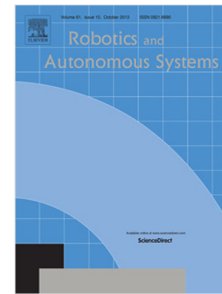


## Accepted Manuscript

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# Teleoperation of the Schunk S5FH Under-actuated Anthropomorphic Hand using Human Hand Motion Tracking

Ilaria Cerulo, Fanny Ficuciello, Vincenzo Lippiello, Bruno Siciliano

**Abstract**—This paper describes the development of a remote handling control of an anthropomorphic robotic hand, the SCHUNK S5FH, using the human hand as master by measuring its motion with OptiTrack Technology. The goal of this work is to enhance manipulation studies on the human hand and to instantly transfer those studies on robotic hands. A preliminary study on methods and devices used for fingers tracking led to the choice of a simplified kinematic model of the human hand on the basis of the available motion tracking system. Using the same criteria, the analysis of protocols for markers allocation led to define the number and a method for their arrangement on the fingers and palm. In order to overcome the limitation of the Motion Capture System, a method for identification and labeling has been developed according to their anatomical arrangement. Afterwards, the tracking is performed using the constraints between marker positions on the kinematic chain of the hand and a dynamic labeling algorithm robust with respect to noise, outliers and loss of markers. The validation is performed using the right hand of different subjects and considering different tasks involving flexion/extension and abduction/adduction of fingers and thumb opposition. For testing and validation, preliminary studies on synergies for manipulation tasks such as screwing a cup, has been conducted on the human hand and transferred on the robotic hand.

## I. INTRODUCTION

The hand is one of the most interesting anatomical part of human body for biomechanical complexity [3], [17] and functional skills [28], [39], [41], for the same reasons is also the most difficult to be reproduced artificially in terms of mechanics, kinematics, sensors [49], [50], [42] and last but not least of planning and control strategies [25], [43] and [26]. The interest of robotics in studying the anatomy and functionality of the human hand is justified in order to reproduce and imitate it for both prosthetic and robotic applications where the human being is replaced together with manipulation skills by an anthropomorphic robot. Once a hand kinematic model is chosen on the basis of well-known studies in literature [22], [23], another daunting task is to track the motion. Hand tracking is of great interest for many research area since it supports neurophysiology studies on motion patterns and multi-sensory integration [4], [29], [30], [37], [45], robotic studies on bio-inspired algorithms for manipulation control [40], [46], anthropomorphic hands design [47], [48], and also

investigation on remote control and telemanipulation [1], [2], [5]. In this paper, we provide a methodological approach to transfer in real time the human hand motion to a robotic hand for remote handling control. First of all, a vision-based method for human hand tracking has been adopted. To provide the tracking system with robustness and reliability, the main contribution is given by finding a marker protocol solution that minimize the number of utilized markers, and an algorithm for dynamic labeling and accurate reconstruction of the movement. The objective is to adapt the available technology to human manipulation studies to be transferred in real time to a robotic device. The adopted solutions, directed towards simplification of motion tracking procedure for remote control are tested on an underactuated robotic hand, the SCHUNK 5-finger hand (S5FH) [16]. Nevertheless, the study is not limited to particular robotic hands with similar kinematics. Indeed, the paradigmatic model of the human hand and the markers layout has been chosen with 15 Degrees of Freedom (DoFs) and 20 degrees of mobility. This model is quite complete and effective to describe the functionality of healthy subjects in performing grasping and manipulation tasks. According to previous studies of the authors [24], this model is suitable to transfer human capabilities to different kinematics of multi-fingered hands. Thus, this work constitutes a smart tool for development of robotic hands planning and control strategies. Consequently to the purpose of the developed method, the validation of the setup rely on the qualitative evaluation of synergy-based manipulation tasks.

## II. RELATED WORKS

The main issues that remain critical in this research field are the kinematic description of the hand (joints model, number of degrees of freedom, location of the link axes and centers of rotation), the marker protocol optimization (visibility of the markers, correct constraints for the movement reconstruction) and the mapping between the movements of the markers and the movement of the hand kinematics. The exact knowledge of the hand kinematics is desirable but not absolutely necessary also because the task complexity and the variation of the anatomical features among different subjects. Rather, it is useful to have a fairly faithful kinematic model to allow the main motion functions. Many studies have been conducted on the functionality of the hand [18], [32], [34], and in particular of the thumb which among fingers is the more complex with increased mobility and opposition capacity [14], [15].

