

THE DEXMART HAND: MECHATRONIC DESIGN AND EXPERIMENTAL EVALUATION OF SYNERGY-BASED CONTROL FOR HUMAN-LIKE GRASPING

G. PALLI, C. MELCHIORRI, G. VASSURA, U. SCARCIA, L. MORIELLO, G. BERSELLI,
A. CAVALLO, G. DE MARIA, C. NATALE, S. PIROZZI, C. MAY, F. FICUCIELLO,
AND B. SICILIANO

ABSTRACT. This paper summarizes recent activities carried out for the development of an innovative anthropomorphic robotic hand called the DEXMART Hand. The main goal of this research is to face the problems that affect current robotic hands by introducing suitable design solutions aimed at achieving simplification and cost reduction while possibly enhancing robustness and performance. While certain aspects of the DEXMART Hand development have been presented in previous papers, this paper is the first to give a comprehensive description of the final hand version and its use to replicate human-like grasping. In this paper, particular emphasis is placed on the kinematics of the fingers and of the thumb, the wrist architecture, the dimensioning of the actuation system, and the final implementation of the position, force and tactile sensors. The paper focuses also on how these solutions have been integrated into the mechanical structure of this innovative robotic hand to enable precise force and displacement control of the whole system.

Another important aspect is the lack of suitable control tools that severely limits the development of robotic hand applications. To address this issue, a new method for the observation of human hand behavior during interaction with common day-to-day objects by means of a 3D computer vision system is presented in this work together with a strategy for mapping human hand postures to the robotic hand. A simple control strategy based on postural synergies has been used to reduce the complexity of the grasp planning problem. As a preliminary evaluation of the DEXMART Hand capabilities, this approach has been adopted in this paper to simplify and speed up the transfer of human actions to the robotic hand, showing its effectiveness in reproducing human like grasping.

1. INTRODUCTION

After more than 40 years of research in the field of robotic hand development [Melchiorri and Kaneko, 2008, Bicchi, 2000], the final objective of reproducing the functionality and dexterity of human hands still seems far away. From a general standpoint, this issue is, in our opinion, a consequence of the fact that most of the current robotic hand prototypes are based on design methodologies mainly inherited from conventional mechanics and industrial robotics. Considering also the current technological limitations that make the miniaturization of the mechanisms, motors and sensors needed for the implementation of a human-size robotic hand almost impossible or cost-ineffective, these design methodologies lead to devices that have poor reliability, are very complex and extremely expensive. These problems impose a very strong limitation in the knowledge, the experimentation and then

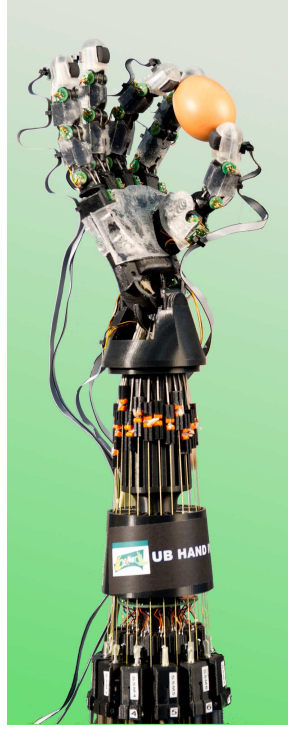


FIGURE 1. The DEXMART Hand.

the development of robotic hands because they limit the possibilities of gaining experience from errors. In fact, the number of trials leading to success needs to be as low as possible because a wrong planning of the grasping operation may result in a failure of the hand itself and, consequently, in a long time and high cost for repairing it, and so the time needed for planning the task grows significantly.

Given this situation, possible attempts for overcoming these issues could be in the direction of: 1) seeking alternative design approaches; 2) reducing the cost and the number of the parts to reduce the overall expense of the robotic hand; 3) simplifying the structure to reduce the manufacturing, assembly and repairing time; 4) developing more “intuitive” strategies for planning manipulation tasks. On the other hand, since possible applications of these devices span from industrial and humanoid robotics to rehabilitation medicine and prosthetics, even from a design perspective the definition of the “optimal functionality” of a robotic end effector is a quite challenging task.

In general, available manipulation devices are specifically designed to fit some particular requirements. For example, industrial manipulators are assumed to operate in completely structured environments and they are often equipped with grippers or other specific tools conceived to increase throughput and reliability [Causey and Quinn, 1998]. In this case, the increase of both the cost and the risk of failure related to the introduction of devices with enhanced manipulation skills must be carefully and critically motivated considering the application requirements. In

the current scenario, if a task cannot be executed for some reason by an industrial robot, it is still more convenient to employ humans to perform the task or to change the task itself to make it feasible using a conventional manipulator. A completely different scenario arises when dealing with the fields of humanoid robotics and prosthetics, where the end effector is expected to provide high flexibility and adaptability, ideally replicating the overall functionality of the human hand. Focusing on the manipulation devices that aim at reproducing the appearance and the functionality of the human hand, the general perception is, however, that current prototypes are either too complex and expensive or too bulky and unreliable to truly represent effective solutions.

Within the DEXMART project [DEX], the simplification of the robotic hand mechanism has been achieved through the introduction of novel design solutions, reducing the number of components and avoiding the use of any conventional mechanical parts such as bearings, pins, bushings and screws. Moreover, an innovative actuation system called the *twisted string* principle [Palli et al., 2013] has been purposely developed for actuating the robotic hand. The actuators are placed in the forearm and the forces are transmitted to the hand by means of tendons, obtaining in this way an integrated hand-forearm system. Since no commercial solutions exist that fit with the requirements of miniaturization of both the sensing elements and the electronics, the adoption of non-conventional design choices implies the development of suitable sensors, purposely designed to be integrated into the hand-forearm structure. Moreover, due to the number of sensors, their conditioning electronics should also be as simple as possible, and a common interface that limits the number of wires for communicating with the control system is needed. The adoption of suitable control strategies for compensating the side effects given by these design choices must be also considered. This fact is a direct consequence of the needs in terms of increased reliability and reduced costs, which shift the complexity of the system from the time-consuming mechanical design to the easy-reprogrammable device control strategies.

While previous publications presented early versions of the DEXMART Hand structure [Berselli et al., 2009, Palli et al., 2012b], the detailed design of finger joints [Berselli et al., 2011b], the tendon transmission design [Borghesan et al., 2010, Palli et al., 2012a], the actuation system [Würtz et al., 2010, Palli et al., 2013], the force, joint angle and tactile sensors [Palli and Pirozzi, 2013, 2012, De Maria et al., 2012], the soft hand covers [Piccinini et al., 2009, Berselli et al., 2011a] and a study on the postural synergies performed on preliminary robotic hand prototypes [Ficuciello et al., 2012a, Villani et al., 2012], this paper is the first comprehensive description of the final hand version resulting from the DEXMART project. On one side, the overall design and integration of the final robotic hand version shown Fig. 1 are presented for the first time, focusing in particular on: 1) the kinematics of the fingers and of the thumb, with particular attention to the opposition between the thumb and the other fingers; 2) the wrist architecture, conceived to achieve complete decoupling between the wrist and the finger motions; 3) the dimensioning of the twisted string actuation system; 4) the final implementation of the optoelectronic position, force and tactile sensors; 5) the integration of the sensors and the actuators into the overall robotic hand structure. On the other side, aiming at the experimental demonstration of the DEXMART Hand capabilities, the grasp synthesis and control problems have been faced by: 1) introducing an innovative

and simple method based on a low-cost and easy to use 3D computer vision system like the Kinect camera for measuring the hand postures of several human subjects during the execution of a reference set of grasps; 2) mapping the human hand configurations to the robotic hand by means of a suitable scaling of the hand kinematics; 3) adopting a robotic hand control strategy based on postural synergies obtained from the measurements performed on the human subjects by applying Principal Component Analysis (PCA). In particular, while the synergy-based control approach here adopted follows copious previous work [Brown and Asada, 2007, Ciocarlie and Allen, 2009], the methods for measuring the human hand postures and for mapping the measurements of different subjects to the robotic hand kinematics are completely new and they have been purposely developed within the DEXMART project.

This paper is organized as follows: Sec. 2 discusses background literature; Sec. 3 focuses on the design of the hand's mechanical structure; actuation and sensory sub-systems are discussed in Sec. 4 and 5 respectively; Sec. 6 is related to synergy-based control; Sec. 7 reports comments and draws conclusions from the adopted solutions.

