathbf{m}}, \quad (2)$$

where $\mathbf{J}_{h_m}$ is the mechanical synergies Jacobian and is computed as

$$\mathbf{J}_{h_m} = \mathbf{J}_h \mathbf{S}_m. \quad (3)$$

In (2), $\dot{\mathbf{x}}$ is the derivative of the position vector of the five fingertips $\mathbf{x} \in \mathbb{R}^{15}$, $\mathbf{J}_h$ is the (15×20) S5FH hand Jacobian, $\mathbf{S}_m$ is the (20×9) matrix of the mechanical synergies, and finally $\dot{\mathbf{m}} \in \mathbb{R}^9$ is the vector of the motor angles. The CLIK algorithm for inverse kinematics resolution can be based on the transpose of the Jacobian $\mathbf{J}_h^T$, or on the pseudoinverse of the Jacobian $\mathbf{J}_h^\dagger$. When the CLIK algorithm is used for mapping grasps from the human to the robot hand, the desired fingertips position in the Cartesian space, $\mathbf{x}_d$, is constant and the required feedforward term of the velocities is null. In this work, the synergies subspace of the hand, constituted by the first three eigengrasps, has been computed with both solutions in the CLIK algorithm, namely $\mathbf{J}_h^T$

and $\mathbf{J}_h^\dagger$. Actually, these solutions do not lead to significant differences in the results. On the other hand, the use of the transpose Jacobian may be easier and more convenient for real-time implementation. Moreover, even in the presence of a variable Cartesian desired position, the latter solution does not require the addition of a feedforward term. For these reasons, in this paper the results obtained with $\mathbf{J}_h^T$ are considered.

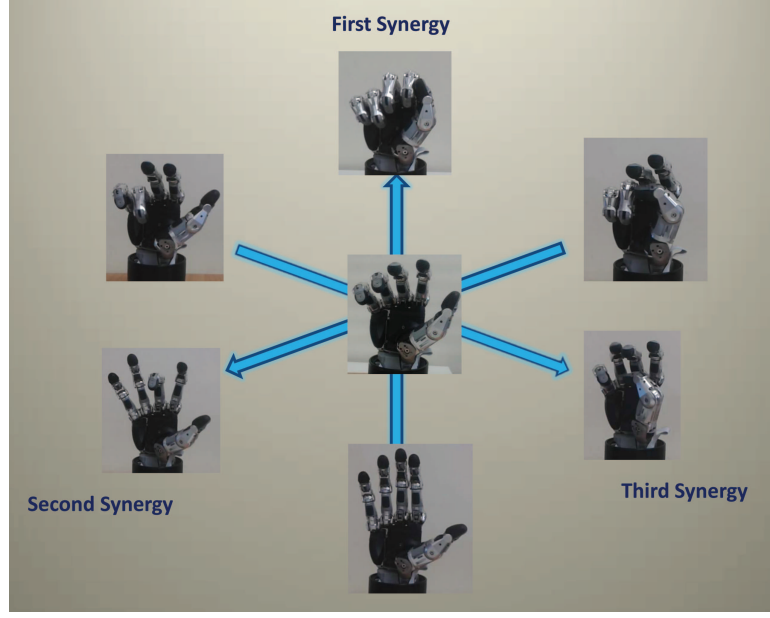


Fig. 3 The first three eigengrasps.

For the sake of brevity, the synergies subspace, resulting from computation, is schematically represented in Fig. 6. Here, the configurations that the hand assumes according to the patterns of the first, second and third synergies when their coefficients vary from minimum to maximum values are represented on the three principal axes of the eigengrasps. The minimum and maximum values of the synergy coefficients are in agreement with the positive direction of the arrows. The obtained results are very similar to those in [6] and the differences are due to the kinematic limitation introduced by the under-actuation. It is worth observing that the first synergy opens and closes the hand acting mainly on the flexion joints by moving them in the same direction. The second synergy generates opposite motions for the metacarpophalangeal flexion and proximal interphalangeal flexion joints. Obviously, this is true for the only two fingers that have no couplings on these joints (index and middle fingers). On the other hand, the third synergy influences mainly the thumb motion both for flexion and opposition.