On the other hand, real time motion tracking of the hand phalanges and articulations is quite challenging and the results strongly depends on the utilized technology. To overcome technological limitations some simplification and assumption are needed [7], [27], [44]. The technologies for the hand motion measurement can be classified into two main classes: glove-based [51] and vision-based methods [6]. Gloves are electromechanical devices simple to use with sensors worn on the hand. They have two fundamental drawbacks: they are not tailored through the hands of various subjects and the finger movements are detected with little accuracy. Vision based methods, on the other hand, are more accurate but have problems with occlusions and noise. About vision tracking, model-based and marker-based method have been developed. Kinect technology has been intensively used over time for hand tracking, since it interprets 3D scenes thanks to the depth sensor combined with an RGB camera. In [52] marker-less visual observations based on the model has been developed for tracking 3D position and orientation of hand links and full articulations. However, the relation between phalanges motion and kinematic and dynamic variables is not simple due to the large number of degrees of freedom and the complexity of the hand biomechanics, thus accurate assessment of kinematics and dynamic model, with real-time marker-less tracking, represents a complex task. On the other hand, tracking angular positions using markers implies the knowledge of hand kinematics that is not completely consistent in anatomical literature [32], [34]. Furthermore, due to occlusions and skin displacements, it requires advanced and dedicated 3D motion tracking technology. Different methods have been proposed in literature, some of them are more suitable for real time applications and each of them proposes solutions to model the hand and to allocate the 3D marker positions depending on the used technology [10], [11]. Furthermore, since motion tracking system features rarely complies with the robotic hand kinematic structure, statistical methods, e.g. unscented Kalman filter and Hierarchical Bayesian filter [12], [13], and optimization approaches [8], [9], are used for motion reconstruction.

### III. THE SCHUNK S5FH

The SCHUNK 5-finger hand (S5FH) [16] is an anthropomorphic robotic hand with electronics completely integrated into the wrist and kinematic structure allowing to perform nearly all human movements. The majority of the joints are actuated through leadscrew mechanisms converting linear into rotational motion and most of them are coupled in such a way to reproduce natural movements using a reduced number of independent degrees of freedom.

#### A. Kinematics of the SCHUNK S5FH

The S5FH has 9 servo-motors moving 21 DoFs (Fig. 1). The little finger articulation for adduction/abduction motion is mechanically coupled with index and ring metacarpophalangeal (MCP) joints to produce fingers spread and has a larger range of motion with respect to the other fingers to better simulate the anatomical function. The MCP, proximal

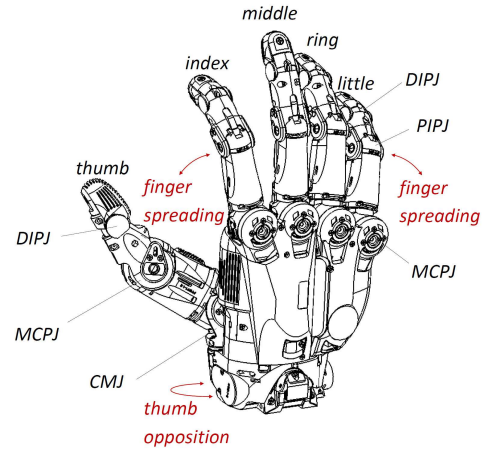


Fig. 1. The finger movements of the SCHUNK S5FH are illustrated.

interphalangeal (PIP) and distal interphalangeal (DIP) joints of the ring and little fingers are coupled and flex together moved by means of one motor for each finger (Fig. 2). The index and middle PIP joints are independently driven by means of a leadscrew mechanism to simulate a trigger fingering action, while the DIP and PIP motions are coupled by means of a rigid linkage. The thumb has two motors. One motor is devoted to the flexion motion of the carpometacarpal (CM), MCP and DIP flexion joints that are mechanically coupled. A second motor determines the opposition of the thumb with the other fingers, in particular the opposition of the thumb is coupled with the motion of two extra DoFs in the palm known in the human hand as the metacarpocarpal (MCC) joints of the little and middle fingers.

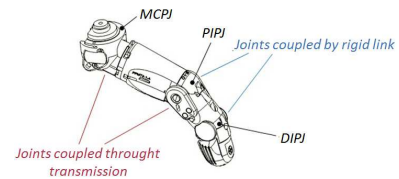


Fig. 2. The SCHUNK SF5H ring finger.