2. RELATED WORK

Aiming at replicating grasping and manipulation abilities of the human hand, many different anthropomorphic robotic hands have been developed all over the world. Inspired by the biological model, i.e. the human hand, tendon transmission is usually preferred due to the technological problems that make the integration of the driving system within the hand a very challenging task if the dimensions, the number of fingers and DOF of the biological counterpart are considered as design specifications. For instance, two antagonistic tendons are used for each joint in the UTAH/MIT Hand [Jacobsen et al., 1984], whereas in the JPL/Stanford Hand [Mason and Salisbury, 1985], an $N+1$ tendon network is adopted to minimize the number of actuators. In the UB Hand III [Biagiotti et al., 2005] sheath-guided tendons are adopted and recently DLR has developed the tendon-driven DLR Hand-Arm system [Griebenstein and Smagt, 2008, Griebenstein et al., 2012] focusing on the robustness of the device as a primary target introducing elements able to absorb and store the energy during impacts. It is also worth mentioning the only commercially available tendon driven device, the Shadow Hand [Shadow Robot Company, 2003]. Moreover, recent technological advancements have allowed the development of modular hands with integrated drive systems during the last 10 years, like the DLR Hand II [Huang et al., 2006], the Twendy-One Hand [Iwata and Sugano, 2009] the Gifu Hand [Mouri et al., 2002] and the RCH-1 Hand [Roccella et al., 2004]. The modular approach allows the potential installation of these hands as end effectors in common industrial arms.

The great interest in the development of anthropomorphic robotic hands is due in part to the possibility of using them as prostheses for human limb replacement, or at least to transfer to this field some technological solutions derived from the development of robotic hands. Several prosthetic devices have been developed, including the SPRING Hand [Carrozza et al., 2004], the Cyberhand [Carrozza et al., 2006], the DLR/HIT prosthetic hand [Huang et al., 2006], the MLR Hand [Johannes et al., 2011] and the work of Dalley et al. [2009]. Among the commercial prosthetic hands it is worth noticing the i-LIMB Hand and the ottobock Michelangelo Hand.

It is important to say that the main issue that limits the technology transfer from the robotic hand design to prostheses is: a) the lack of both effective and reliable interfaces [Carrozza et al., 2005, Zollo et al., 2007] between the user nervous system and the artificial hand; and b) the intrinsic limitations in terms of duration and dimensions of portable power sources. These facts make preferable the use of very simple body-powered prostheses with a limited number of DOF.

To solve the problem of complexity, different prototypes of underactuated robotic hands have also been developed [Birglen and Gosselin, 2003, Birglen et al., 2008, Odhner and Dollar, 2011]. In these devices, a reduced number of actuators are employed with respect to the DOF, and the non-actuated DOF are coupled together in a proper way by means of leverages and springs to allow the execution of stable grasps. More recently, the concept of underactuation and postural synergies have been combined together by Praticchizzo et al. [2010] considering not only the execution of grasps but also providing to the robotic hand some internal manipulation features. Recently, design solutions based on compliant structures and innovative manufacturing processes have been investigated for simplifying the mechanical structure and the implementation of robotics hands [Biagiotti et al., 2005, Dollar and Howe, 2006, 2009, Palli et al., 2012b].

From the control point of view, recent studies on neurosciences and robotics have shown that imitating human prehension is a promising way to simplify and improve grasp planning and control issues related to high multiple DOF devices such as anthropomorphic robotic hands. In Santello et al. [1998], the authors measure a set of static human hand postures by recording 15 joint angles and, by means of PCA, they show that the first two principal components account for >80% of the hand postures. Thus, the use of the principal components, also called postural synergies, holds great potential for robotic hand control, implying a substantial reduction in the dimension of the grasp synthesis problem. Transferring human hand motion to a robotic hand is quite a challenging problem due to the complexity and variety of hand kinematics and the dissimilarity with the robotic hand. Indeed, in order to obtain a thorough estimation of human hand posture, a reliable kinematic hand model and highly accurate motion tracking instrumentation are required. A synergy mapping from the human hand to the robotic hand has been addressed by Gioioso et al. [2011]. The proposed mapping strategy between the synergies of a paradigmatic human hand and a robotic hand is carried out in the task space and is based on the use of a virtual sphere. Three synergies have been extracted from data on human grasping experiments and mapped to a robotic hand by Geng et al. [2011]. In Oikonomidis et al. [2011] a model-based method for recovering and tracking the 3D position, the orientation and the full articulation of a human hand has been proposed from marker-less visual observations. In Frati and Prattichizzo [2011] a heuristic hand tracker has been developed for animating a hand avatar in virtual reality and for implementing force rendering in wearable haptics. In Ficuciello et al. [2012a] and Villani et al. [2012] a set of 36 human hand grasp configurations was selected and adopted for experiments carried out on the UB Hand IV [Berselli et al., 2009, Palli et al., 2012b]. In Ficuciello et al. [2012b], neural networks have been integrated to allow synergy-based grasp planning relying only on geometric features of objects and task requirements. In Lippiello et al. [2012, 2013b] a grasp planning algorithm for the optimization of the contact forces is proposed, while in Lippiello et al. [2013a] a vision system is used for grasp planning of unknown objects. In

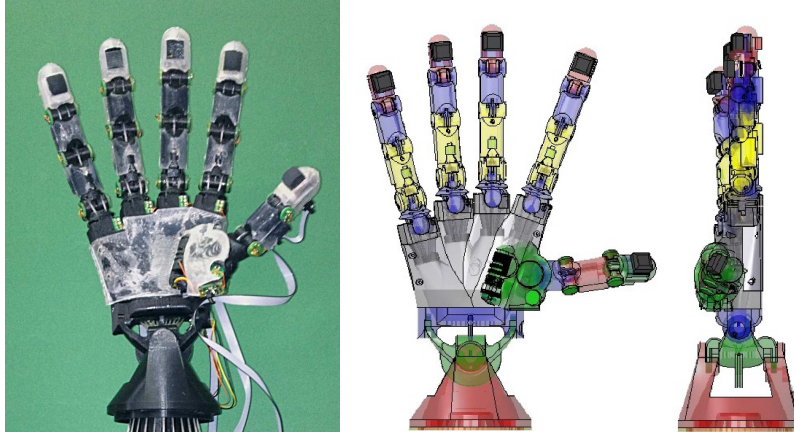


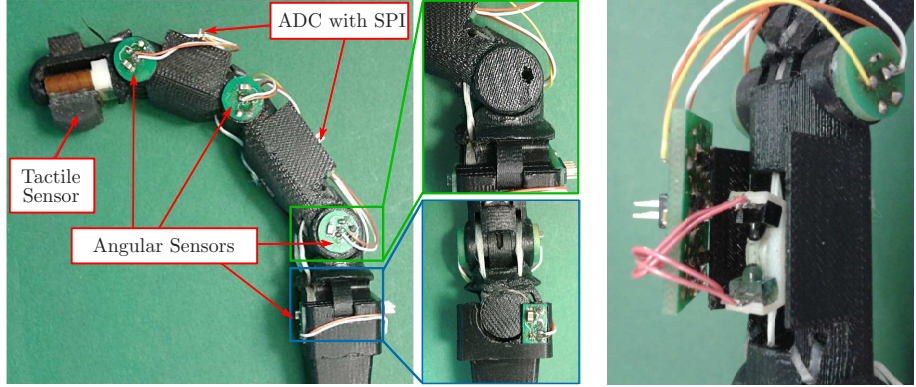
FIGURE 2. DEXMART Hand: Detailed view of the hand design.

Lippiello et al. [2013c] the dynamics properties of the object are exploited for the grasp planning.

What can be summarized from this wide scenario is that dozens of different design and control proposals can be found in literature, and the comparison between the different solutions and design philosophies is therefore very difficult, thus limiting the possibilities of adopting previous achievements as a starting point for the development of new robotic hands. For this reason, we started the development of the DEXMART Hand, taking the human hand as a design and behavioral model, investigating alternative and innovative solutions for the mechanical structure, the actuation, the sensors and the action planning, as detailed in the following sections.

3. THE DESIGN OF THE DEXMART HAND

In general, the design of any mechanical system is heavily dependent on the inseparable binomial material technology. Nowadays, different technologies and a wide range of materials (including lightweight metal alloys) can be used in order to produce even very complex mechanical parts in a single production step. Such technologies include CNC machining, plastic molding (such as Shape Deposition Manufacturing (SDM)), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Stereo-Lithography (SLA) and Electron Beam Melting (EBM). Nevertheless, recent advances in plastic materials technology suggest that the use of polymers might be well suited for the production of artificial hands once a lightweight, relatively economical solution is sought. For instance, plastic materials recently developed for SLA and FDM are beginning to offer acceptable performance and costs allowing the production of complex joint shapes (as it is remarked by the introduction of plastic grippers obtained through FDM within the robotic industry), and the continuously improving working precision of these manufacturing processes is today satisfactory for robotic applications. For these reasons, and also to allow a fast evaluation of different design solutions, all parts constituting the mechanical structure of the DEXMART Hand have been produced by means of FDM in ABS plastic. It is also important to say that the DEXMART Hand has not been conceived for mass production, but it is a test-bench for the evaluation



(a) Details of the tactile and position sensors.

(b) Detail of the tendon force sensor on the finger back side.