4 Grasping Control in the Synergies Subspace

Once the (9×3) $\mathbf{S}_s$ synergy matrix has been computed, in order to test the efficiency of the mapping method, different grasps have been reproduced in the three-dimensional synergies subspace. Reproduced power grasps of spherical and cylindrical objects are represented in Figs. 4(a) and 4(b). Actually, since mechanical synergies affect the mapping from the human hand, the projection of a grasp from the data set in the synergies subspace is not so effective as for the full-actuated anthropomorphic hands [6], [8]. Thus, the reproduction is not successful for all the grasps. This means that a control strategy is required to adjust the reference grasp in order to let the hand adapt to the object while moving in the synergies subspace. The kinematic

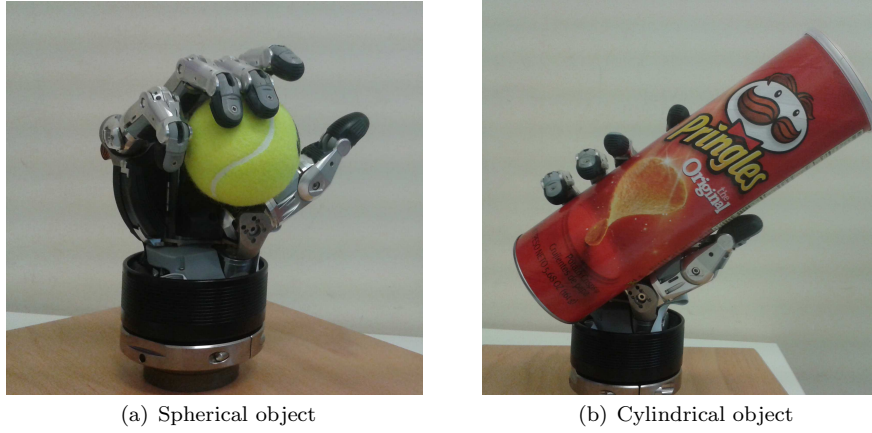


Fig. 4 Some examples of reproduced grasps

control of the hand in the synergies subspace is again a CLIK algorithm, but in this case it is based on the synergies Jacobian given by $\dot{\mathbf{x}} = \mathbf{J}_{h_{m_s}} \dot{\boldsymbol{\sigma}}$, where $\mathbf{J}_{h_{m_s}} = \mathbf{J}_h \mathbf{S}_m \mathbf{S}_s$ and $\dot{\boldsymbol{\sigma}}$ are the synergy coefficients. The differential mapping between synergies coefficients and joint velocities is given by the following equation

$$\dot{\mathbf{q}} = \mathbf{S}_m \dot{\mathbf{m}} = \mathbf{S}_m \mathbf{S}_s \dot{\boldsymbol{\sigma}}.$$

A simple strategy to modify the reference grasp can be adopted. The fingertips desired positions are modified in the control algorithm in order to reduce their distance with respect to the centroid of a virtual object computed as the centroid of the fingertips involved in the desired grasp. Moreover, in order to limit the grasping forces, the desired target of the CLIK algorithm is modified on the basis of the measured motor current and of a defined threshold that is related to the texture of the object. The experiments demonstrate that the synergies subspace is suitable for hand control in grasping a wide variety

of objects, i.e. the algorithm is stable and effectively regulates the grasping forces by modifying the motor positions in the synergies subspace. Thus, to improve the grasping capabilities as future work, strategies based on quality indexes to close the hand toward the object in the synergies subspace will be tested. In Fig. 5 two different grasps of the same object are controlled in the synergies subspace using different current thresholds.



Fig. 5 A cylindrical object is grasped

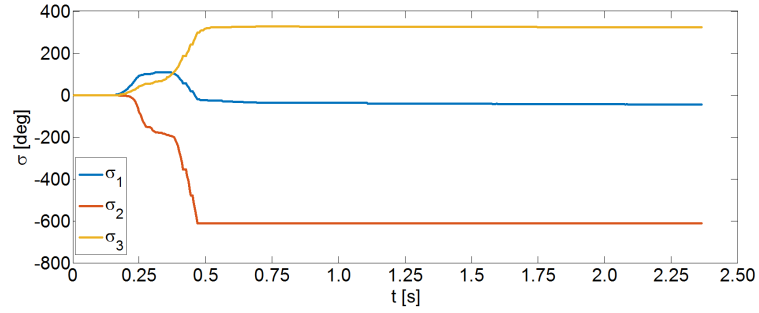


Fig. 6 Time history of synergy coefficients during grasping a cylindrical object with contact forces regulation.

In Fig. 6, the synergies coefficient are reported for one of the cylindrical grasps described above. It is possible to observe that the control modifies the synergies coefficients until reaching a steady-state value which depends on the allowed motors current limits.

5 Conclusions

The S5FH synergies subspace has been computed by mapping human hand grasps using a method based on fingertips measurements. The features of the first three synergies have been evaluated and the results are very similar to those of fully actuated anthropomorphic hands. Furthermore, the synergies subspace has been tested for hand control using a CLIK algorithm based on the synergies Jacobian. The experiments have demonstrated that the method used to compute synergies provides good results since the hand can be successfully and stably controlled in a three-dimensional synergies subspace for grasping purpose while guaranteeing suitable regulation of the contact forces.

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