### IV. OPTITRACK MOTION CAPTURE SYSTEM

The motion capture system used for human hand tracking is constituted by the Optitrack mocap technology [33] with 20 cameras of Prime 13 category positioned on a structure as shown in Fig. 3, a hand kit suit and the Motive Tracker software for 6 DoF Object Tracking. The available tracker software is not conceived for body motion tracking and especially for hand tracking. To adapt the system to our needs we selected 10 of the 20 cameras in order to reduce the observed space and thus the flickering of the tracking due to the fact that the more distant cameras may not be able to detect a given marker at each frame. The choice of the camera disposition and orientation has been done in such a way that each marker

during all possible motions is tracked by at least two cameras to triangulate the 3D position. Since for our purpose we need



Fig. 3. The flying arena.

to track 13 markers at very close range, precise calibration is required. Once the group of cameras have been chosen and suitably oriented, only a reduced volume with respect to the whole flying arena has been calibrated by moving in the space a versatile wand with multiple configurable marker sets. Once the cameras calibration has been performed and their position in the space has been obtained, an object with attached markers at known positions, the so-called "ground plane", is settled as the origin of the reference system of the work volume.

#### A. Hand kit

For hand tracking we have used a kit consisting of two gloves, ten finger markers and four markers for wrists and forearms. This motion capture suit is thought to be used with the Motive Body software. For our set-up and purpose we used only one glove, ten small markers for one hand fingers and three big markers for the palm as detailed further on depicted in Fig. 7.

### V. THE HUMAN HAND

The human hand kinematics is not completely consistent in the anatomical literature [32], [34] and hence it is possible to find several studies on the identification of valid models [15], [17], [18]. In order to model the kinematic structure of the human hand, each finger can be represented schematically by means of a kinematic chain and the base of the palm (center of the wrist) may be considered as the origin of the reference frame.

#### A. Kinematics of the Human Hand

Due to similarities with the S5FH hand we refer to the work in [31]. The fingers metacarpophalangeal (MCP) joints have two degrees of freedom (Fig. 4) so it is convenient to represent them with an ellipsoidal joint allowing flexion/extension ( $MCP_f$ ) and adduction/abduction ( $MCP_a$ ); proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints have one degree of freedom and may be modeled with a hinged joint which allows flexion/extension movements. About the thumb, the trapeziometacarpal (TM) joint is like a saddle joint allowing flexion/extension, adduction/abduction and circumduction motion, the interphalangeal (IP) and metacarpophalangeal (MP) joints have one degree of freedom. Moreover, the little and middle fingers have one extra DoF in the palm such as the metacarpocarpal (MCC) joint. The most commonly used constraints on the joints movements [14], [15], are enumerated as follows:

- 1) The range of motion of the finger's joints can be assumed as:

$$\begin{cases} \deg 0 \leq \theta_{MCP_f} \leq \deg 90 \\ \deg 0 \leq \theta_{PIP} \leq \deg 110 \\ \deg 0 \leq \theta_{DIP} \leq \deg 90 \\ \deg -15 \leq \theta_{MCP_a} \leq \deg 15. \end{cases} \quad (1)$$

- 2) For the adduction/abduction range of motion of the middle finger it's commonly adopted an approximation of 0 degrees:

$$\theta_{MCP_a} = 0. \quad (2)$$

- 3) The correlation between the PIP and DIP joints of the fingers can be assumed as:

$$\theta_{DIP} = 0.7\theta_{PIP}. \quad (3)$$

#### B. Paradigmatic Model

Starting from the above described model, the kinematics of the paradigmatic model of the human hand has been chosen and described below. The palm is considered rigid, thus, the MCP joints of the four fingers and the TM joint of the thumb are considered fixed and their relative distance does not change. This choice has a positive findings in mapping motion on the S5FH due to the kinematic couplings between the thumb opposition and the extra joint in the palm that allows the ring and little finger opposition. For sake of simplicity, it is assumed that the adduction/abduction motion of the thumb is essentially given by the TM articulation provided of 2 degrees of freedom ensuring also the flexion/extension motion, and that the MCP articulation has only one degree of freedom and is coupled with the IP flexion motion. The fingers kinematics are equal and present 3 DoFs each with a coupling between the PIP and DIP joints. From the foregoing, it's possible to represent the kinematic chain of human fingers as shown in 5.