FIGURE 3. Detailed view of the DEXMART Hand finger.

and the integration of innovative solutions for robotic hands. Then, further steps are necessary for the industrialization of the system since some of the adopted solutions are not optimized from the point of view of the lifecycle. This is true also for the mechanical parts, and in particular for the adopted manufacturing process. The DEXMART Hand design is, however, compatible with alternative production processes, such as injection molding adopting high-performance plastic materials. Indeed, the mechanical parts manufactured by means of rapid prototyping can be used for creating molds for large scale production.

The design of the robotic hand is based on an endoskeletal structure articulated by means of non-conventional joints and actuated through a tendon-based transmission system by actuators that are remotely located in the forearm. The tendons are routed from the forearm through the wrist, the palm and the fingers by means of sliding paths (*sliding tendons*). To exhibit a proper compliance, the contact surface of the hand has been covered by a purposely designed soft cover mimicking the human dermal-epidermal layers [Piccinini et al., 2009, Berselli et al., 2011a]. A general view of the present DEXMART Hand prototype is shown in Fig. 1, whereas in Fig. 2 it is possible to see the mechanical structure of the robotic hand in detail and in particular to appreciate the limited number of mechanical parts (only 29) that compose the hand itself. The DEXMART Hand can be assembled very fast and simply without the need of any screw or other fixing parts. This result has been achieved by means of a design approach oriented to a systematic integration of the mechanical parts and by exploiting the potentialities of FDM. This approach allows a reduction of the production time, of the weight and the cost of the overall hand system, increasing its "affordability."

3.1. Finger Design. In Fig. 3 a prototype of the DEXMART Hand finger is shown. In particular, Fig. 3(a) shows the location of the position and tactile sensors, while the location of the tendon force sensor inside the finger is detailed in Fig. 3(b). The design of the finger is oriented to the maximum achievable integration between the mechanical structure, the sensors, the electronics, the actuation and the soft

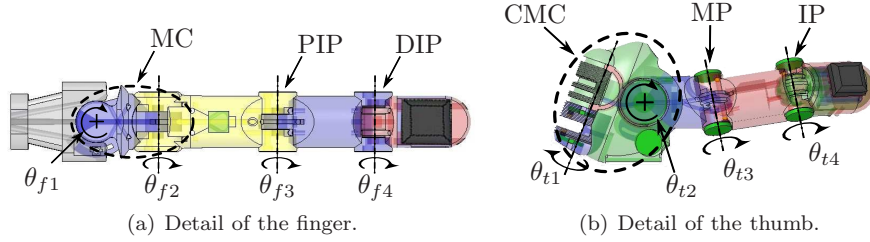


FIGURE 4. Details of the DEXMART Hand finger and thumb design.

pads and in light of structural simplification, allowing one-step monolithic manufacturing of each finger link and consequent reduction of the assembly complexity. With reference to Fig. 4(a), the fingers are composed of the distal, the medial and the proximal phalanges, connected by distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints and by a base whose function is twofold: it implements the 2-DOF metacarpal (MC) joint and allows an easy connection of the finger to the palm. The structure of the thumb is quite different with respect to the other fingers, as can be seen in Fig. 4(b). It is shorter and stronger than the other fingers (as in the human hand) and is composed of 3 links, the distal phalanx, the proximal phalanx and the metacarpal, connected by the interphalangeal (IP) and the metacarpophalangeal (MP) joint, and by a base that implements, together with the palm itself, the 2-DOF carpometacarpal (CMC) joint. In particular, the implementation of the MC, the MP and the CMC joints represents a technical solution that aims both at replicating the functionality of the biological counterpart and at simplifying the manufacturing and the assembly of the overall robotic hand. As a fundamental component of the whole robotic system, particular attention has been paid to simplifying the design of the finger joints, avoiding the use of mechanical parts such as bearings or other similar hardware that may cause problems in the integration of the sensors and the tendon network in the proximity of the joint itself. After evaluating several alternatives including compliant joints [Berselli et al., 2011b], pin joints with sliding profiles integrated into the phalanx body - simply consisting of a plastic shaft that maintains the joint assembled and by a circular profile which slides on a cylindrical surface (Integrated Pin Joints, IPJs) - have been selected for the implementation of the joints that connect the phalanges of both the fingers and the thumb. Due to the different requirements in terms of strength of the finger base and to allow the dislocation of the finger in case of overload or impact, thus avoiding damages to the mechanical structure of the hand, a slightly different implementation of the same concept has been adopted for both the MC and the CMC joints. The assembly pin has been removed and the joint simply comprises two sliding profiles that are maintained in contact by the tendon tension, and a minimum tendon tension is ensured by the actuator controller. Figure 5 reports a detail of the MC finger joints where both of these solutions are used: in particular, Figure 5(a) shows the disassembled joints, whereas in Fig. 5(b) the final assembly of the MC joint is shown. As stated before, the selected implementation of the finger joints targets simplification of both the design and assembly and at increasing the robustness of the mechanical structure in case of finger overload. However, it introduces a non negligible friction at the joint level. This issue has

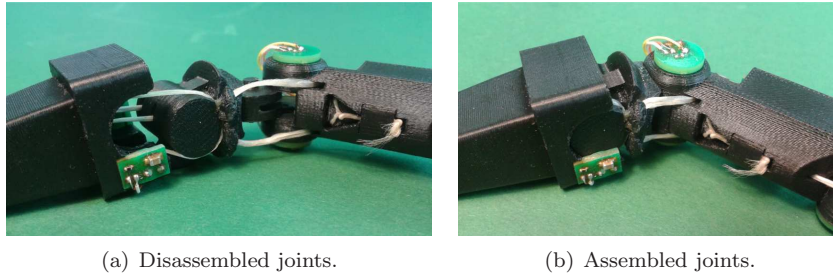


FIGURE 5. Detail of the base and the proximal joints.

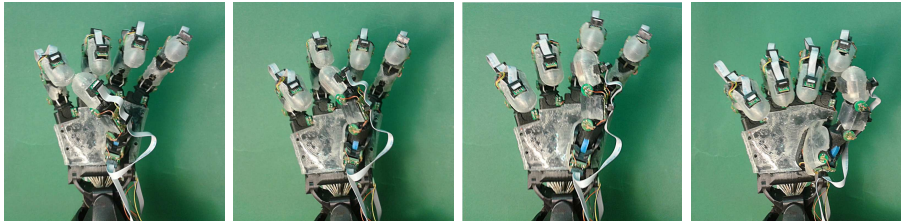


FIGURE 6. Opposition between the thumb and the fingers.

been investigated deeply in previous work [Borghesan et al., 2011] with the aim of mitigating its effects by means of the hand control system.

3.2. Hand Kinematics. It is well known that large differences exist in the dimensions and the joint mobility of the human hand among different subjects without significantly affecting grasping and manipulation capabilities [Napier and Tuttle, 1993]. As a consequence, it is not possible to define an optimal kinematics for a robotic hand [Grebenstein et al., 2010], so the design of robotic hand kinematics must be focused on replicating the main functional aspects of the human hand, which are the opposition between the thumb and the other fingers [Tubiana et al., 1998], see Fig. 6. This can be achieved by a suitable misalignment between the rotational axes of the thumb joints and by a suitable inward rotation of the base of both the little and the ring fingers. It is worth mentioning that the hamatometacarpal (HMC) joint of the little finger, which allows the motion of the little finger metacarpal toward the thumb, has not been implemented in the DEXMART Hand because of its limited range of motion and to achieve the maximum design simplification. Moreover, the 2-DOF CMC joint of the thumb has been implemented in a particular way compared to the 2-DOF MC joints of the other fingers: 1) it is stronger to support the larger force that the thumb provides; 2) the two rotational axes are combined in a different way compared to the other fingers, see Fig. 4; 3) it provides a larger movement range than the MC joint to increase thumb mobility. In Tab. 1 the Denavit-Hartenberg parameters of the DEXMART Hand are reported, showing the particular arrangement of the finger joints that allows this result to be achieved.

3.3. Implementation of the Wrist Mechanism. As for the other parts of the system, also the wrist has been conceived to achieve the maximum manufacturing

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

Link (Thumb)	d [mm]	θ	a [mm]	α [deg]
1	7.53	$\theta_1 + 85$	19.64	-110
2	-42.5	$\theta_2 - 80$	18	-90
3	-1.65	$\theta_3 + 10.62$	24.57	70.32
4	4.89	$\theta_4 - 3.61$	30	0
5	0	θ_4	30	0
Link(Index)	d [mm]	θ	a [mm]	α [deg]
1	40.75	θ_1	82	-95
2	-2.91	$\theta_2 - 20$	18	90
3	0	θ_3	38	0
4	0	θ_4	28	0
5	0	θ_4	28.5	0
Link (Middle)	d [mm]	θ	a [mm]	α [deg]
1	14.34	θ_1	86	-86
2	-4.91	θ_2	18	90
3	0	θ_3	40	0
4	0	θ_4	28	0
5	0	θ_4	28.5	0
Link (Ring)	d [mm]	θ	a [mm]	α [deg]
1	-11.16	θ_1	82	-80
2	-1.93	$\theta_2 - 5$	18	90
3	0	θ_3	38	0
4	0	θ_4	28	0
5	0	θ_4	28.5	0
Link (Little)	d [mm]	θ	a [mm]	α [deg]
1	-36.1	θ_1	68	-75
2	4.24	$\theta_2 + 15$	18	90
3	0	θ_3	35	0
4	0	θ_4	28	0
5	0	θ_4	28.5	0

and assembly simplification. As shown in Fig. 7, it is composed of only three parts (manufactured by means of FDM), and no bearings, screws or other hardware are necessary for its assembly. It implements 2 DOF, the flexion/extension and the adduction/abduction movements (the pronation/supination movement has not been implemented since, in robotic hands with integrated forearm, it usually occurs at elbow level), and also in this case the joints are composed of sliding profiles that can be eventually dislocated in case of overload to prevent damage to the mechanical structure of the hand. Since the tendons go from the forearm, where the actuators are placed, to the fingers passing through the wrist, particular attention has been paid to achieve decoupling between the wrist and the tendon movements. Several technical solutions that allow decoupling of the wrist and the finger movements can be found in literature, but in our case this goal has been achieved by introducing a certain distance (20 mm) between the two orthogonal axes of the wrist (this distance is about 5 mm in humans [Tubiana et al., 1998]) to allow the tendons to pass through both rotational axes. Figure 7 shows the routing of the tendons through the wrist. With the aim of reducing the friction acting on the tendons, during the wrist design particular attention has also been given to avoiding any contact between the different tendons and to minimizing the tendon curvature [Palli et al.,

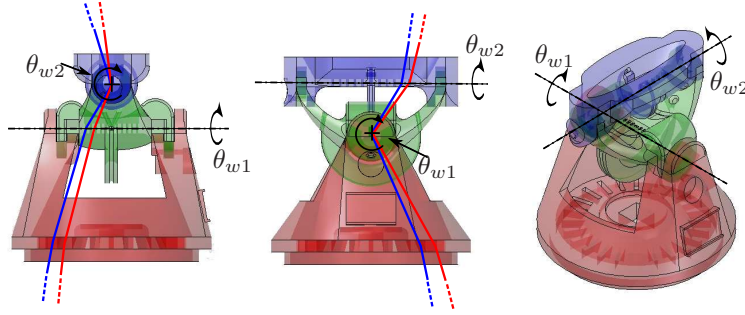


FIGURE 7. Details of the DEXMART Hand wrist design.

2012a]. Not only the fingers, but also the wrist, is driven by means of tendons, and its actuators are located in the forearm. Considering also the larger force required, two antagonistic actuators have been used for each DOF, resulting in a total of 4 actuators used to drive the wrist.

4. THE DEXMART HAND ACTUATION

Despite the continuous evolution of actuator technology, the current state of the art in this field does not allow arranging twenty or more actuators in a robotic hand with dimensions similar to those of a human hand and with suitable requirements in terms of speed and forces. The tendon-based transmission system partially solves this problem allowing the allocation of the actuators within the forearm, where the most powerful muscles are located in the biological model and more space is available for the motors. This actuator arrangement simplifies the hand construction, frees up space in the fingers for the integration of the sensors and achieves a more anthropomorphic weight distribution. Consequently, the tendon-based transmission system represents the most promising solution for dexterous anthropomorphic robotic hands.

The DEXMART Hand is actuated by means of four tendons for each finger, plus four additional tendons for the wrist actuation, resulting in a requirement of 24 independent actuators. In the following, the tendon-based transmission system of the device is detailed and the twisted string actuators are described.

4.1. The Tendon Network. The way the tendons are routed from the motors to the joints is a fundamental design problem in tendon-based actuation. Usually, tendons are routed by means of pulleys, sheaths or sliding surfaces: pulleys have been widely used for the implementation of tendon-driven robots, and in particular for robotic hands, since they minimize the friction forces acting along the tendon. The drawback of this approach consists in a more complicated mechanical design due to the presence of bearings and similar hardware, which partially reduce the advantages introduced by the use of tendons. The use of sheaths is a convenient solution due to its simplicity, but it introduces distributed friction along the tendon, which introduces hysteresis and dead-zones in the transmission system characteristic [Kaneko et al., 1991, Palli et al., 2012a]. In the DEXMART Hand, the routing of the tendons from the actuators in the forearm to the fingers is implemented by a series of sliding paths enclosed directly within the finger structure. As for sheath

routing, also in this case the stiction and the dynamic friction acting on the tendons affect the performance of both the position and the force control of the finger. To limit this undesired effect, a suitable low-level control strategy able to minimize the internal tendon forces (the tendon forces that do not contribute to the overall joint torques) has been adopted, see Borghesan et al. [2010] for additional details.

Instead of directly imitating the biological model, many different simplified solutions have been proposed in the literature to replicate the functionality of the quite complicated human tendon network. Whereas in the biological model the tendons slide around the bones, for the optimization of the transmission system in terms of reducing both the friction and the coupling among the hand movements, the structure of the hand has been designed to allow the tendon to pass through the endoskeleton by means of suitable channels. In this way, the tendons can be routed through the center of rotation of the joints when needed, obtaining a complete decoupling between the movements of consecutive joints.

Different studies confirm that the total amount of friction acting along the tendon depends only on the friction coefficient and on the total curvature of the tendon path from the motor to the joint [Kaneko et al., 1991, Palli et al., 2012a]. In the DEXMART Hand, this non-trivial design problem has been faced by minimizing the tendon path curvature, by making the path of each tendon as straight as possible and by a suitable selection of the tendon materials in addition to the use of tendon lubrication. Usually, very thin steel cables are used allowing a linear force-elongation behavior of the tendon to be obtained but introducing some design and assembly constraints due to the limited curvature radius of steel cables. In the last years, polymeric fibers have largely been adopted to improve the design flexibility of tendon transmissions, and in particular a Dyneema-based fiber called Fast-flight has been used for the tendons of the DEXMART Hand. It is also worth mentioning that the nature of the mechanical part surfaces obtained (in ABS plastic) by means of FDM imposes that: 1) the diameter of the tendons cannot be too small (less than 1 mm from our experience) to avoid that the tendon may “cut” the plastic parts in case the tendon applies a load along the material deposition plane; 2) the surface of the tendon must be smooth to reduce the friction coefficient and the wear of the sliding surfaces. These are among the main motivations that brought us to the selection of the Fast-Flight cables for the tendon network of the DEXMART Hand. This cable is characterized by a very smooth and continuous surface (it does not have any external cover for protecting the fibres) that allows achieving a very reliable transmission system avoiding the use of pulleys or other additional elements for the sliding surfaces. Indeed, by adopting these design expedients, no failure in the sliding surface of the tendons has occurred. Moreover, it is also important to note that these issues imposed the use of different materials for the implementation of the twisted string actuation (whose cables do not slide over any surface) and the tendon network of the hand itself. In [Palli and Melchiorri, 2006, Palli et al., 2012a], the tendon-based transmission system of the hand has been studied in detail, and suitable control strategies for the compensation of the friction acting on the tendons have been proposed and experimentally tested.

The fingers of the DEXMART Hand are actuated by means of an $N+1$ tendon network, whereas a $2N$ approach has been used for the wrist actuation due to the higher requirements in terms of amplitude and “symmetry” of the actuation force. In Fig. 8, a detailed view of the tendon path inside the finger and the DEXMART

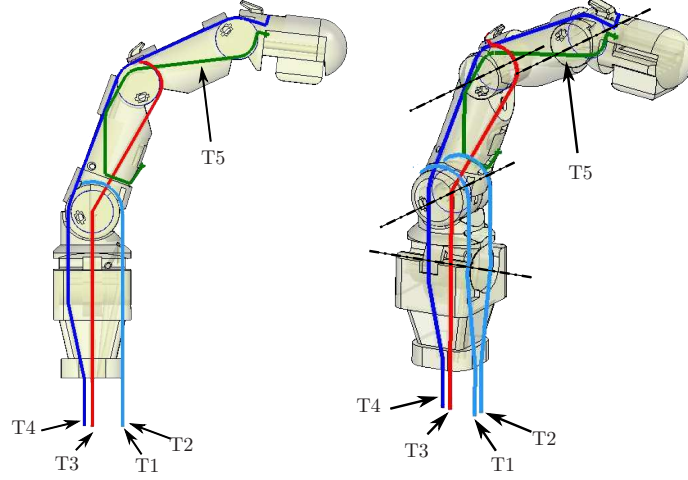


FIGURE 8. Details of the tendon network inside the finger.