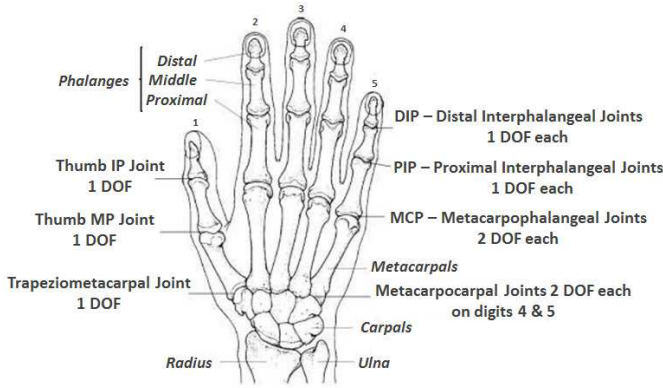


Fig. 4. Human hand [31].

## VI. TECHNICAL APPROACH FOR HUMAN HAND TRACKING

### A. Marker protocol

Recent advances in terms of sensors resolution have enabled the use of small markers to catch small size volumes where natural movements of the hand can be reproduced. However, the selection of the number of markers and their arrangement is a critical issue to minimize obstructions and loss of information. In this work, each finger phalanx has been identified using a single marker. Due to the small size of the human hand, the short reciprocal distance have made difficult the reconstruction of the movements. This happens most likely when the tracking system is thought to track rigid objects that move in a space much bigger then the hand workspace. By assuming constraints and implicit pairs of the human hand, the problem is solved by reducing as much as possible the number of markers, arranging them as far apart as possible but properly to reconstruct the movements of all the phalanges, and by making the reconstruction algorithm robust with respect to noise, outliers and loss of markers. Compared to the work analyzed in literature [19]–[21] we used a smaller number of markers, in particular 13 markers have been used, 10 on the fingers and 3 on the back of the hand (Fig. 7). The three markers on the back of the hand are used just to operate the transformation between the palm and the camera frame in such a way to obtain the coordinates of the 10 finger markers in the palm frame. The 10 markers on the fingers are positioned close to the MCP and DIP joints of the thumb, and PIP and DIP joints of the fingers. To detect flexion/extension and adduction/abduction motion of the MCP finger joints and of the TM thumb joint, virtual markers are considered on the hand and positioned on the paradigmatic model after calibration performed on the subject hand dimensions. In particular, the markers are allocated at the fingers base frame. The calibration is described in the following subsection.

The algorithm for the dynamic labeling, to prevent loss of markers and to ensure the continuity across frame transition, is based on the assumption that the number of markers is preserved, thus the frame is discarded when a lower number of markers (due to occlusions) or a higher number of markers

(due to misreading) is detected. Moreover, the markers coordinates are updated in the transition from a frame to the next one only if the distance in between is less then a certain threshold

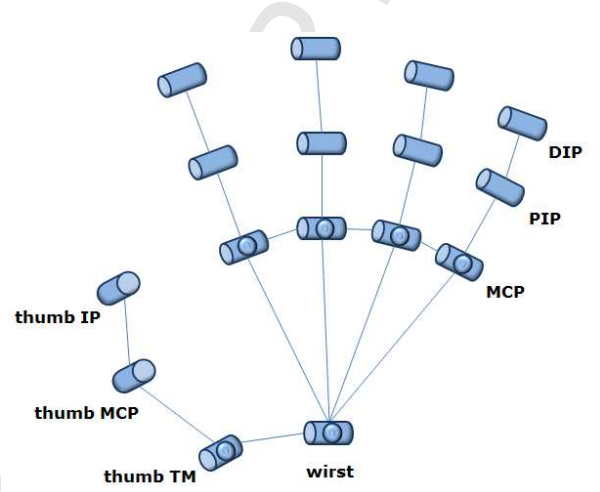


Fig. 5. Simplified kinematic model of the human hand.

(which is assumed to be 0.7 mm). Once a marker protocol solution that minimizes the number, and an algorithm for dynamic labeling have been adopted, reliability and robustness of the tracking algorithm have increased dramatically until reaching more than 98% of success in performing a complete screwing task, allowing a qualitative evaluation of synergy-based manipulation tasks, as described in Sec. VII-B.

### B. Human hand motion tracking

Fingers motion is reconstructed from markers, tracked in the palm frame, on the basis of the paradigmatic model of the human hand suitably scaled on the subject hand dimensions.

The calibration of the paradigmatic hand model is performed at the early stage during the initial homing procedure on the basis of the hand dimensions of each subject. For each subject, the fingers length is measured and the paradigmatic model kinematics is differently scaled for each finger by multiplying the linear Denavit-Hartenberg parameters, settled equal to the unity, for a ratio of the human finger total length. The validation of the model is then performed to test the goodness of the kinematics using Matlab simulation by comparing the fingertips position in the palm frame of the human hand and of the paradigmatic hand in the home configuration. During the homing the hand is placed, with the aid of a support, in a position where all the joints of the model are set to zero.

Since the 3D marker positions are measured in the camera frame, the homogeneous transformation between camera and palm frame is needed at each acquired image. When positions of at least three markers is known in both the frames, the homogeneous transformation can be computed at each sample time. For this purpose, three markers are disposed on the opisthenar of the hand and precise coordinates in the palm frame are obtained during the initial homing procedure. This procedure serves to obtain the first homogeneous transformation between the camera and palm frame and to label the

markers on the hand. Using five markers located at known positions with respect to the palm frame (see Fig. 6) and acquiring their position in the camera frame, the homogeneous transformation is computed and the opisthenar markers are reported in the palm frame. The palm frame (Fig. 6) has the y-axis aligned in the direction of the middle finger, the x-axis is orthogonal in the palm plane and directed toward the little

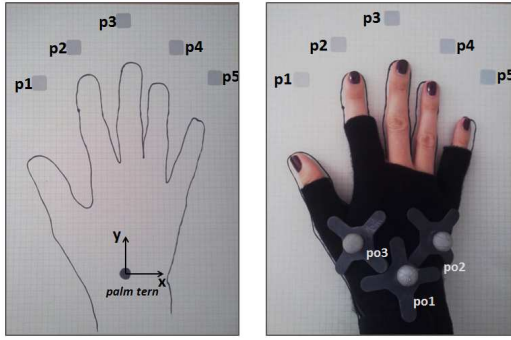


Fig. 6. The homing position.



Fig. 7. Markers arrangement on the hand.

finger, the z-axis is directed to form a right handed frame. The base frames of each finger has the same orientation of the palm frame while the thumb frame is rotated around the z axis of 40 deg and the origin is centered at the TM articulation. For the static labeling, the fingers and each marker disposed on it are identified the procedure described below. The thumb is identified by operating a control on the x coordinate starting from the lowest value toward the x-axis positive direction and then considering the minimum distance from the palm frame. For the other fingers instead we make a markers control, first on the x-axis then on the y-axis. First of all, the x coordinate are identified in ascending order, then the corresponding y coordinate is evaluated in such a way to group the markers pairwise from the index to the little finger. The smaller y-coordinate of each fingers group, determine the PIP joints identification and thus the DIP is identified consequently. For better understanding see Fig. 8 For motion tracking, the joint angles displacement are computed from constraints between marker positions on the kinematic chain of the hand. The coordinate transformation of a marker  $P_1$ , expressed in the link local, in the frame attached to the previous link in the kinematic chain,  $P_p$  is given by the following equation:

$$P_p = R_Z(\beta)R_X(\alpha)P_1, \quad (4)$$

where  $R_Z(\beta)$  and  $R_X(\alpha)$  are two elementary rotation matrix. The rotational axes and the succession between the elementary rotations depends on how the frames are allocated on the links, while the angles of rotation depend on the human hand motion and constitute the unknown quantity that we want to get by solving eq. (4) arise in this form since the reference frame on the links are allocated according to the Denavit-Hartenberg convention. In particular eq. (4) holds when the marker is on the proximal phalanx whose motion is given by the MCP joint with 2 DoFs. When the marker is attached to the middle phalanx only one rotation matrix is considered.

### C. Motion Mapping on the Schunk Kinematics

The Schunk hand is under actuated and provided of 9 motors, thus has joint and finger couplings. The considered human hand paradigmatic model has 15 independent joint variables assuming that holds eq. (3), consequently we have redundant information which are mapped as described below.

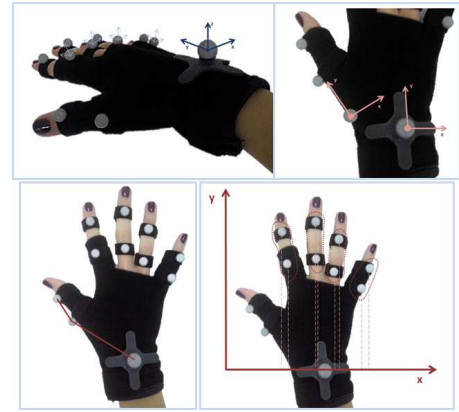


Fig. 8. Static labeling procedure.