Hand is shown. With reference to Fig. 8 where the tendon path inside the finger is reported, the tendons that actuate the MC joint (T1 and T2) are connected directly to the proximal phalanx, whereas the antagonistic tendon (T4) slides over the joints on the back of the finger. The tendon that actuates the PIP joint (T3) is routed very closely to the center of the rotational axes of the MC joint to limit as much as possible the coupling between the movements of this joint and the others. The path of the tendon (T5) that connects the PIP to the DIP joint inside the medial phalanx is straight so as to limit the friction acting on the tendon. This tendon is not driven by any actuator but it is only used to couple the motion of the DIP and the PIP joints in the same way they are coupled in the human hand. By neglecting the tendon elasticity (thanks to the very high modulus of the tendon material [Palli et al., 2012a]), the relationship between the tendon displacements and the finger joint positions can be expressed by the following relations:

$$(1) \quad l = H\theta, \text{ with } H = \begin{bmatrix} r_{11} & r_{21} & 0 & 0 \\ -r_{12} & r_{22} & 0 & 0 \\ 0 & 0 & r_{33} & 0 \\ 0 & -r_{24} & -r_{34} & -r_{44} \\ 0 & 0 & -r_{35} & r_{45} \end{bmatrix},$$

$$(2) \quad v = \dot{l} = H\dot{\theta},$$

where $l = [l_1 \ l_2 \ l_3 \ l_4 \ l_5]^T$ is the vector of the tendon displacements with respect to the zero position, i.e. with the finger in the straight configuration, v is the tendon velocity vector, $\theta = [\theta_1 \ \theta_2 \ \theta_3 \ \theta_4]^T$ is the vector of the finger joint angles and r_{ij} is the distance of the j -th tendon with respect to the i -th joint rotation axis. The numerical values of r_{ij} are reported in Tab. 2. Note that, thanks to the DEXMART Hand design, the value of r_{ij} is constant, and in particular it does not depend on the joint configurations. The coupling given by the introduction of the coupling tendon T5 results in a kinematic constraint that can be expressed

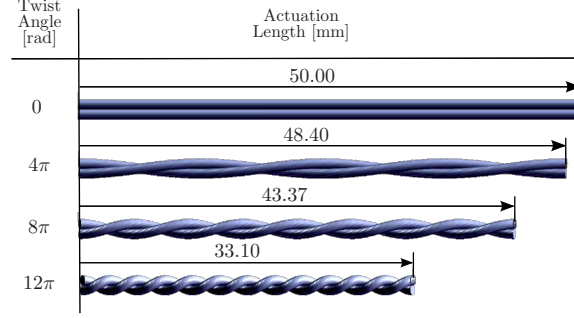


FIGURE 9. Basic concept of the twisted string actuation system.

as

$$(3) \quad \theta_4 = \frac{r_{35}}{r_{45}} \theta_3.$$

Due to the virtual work principle, the relation between the tendon force f and the finger joint torques $\tau = [\tau_1 \quad \tau_2 \quad \tau_3 \quad \tau_4]^T$ can be computed as:

$$(4) \quad \tau = H^T f.$$

Since the dimensions of the tendons and the joint space are different, i.e., 5 and 4 respectively, in order to compute the actuation forces f given the desired joint torques τ , the pseudo-inverse H^{T+} of the matrix H must be used:

$$(5) \quad \hat{f} = H^{T+} \tau$$

$$(6) \quad f = \hat{f} + \lambda f_k$$

where $\hat{f}$ is the minimum module force vector so that $\tau = H^T \hat{f}$, f_k is a base of the null space of H^T , and $\lambda \in \mathbb{R}$ is chosen in order to impose the tendon tensions above a certain threshold f_0

$$(7) \quad \lambda = \max_{i \in \{1, \dots, 5\}} \frac{f_{0i} - \hat{f}_i}{f_{k_i}}$$

where i denotes the element index of each vector. The force computed in (5) is then a five elements vector, including the force applied to the passive tendon. The forces to be applied by the actuators consist then in the first four elements of f , whereas the passive tendon tension f_5 will be univocally determined by the forces applied by the actuators on the other tendons. Then, the low-level controller of the twisted actuation system applies the desired force to each tendon ensuring also the minimum desired tension in the passive tendon, as described in detail in Palli et al. [2013]. Together with the kinematic parameters reported in Tab. 1, eq. (1)-(5) allow computing the relation between the fingertip, the joints and the tendon motion.

r_{11}	r_{12}	r_{21}	r_{22}	r_{33}	r_{24}	r_{34}	r_{44}	r_{35}	r_{45}
8.2	8.2	7.8	7.8	6.3	5.3	5.3	5.3	3.5	5.0

TABLE 2. Values of r_{ij} (in mm).

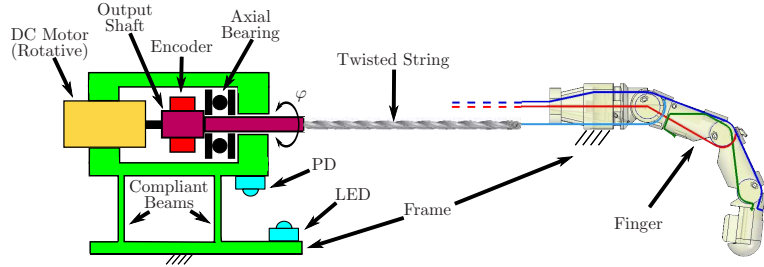


FIGURE 10. Schematic representation of the DEXMART Hand actuation system structure.

4.2. The Twisted String Actuation System. The actuation of the robotic hands developed so far are based essentially on rotative electric motors [Liu et al., 2008, Kawasaki et al., 2002, Dalley et al., 2009] or linear pneumatic actuators [Shadow Robot Company, 2003], usually McKibben motors [Chou and Hannaford, 1996]. The use of pneumatic actuators, besides the higher power density compared to electric motors, presents some difficulties from the control point of view and also conflicts with the integration requirements, since the valves and the compressor cannot be included into the hand structure due to their dimensions and weight. Considering robotic hands with electric actuators, besides differing in terms of the type of motors (DC or brushless), different types of transmission systems have been adopted: a) the motors can be directly placed within the fingers and the palm and connected to the joint by means of harmonic drive [Butterfass et al., 2001], spur and worm gears [Kawasaki et al., 2002, Townsend, 2000]; b) the motors can be placed in the forearm transmitting the mechanical power by means of flexible shafts [Lovchik and Diffler, 1999] or leverages [Fukaya et al., 2000] or tendons routed by means of pulleys [Salisbury and Roth, 1983, Melchiorri and Vassura, 1993] or sheaths [Biagiotti et al., 2005, Caffaz et al., 2000, Berselli et al., 2009].

Although the actuation solutions adopted in robotic hands developed so far have their own benefits and shortcomings, the so-called twisted string actuation system has been developed for the DEXMART Hand, aiming at fitting with its design requirements. Compared to conventional solutions, the main advantages of this actuation system consist in the direct connection between the motor and the tendon without any intermediate mechanisms such as gearboxes, pulleys or ballscrews, in the direct transformation from rotative to linear motion, in the extremely reduced friction (only an axial bearing is needed), in the very high reduction ratio, in its intrinsic compliance and in the use of very small high-speed motors. The basic idea of this quite simple actuation system is illustrated schematically in Fig. 9: two or more strands are connected in parallel on one end to a rotative electrical motor and on the other end to the load to be actuated. Twisting the strands at the one end by means of the motor reduces the length of the transmission, resulting in a linear motion of the other end.

The basic principle of this actuation concept has already been used for different applications [Jacobsen et al., 1975, Pottebaum and Beaman, 1983, Mennitto and Buehler, 1997, Shoham, 2005], and the growing interest in this actuation concept, in particular for robotic hand development, is shown by several recent publications [Sonoda and Godler, 2010a,b, Shin et al., 2012]. In contrast with previous designs

reported in the literature, the twisted string actuation system adopts very thin and long strings twisted around themselves allowing the use of very small high-speed motors without a speed-reducer, reducing the costs of the motors and simplifying the mechanical design. As a specification for the actuation system design, a 10 N load applied perpendicularly to the tip of an outstretched finger has been considered. Taking into consideration the finger kinematics and the tendon routing, this requirement translates into a maximum force of 80 N and a displacement corresponding to full closure of the hand of 25 mm maximum for each tendon. The twisted string actuators of the DEXMART Hand have been organized in two levels, characterized by different lengths of the strands, 0.21 m (Actuation Level 1, AL1) and 0.28 m (Actuation Level 2, AL2), respectively, to reduce the overall dimension of the actuation system. The twisted string actuators are composed of 2 strands each, and each strand has a diameter of 0.14 mm. Since each strand can support a maximum load of 160 N, this element represents the weak point in the force transmission chain from the motors to the joints, allowing the use of the strand as a mechanical fuse, also thanks to its extremely low cost, in case of actuation system overloading. Suitable research has been carried out to select a proper fixing mechanism of the strands to both the motor and the linear guide on the tendon side to increase the lifetime of the strands and allow an easy and fast substitution of this element in case of damage. The solution for fixing the strands adopted in the DEXMART Hand allows the twisted string actuators to resist more than 10000 working cycles [Palli et al., 2013]. For implementing the twisted string actuators, the coreless DC motors A12C-12S from C.I. Kasei Co. have been selected. They are characterized by an outer diameter of 12.4 mm, a length of 30.8 mm, a stall torque of 21.3 Nmm and a maximum rotating speed of 21600 rpm. According to the kineto-static model of the twisted string actuation system presented by Palli et al. [2013], the relationship between the motor angle φ and the length of the actuator p can be easily derived from the geometry of the helix formed by the strands:

$$(8) \quad L = \sqrt{\varphi^2 r^2 + p^2},$$

$$(9) \quad \sin \alpha = \frac{\varphi r}{L}, \quad \cos \alpha = \frac{p}{L}, \quad \tan \alpha = \frac{\varphi r}{p},$$

where α is the helix slope and L is the strand length. From eqs. (8) and (9) it follows that:

$$(10) \quad \dot{L} = \dot{p} \cos \alpha + \dot{\varphi} r \sin \alpha.$$

From this last equation, the maximum speed of the actuation can be computed neglecting the finite stiffness of the strands or, in other words, in case of small load (free hand motion), which implies a constant length of the strand, i.e.:

$$(11) \quad \dot{L} = 0 \implies \dot{p} = \dot{\varphi} r \tan \alpha = \dot{\varphi} \frac{\varphi r^2}{p} = \dot{\varphi} / h.$$