- The index and middle are the only two fingers whose flexion motion can be mapped accurately joint by joint since MCP and PIP flexion joints are moved by individual motors. Thus, the tracked joint angles are given as reference to the related four motors.
- The ring and little fingers have only one motor collocated at MCP flexion joint that, through mechanical couplings, moves also PIP and DIP articulations. Thus, the measured MCP flexion from the human hand motion is used as the reference for the unique motor that moves the three flexion joints of the two fingers.
- About the thumb, the adduction/abduction motion is measured from the human hand and is given as reference to the motor previous an offset to adapt the different ranges of motion for the opposition. The thumb opposition is coupled with the extra joint motion allocated in the palm providing the opposition of ring and little fingers. For the three flexion joints, the robotic thumb has a single independent motor. In the human thumb the TM flexion joint moves less and independently with respect to the MCP joint. Thus, if we give the measured motion of the first flexion joint of the human thumb as reference to the

motor of the robotic hand, the flexion motion cannot be appreciated and is not faithful to that of the human hand, for this reason we have chosen to consider the average between TM and MCP measured flexion to control the S5FH.

- About the spread motion, the Schunk hand has one single motor located at the little finger that moves all fingers simultaneously, except the medium that has the abduction always zero. Thus, the measured adduction of the human little finger is given as spread joint variable of the robotic hand due to the similarity between the ranges of motion and the human like couplings of the S5FH.

Finally, for what has been said up to now the movements of the human hand are not faithfully reproduced due to structural limitations, this applies in particular to the thumb and the last two fingers.

## VII. EXPERIMENTS

The experimental set up is constituted by different hardware and software component connected using UDP client/server applications. The connection scheme is shown in Fig. 9. The Optitrack system is constituted by 1.3 Megapixel cameras (1280x1024 resolution and 240 FPS) that detects the reflective markers placed on the glove and the fingers. Markers positions in global frame are transmitted using a NatNet SDK via LAN to the pc that drives the Schunk hand connected via USB. The NatNet Client has been modified according to the application needs. The S5FH is controlled using a Robot Operating System (ROS) package that contains the driver for the low level interface and enables an easy control of the hand using a customized library written in C++. The Robotics System Toolbox is used to provide an interface between MATLAB and ROS in such a way to create a ROS node in MATLAB to exchange messages with the hand driver node. In particular, the information provided by the Optitrack are processed in the MATLAB node for coordinate transformation and direct kinematic computation in order to calculate the variables of interest and subsequently to generate motor references for the robotic hand.

### A. Hand Tracking and Teleoperation

To test the goodness of the technical approach for markers arrangement, dynamic labeling and data processing, the acquired positions have been processed and then used offline to reconstruct the human hand motion in MATLAB simulation. A qualitative evaluation of the simulated motion provides good results since different tasks, like screwing a cup and counting, has been reproduced realistically, see Figs. 10 and 11.

After a qualitative evaluation of the human hand motion tracking, the mapping on the Schunk hand has been performed in real time for remote robotic hand control in teleoperation. In Fig. 12 selected postures of the S5FH during real-time remote control for counting task are reported together with the relative images from the Optitrack software that manages markers tracking. Analyzing the images from the Motive Tracker software, it can be observed that the number of markers can become less than 13, like in the first image. This is because



Fig. 9. Simplified block diagram of the hardware components and connections.

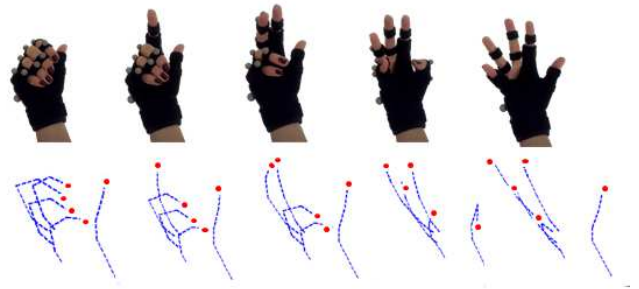


Fig. 10. Tracking the human hand in counting.

the cameras are far from the hand and the markers can be lost or occluded during motion. The continuity algorithm in these cases keeps track of the positions of the lost marker at the previous stage in such a way that the Schunk hand continues to follow and reproduce the movement. Thus, the tracking algorithm and the whole mapping procedure work properly as can be observed in Fig. 13, where images of the human hand that drives in real-time the robotic hand are reported for discrete postures.

### B. Human Manipulation Studies for Validation

The developed application allows calibration of the hand kinematics model tailored to the anatomical characteristics of different subjects, validation of different configurations of markers, animation in real time in a virtual scene, recording movements for kinematic analysis, and real time mapping of the motion on a robotic hand. Due to the arbitrariness in the choice of the kinematic model of the human hand and to the inaccuracy of motion mapping on the robotic hand, since the under actuation does not allow a 1:1 joint mapping, the results of the process were assessed by qualitative point of view exploiting manipulation studies on the human hand well know in literature, [35]. Besides the evaluation of the results, those studies represent one of the aim for future work. The computation of manipulation synergies has been performed



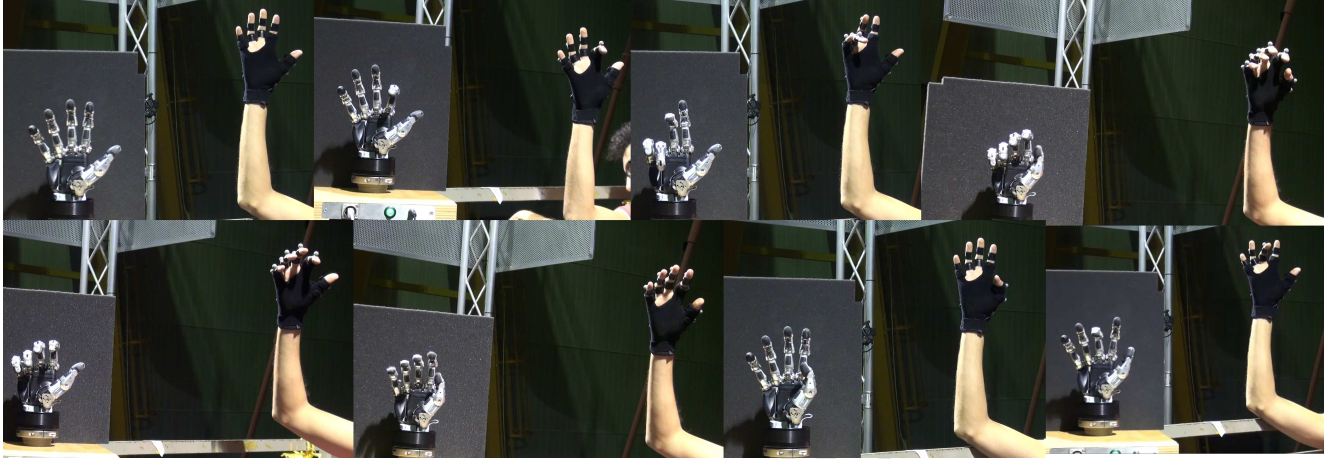


Fig. 13. Snapshots of a video showing the teleoperation of the SCHUNK S5FH driven by the human hand.

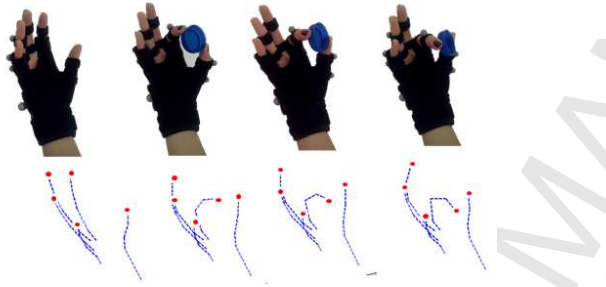


Fig. 11. Tracking the human hand in screwing a cup.

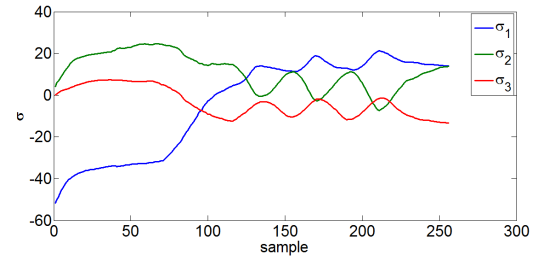


Fig. 14. Synergies coefficient of a screwing task. The y-axis of the palm forms an angle of 90 degrees with respect to the bottle axis of symmetry.

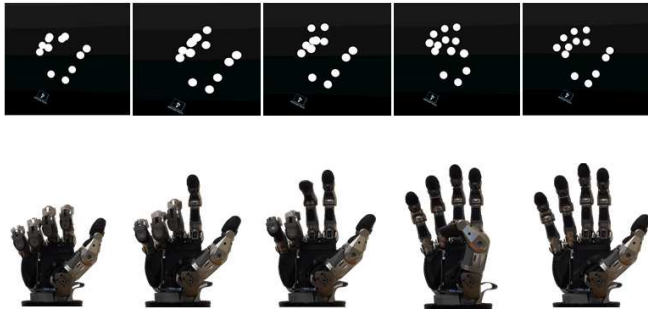


Fig. 12. Real time remote control of the SCHUNK S5FH for counting task.