Note that eq. (11) defines the configuration dependent generalized reduction ratio $h = p/(\varphi r^2)$ of the twisted string actuator since it also converts rotative to linear quantities. The equilibrium between the motor torque τ_m and the force acting in each strand F_i (along the strand direction) is:

$$(12) \quad \tau_m = 2 r F_i \sin \alpha.$$

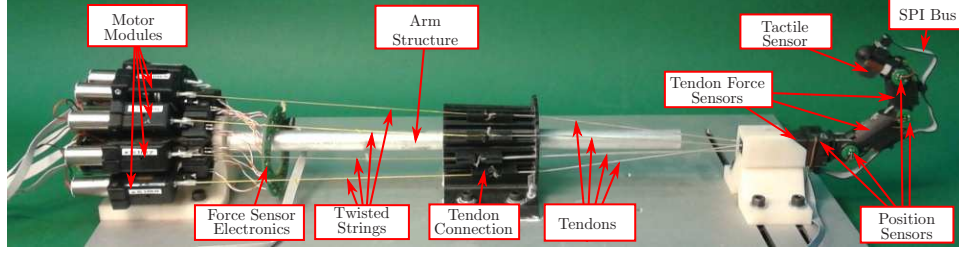


FIGURE 11. Detailed view of the finger actuation module and sensory equipment.

The resulting actuation force F_z is then:

$$(13) \quad F_z = 2 F_i \cos \alpha \Rightarrow \tau_m = F_z r \tan \alpha = F_z \frac{\varphi r^2}{p} = F_z / h.$$

Since the model (8) is singular with respect to the configuration $\varphi = 0$, the twisted string actuation of the DEXMART Hand has been designed to present a minimum actuator contraction of 5 mm to prevent control singularities [Palli et al., 2013]. While considering a maximum tendon displacement of 25 mm, the maximum needed actuator contraction is 30 mm. From eq. (13) follows that the reduction rate of AL1 ranges from $2.4 \times 10^4 \text{ m}^{-1}$ to $6.6 \times 10^4 \text{ m}^{-1}$, while the one of AL2 ranges from $3.2 \times 10^4 \text{ m}^{-1}$ to $7.4 \times 10^4 \text{ m}^{-1}$. The actuators have been designed to satisfy the actuation requirements for both AL1 and AL2 with a suitable margin for preventing performance degradation due to undesired effects like motor friction. Then, the maximum force requirements must be tested against the minimum reduction ratio of AL1, while the speed requirements need to be verified against the maximum reduction ratio of AL2. From eq. (11) and considering that the motors present the maximum output power at about 10000 rpm, it follows that the maximum contraction velocity of AL2, in the worst conditions, is about 0.014 m/s, while the minimum force of AL1, in the worst conditions and neglecting friction, is about 288 N. Moreover, the maximum time required by the actuators to accomplish a complete contraction movement is about 0.84 s. The actuation force is then limited by the actuator's low-level control system to a maximum value of 80 N to prevent both damage to the transmission system and motor overheating.

It is worth remarking that the force applied by the twisted string system can be efficiently controlled using only force feedback, while neither measurement of the motor angular displacement and velocity or of the load position and velocity, nor an accurate knowledge of the system parameters (e.g. string or actuation length, string radius, motor or string preload angle, load parameters) are required. Moreover, due to the finite stiffness of the strings and to the particular implementation, a non-negligible configuration-dependent compliance of the proposed transmission systems was observed during the early experimentation. This phenomenon has been exploited to improve the robustness of the device and for safety purposes [Bicchi et al., 2005]. Another important feature of this transmission system is the fact that, due the high reduction ratio, the twisted string transmission system is (practically) non-backdrivable, a fact that together with its inherent compliance, allows maintaining also large gripping forces without needing to continuously supply

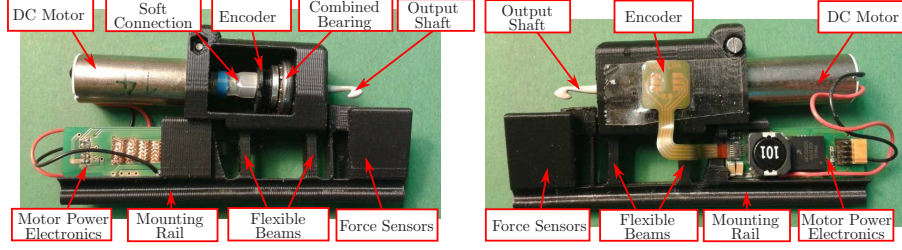


FIGURE 12. Detail of the motor module.

power to the motors, and thus allowing a significant reduction of the overall control action requirements and power consumption.

With the aim of providing an effective description of the actuation system of the DEXMART Hand, a schematic representation of the actuation system is reported in Fig. 10 and a picture of a preliminary prototype of the actuation system for the finger is reported in Fig. 11. This module allows the detailed view of all of its basic components: from left to right, the system is comprised of the motor modules (see also Fig. 12), the acquisition electronics of the motor force sensors, the twisted string, the linear guides for the connection of the twisted strings with the finger tendons and the finger. As can also be seen in Fig. 1, the actuators are placed around the supporting structure of the forearm, allowing easy access to each actuation module for rapid repair and assembly. A detailed view of the motor module is reported in Fig. 12. Also the body of this part is manufactured in ABS plastic by means of FDM and is characterized by a mounting rail for rapid mechanical connection with the forearm structure, which eases assembly and repair of the system. A pair of flexible beams give the structure a certain compliance as well as facilitate implementing the force sensor (whose working principle will be detailed in the next section). Lateral barriers prevent cross coupling between the sensors of adjacent modules, while a case hosts the DC motor. As shown in Fig. 12, also the motor power electronics is arranged in the motor module, whereas the connection between the motor shaft and the transmission shaft has been implemented by means of a silicon tube in such a way as to introduce suitable flexibility for compensating any misalignment between the rotational axes of the motor and that of the transmission shaft (where the twisted string is attached). The particular structure of the motor module allows the transmission force to be entirely supported by the output shaft through a combined bearing, whereas the motor is only used to transmit the necessary torque for driving the twisted string actuation to the output shaft.

5. THE SENSORY SYSTEM

The DEXMART Hand is equipped with angular position sensors for the measurement of both the joints and the actuator configurations, with force sensors to measure the actuation force and with force/tactile sensors in the fingertips to reconstruct the pressure map as well as the contact area during the contact. Optoelectronic components have been implemented in all the sensors to achieve a fundamental simplification of the conditioning and acquisition electronics, thanks to their inherently high immunity to electromagnetic disturbances and with limited

requirements in terms of amplification. As a consequence, the same conditioning circuit can be adopted for all of the sensors, and no amplifiers are needed for the resulting signal. The schematic illustrating the very simple acquisition electronics adopted in the DEXMART Hand for all of the sensors is shown in Fig. 13; the data collected from the sensors are, in this way, directly digitalized and transmitted through a digital SPI bus to the hand control system. A crucial aspect in the use of this type of optoelectronic sensor is the stability of the LED current. In our experience, the use of a stabilized power supply is sufficient to avoid any appreciable current fluctuations and, as a consequence, sensor measurement variations. Alternatively, the current flowing in the LEDs can be fixed by using a controlled current supply, with a minimal additional electronic circuit. Another aspect to take into account is the thermal inertia of the LED: due to this phenomenon, it is necessary to wait a couple of minutes after the system power is on to reach a stable value of the device current and then a reliable response of the sensor. The electronics of the DEXMART Hand is based on Surface Mount Devices (SMD) both to reduce the dimensions of the boards and to allow automating the assembly of the electronics. Moreover, the DEXMART Hand electronics, as well as the hand mechanics, have been conceived to be modular and easy to mount on the mechanical structure of the hand. The DEXMART Hand has not been conceived for mass production nor for prostheses but is a test-bench for the evaluation of suitable solutions toward the next generation of robotic hands. Therefore, no particular investigation has been performed about the robustness of the wiring between the boards. Rather, standard miniaturized cables for digital data and digital communications for all the data that flow through the system have been adopted to reduce the risks of stability in electrical interfaces. This result has been achieved by simplifying the electronics as much as possible, thanks to the use of sensors based on optoelectronic components as shown in Fig. 13, and by digitalizing the data as closely as possible to the sensors in such a way as to interconnect all the sensors (as well as the actuators) to the control system by means of digital buses. As in the case of the hand mechanics, the adopted solution has been inspired by simplicity in assembling and by low cost. On the basis of our experience, the solutions adopted for the DEXMART Hand electronics do not require long to be assembled on the hand compared to the other manufacturing and assembly steps required for the hand production. They also do not detract anything nor negatively influence the evaluation of the solutions adopted for the DEXMART Hand, and in particular for the mechanical components. In the remainder of this section, a brief description of the developed sensors is reported with reference to the related literature. The location of all sensors in the finger of the DEXMART Hand can be clearly identified from Fig. 11, while the details about each sensor are reported in the following subsections. The description of the motor position sensors is not reported in this paper since they are simple, custom made optical encoders.

5.1. The Motor Force Sensor. The motor module force sensor exploits LED and PhotoDetector (PD) couples with a narrow angle of view to measure the small deformations imposed by the tendon force to the motor module itself. As schematized in Fig. 14(a), the compliant beams implemented in the motor module produce a translation Δx of the upper part of the structure under the effect of the transmission force F . The linearized deformation behavior of the beam with translation constraints at both its ends, highlighted by the red dashed rectangle in Fig. 14(a),

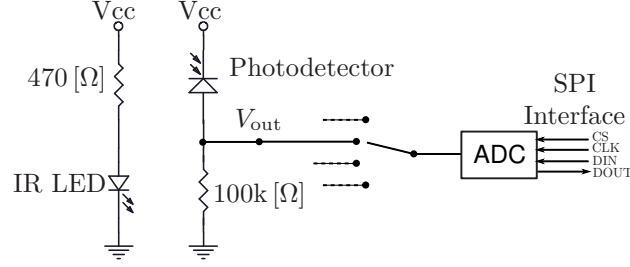


FIGURE 13. Measuring circuit for the sensors based on optoelectronic components.

is given by the contribution of the two compliant beams as

$$(14) \quad \Delta x = \frac{1}{2} \frac{F L^3}{12 E I_b} = \frac{F L^3}{24 E I_b}$$

where

$$I_b = \frac{h^3 b}{12}$$

is the moment of inertia of the beam sectional area, L is the beam length, E is the Young modulus of the material and h and b are the height and the thickness of the beams, respectively. The displacement Δx causes a variation of both the light angle and the distance between the LED and the PD, allowing an indirect measurement of the force F through the change in the PD photocurrent caused by the deformation of the motor module structure. Figure 14(b) shows a LED and a PD positioned symmetrically to each other, similarly as they are mounted on the compliant frame. In this symmetrical configuration, β represents the angle between the LED (or the PD) mechanical axis and the segment that indicates the distance d from the tip of the PD to the tip of the LED. In this state a certain amount of light emitted by the LED reaches the PD and is proportionally converted into a photocurrent $I(\beta)$. When the relative position x of the optoelectronic components experience a variation Δx compared to its initial value due to the deformation of the compliant frame, also the viewing angle β between the optoelectronic components varies and a different amount of light will be sensed by the PD and converted into a variation of the photocurrent $I(\beta - \Delta\beta)$. This happens because both the radiation pattern value of the LED and the responsivity pattern value of the PD vary with the viewing angle β , and the distance d between the two components varies with the relative position. Recalling the theory on LED radiation patterns [Kasap, 2001], it is possible to model the system in order to optimize the selection and the positioning of the optoelectronic components. In particular, if the distance d is large enough to assume the far-field approximation valid, the LED and the PD could be regarded as a point source and a point receiver respectively. In this case the photocurrent $I(\beta)$ can be expressed as

$$(15) \quad I(\beta) = K \frac{\mathcal{I}(\beta) \mathcal{R}(\beta)}{d^2(\beta)}$$

where K is a dimensional multiplicative constant, $\mathcal{I}(\beta)$ is the radiant intensity pattern of the LED, $\mathcal{R}(\beta)$ is the responsivity pattern of the PD and d is the distance between the components. This model explains that the sensor characteristics, in

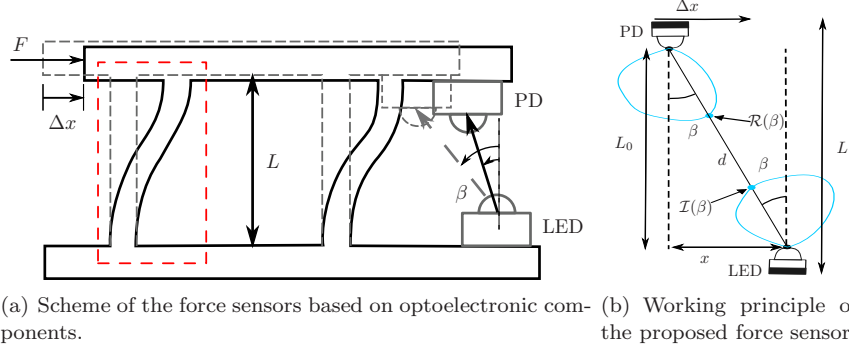


FIGURE 14. Schematic representation of the force sensor implemented in the actuation module.

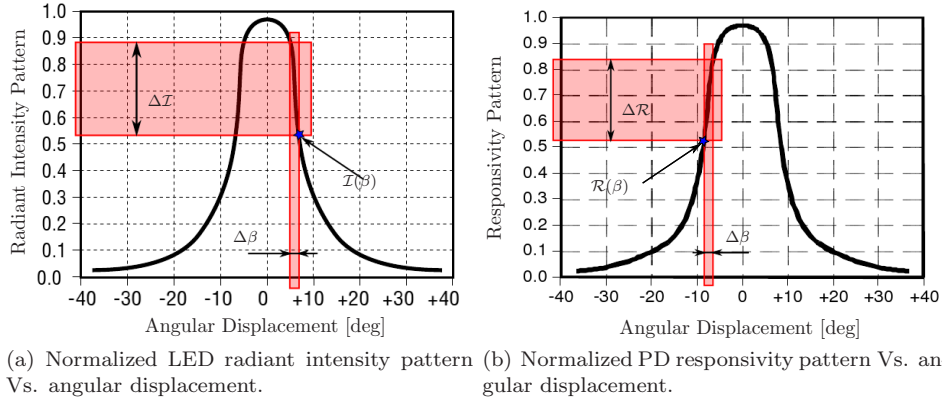


FIGURE 15. Characteristics (from datasheets) of the optoelectronic components used in the force sensors, SEP8736 (LED) and SDP8436 (PD), both from Honeywell .

terms of sensitivity, full-scale and SNR, depend on how the responsivity and radiation patterns of the optoelectronic components are sensitive to β variations. In Fig. 15(a) and 15(b) the characteristics of the LED and of the PD are reported and the large variation of radiant intensity pattern $\Delta \mathcal{I}$ and responsivity pattern $\Delta \mathcal{R}$ over a very limited variation of the angular displacement in a suitably selected region has been highlighted.

On the basis of the radiant intensity pattern of the LED and the responsivity pattern of the PD reported in Fig. 15, by exploiting eq. (16) the following optimization problem can be solved to choose the relative initial positioning (i.e., β) of the optoelectronic components that maximize the sensor sensitivity:

$$(16) \quad \max_{\beta} J(\beta) = \max_{\beta} \left| \frac{\mathcal{I}(\beta - \Delta\beta) - \mathcal{I}(\beta)}{\mathcal{I}(\beta - \Delta\beta)} \right| 100.$$

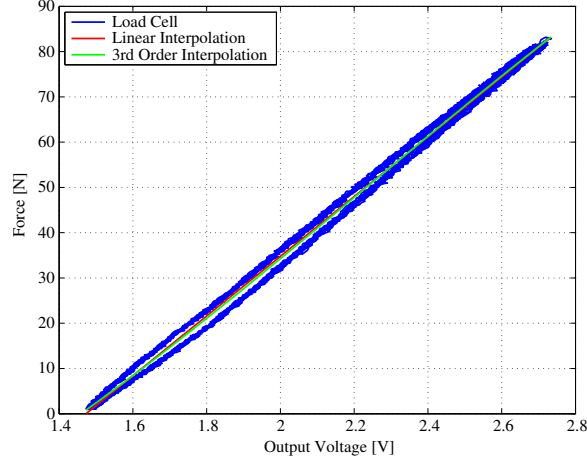


FIGURE 16. Calibration curve of the tendon load cell based on optoelectronic components.

The details of this optimization procedure can be found in Palli and Pirozzi [2012], from which the optimized value $\beta = 7.15$ deg has been determined and then implemented in the sensor prototypes.