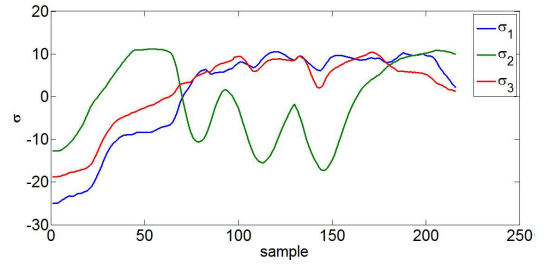


Fig. 15. Synergies coefficient of a screwing task. The y-axis of the palm forms an angle of 45 degrees with respect to the bottle axis of symmetry.

using Principal Component Analysis on acquired motion of different subjects during screwing a cup in correspondence of different orientations of the palm relative to the bottle axis of symmetry. Two representative motion have been projected in the subspace of the first three synergies and the time history of their coefficients  $\sigma$  are reported in Figs. 14 and 15. The trend about sinusoidal of the coefficients and the dependence of the sinusoidal wave from the orientation of the palm is confirmed by studies in [36]. The so computed synergistic motion has been reproduced on the robotic hand and the results are represented in Fig. 16 for the orientation of Fig. 14. With respect to the mapped motion the execution in the synergies subspace is performed with a joints average error depicted in Fig. 17.

## VIII. CONCLUSIONS AND FUTURE WORK

The developed remote handling control using marker-based tracking of human hand motion, revealed its value proving to be well suited to the study of the human hand motion even during the execution of manipulation tasks and to transfer the motion in real time to an anthropomorphic under actuated hand. This study represents an attempt to provide a method for human hand motion studies oriented toward the control of robotic hands on the basis of bio-inspired algorithms. Future developments will focus on the study of human hand synergies for different manipulation tasks to be reproduced on the Schunk S5FH and on the optimization of the set up for a more suitable arrangement of the cameras to provide motion tracking in smaller working volume and to minimize occlusion problems.



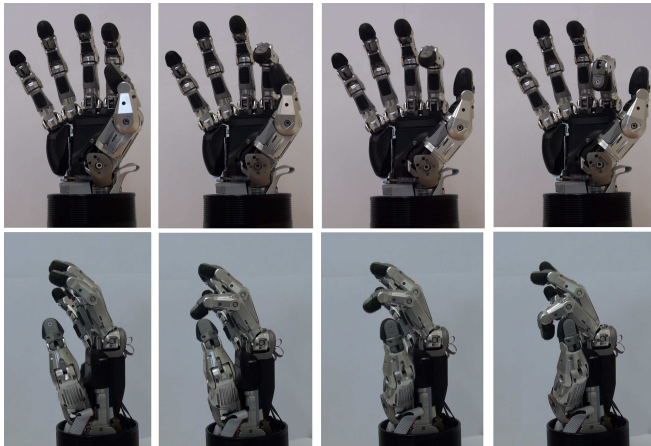


Fig. 16. The SCHUNK S5FH screwing a cup.

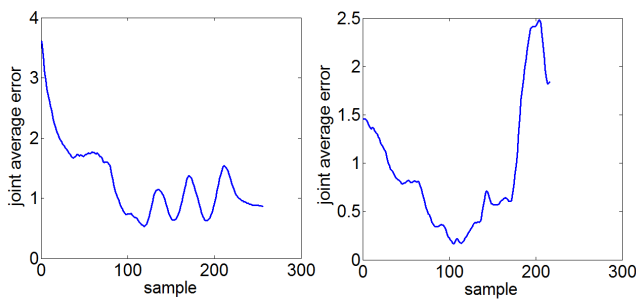


Fig. 17. Average of the joints error for the reproduced motion in the synergies subspace. Two different orientation of the y-axis of the palm with respect to the bottle axis of symmetry, the angles are respectively 90 and 45 degrees.

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## Highlights

- A remote handling control of an anthropomorphic robotic hand, the SCHUNK S5FH, has been developed using the human hand as master by measuring its motion with OptiTrack Technology.
- The goal of this work is to enhance manipulation studies on the human hand and to instantly transfer those studies on robotic hands.
- A preliminary study on methods and devices used for fingers tracking led to the choice of a simplified kinematic model of the human hand on the basis of the available motion tracking system.
- Using the same criteria, the analysis of protocols for markers allocation led to define the number and a method for their arrangement on the fingers and palm.
- To provide the tracking system with robustness and reliability, the main contribution is given by finding a marker protocol solution that minimize the number of utilized markers, and an algorithm for dynamic labeling and accurate reconstruction of the movement.