5.1.1. Sensor Calibration. The calibration curve of the proposed sensor has been derived using a strain-gauge load cell as reference sensor and applying a continuously varying load to the motor module up to the maximum desired value (80 N). The calibration curve of the proposed sensor is reported in Fig. 16: in this plot several pulling and release phases are reported to show both the limited hysteresis, given mainly by the properties of the plastic material of the flexible beams, and the repeatability of the sensor. Moreover, the experimental data have been interpolated by means of both a linear function and a 3rd-order polynomial to show simple methods to reconstruct the force information: even though the linear function gives a quite good estimation of the effective force in all the conditions, the use of a 3rd-order interpolation function results in a maximum estimation error of about 2 N, which is compatible with the tendon-driven robotic system.

5.2. The Tendon Force Sensor. The tendon force sensor exploits the same optoelectronic components of the previously described sensor to measure the small deformations imposed by the tendon tension on a suitably designed deformable structure, also referred to as “compliant frame”. For a detailed description of the sensor optimization both for the compliant frame and the optoelectronic components positioning, together with a complete characterization of the sensor, the reader is referred to Palli and Pirozzi [2012]. A CAD model of the whole sensor, constituted by the compliant frame and the optoelectronic components, is depicted in Fig. 17, while Fig. 17(b) illustrates the interaction between the LED and the PD, assuming that the LED and the PD are positioned with an initial relative angle between their mechanical axes $\gamma = \beta_1 + \beta_2$. In Fig. 17(b), β_1 represents the angle between the LED mechanical axis and the segment that indicates the distance d from the tip of the PD to the tip of the LED, and β_2 representing the angle between the PD mechanical axis and the same segment. In this state a certain amount of

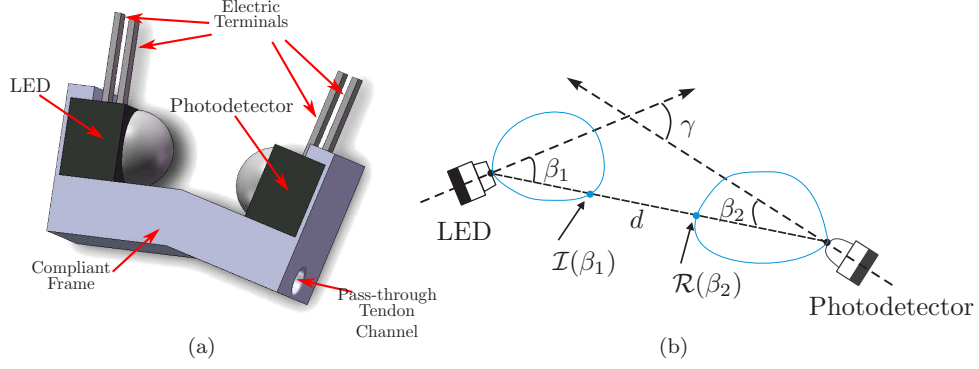


FIGURE 17. Overall view of the force sensor (a) and working principle (b).

light emitted by the LED reaches the PD and is proportionally converted into an electrical current I_γ .

When the angle γ experiences a variation compared to its initial value a different amount of light will be sensed by the PD and converted into a current different from I_γ . This happens because the radiation pattern of the LED varies with the angle β_1 , see Fig. 15(a), so that the receiver detects different values of radiant flux for different values of β_1 . At the same time, also the way the PD weights received light varies according to the variations of its responsivity pattern with β_2 , see Fig. 15(b). The combination of these two effects leads to the observed variations of the photocurrent.

The compliant frame is a monolithic element suitably designed to obtain an angular displacement of the optical axes of the optoelectronic components linearly proportional to the tension force applied to the tendon. Compared to previous solutions, the particular characteristic of the designed sensor is that it can be mounted in any position along the tendon and needs not to be designed as a structural element, i.e. it can be designed independently of the other components of the robot. This is possible thanks to the V-shaped channel that traverses the length of the compliant frame through which the tendon passes: the surface friction ensures that a minimal tendon tension prevents the frame from slipping along the tendon, while the shape of the channel allows the frame to be inflected because of the reaction forces exerted by the tendon on the channel as the effect of its tension. The compliant frame can then be modeled as a flexible beam with concentrated load at its middle point and constrained at its ends. This simplified modeling allows designing the compliant frame starting from the maximum tendon tension and the corresponding desired optical displacement of the optoelectronic components.

Figure 18(a) reports a picture of a sensor prototype, while Fig. 18(b) shows a typical calibration curve. It is noteworthy that the voltage variations of this sensor output allow direct digitalization by means of the ADC without any additional amplification/filtering stage and as a consequence a direct connection to the DEXMART Hand control electronics through the SPI digital bus.

5.3. The Tactile Sensor. The tactile sensor developed for the DEXMART Hand is based on commercial SMD optoelectronic components and is capable of providing

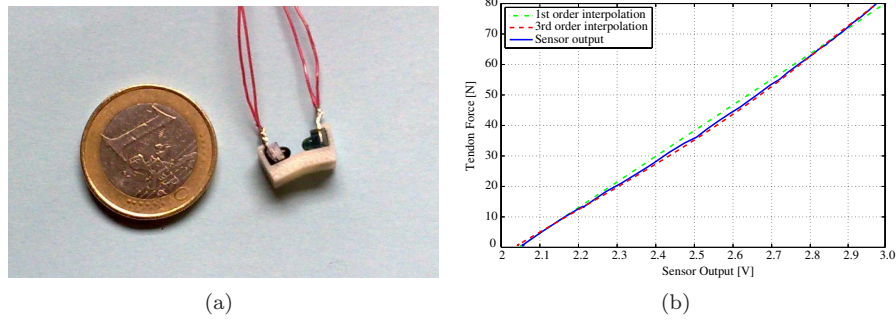


FIGURE 18. Prototype of the tendon force sensor based on optoelectronic components (a) and its calibration curve (b).

a tactile image of the contact area, a measurement of the contact force and torque components and an estimation of the position and orientation of the contact plane, which is assumed to be the surface of the object in contact with the sensor. Also this sensor integrates an ADC with an SPI digital interface to allow the direct connection with the robotic hand control electronics. The details on the sensor technology and its functionality can be found in D’Amore et al. [2011]. Here a short description is reported for the sake of completeness.

5.3.1. Working Principle. The tactile sensor is constituted by a deformable elastic layer with an hemispherical shape positioned above a matrix of sensitive points, called “taxels”, realized with LED/Phototransistor couples. The optoelectronic component couples are organized in a 4×4 matrix structure. For each couple, the LED illuminates the reflecting surface which coincides with the bottom facet of the deformable layer. In practice, the deformable layer transduces an external force and/or torque into a deformation of its bottom facet through its stiffness. An external force applied to the deformable layer produces local variations of the bottom surface of the elastic material and the optoelectronic couples measure the deformations in a discrete number of points. These deformations produce a variation of the reflected light intensity and, accordingly, of the photo-current flowing into the photo-detector. The photo-current variations are finally transduced into voltage signals by using standard resistors. The deformable layer is realized with black silicone in order to avoid optical cross-talk between taxels and ambient light disturbances. Only the surface which faces each sensitive point is white to increase the sensor sensitivity. The top of the deformable layer is a section of a sphere with a radius of 11.4 mm. With the silicone choice, according to the numerical simulations reported in D’Amore et al. [2011], the expected measurement range of the sensor prototype is $[0, 4]$ N, the sensitivity is about 0.1 N and 1 Nmm for forces and torques, respectively. The selected tactile sensor measurement range is suitable for most of the common manipulation tasks, as shown in Palli et al. [2012b]. Instead, during grasping tasks which involve larger forces, the measurements of the tendon force (whose full scale is 80 N), can be used to control the task execution. The silicone rubber adopted for the implementation of the tactile sensor described in this paper presents shore hardness 9A. The working range of the tactile sensor can be changed by selecting a silicone rubber with different shore hardness for the implementation

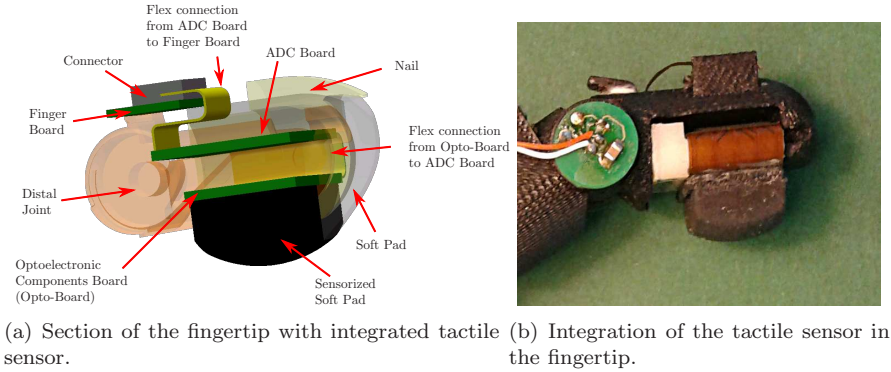
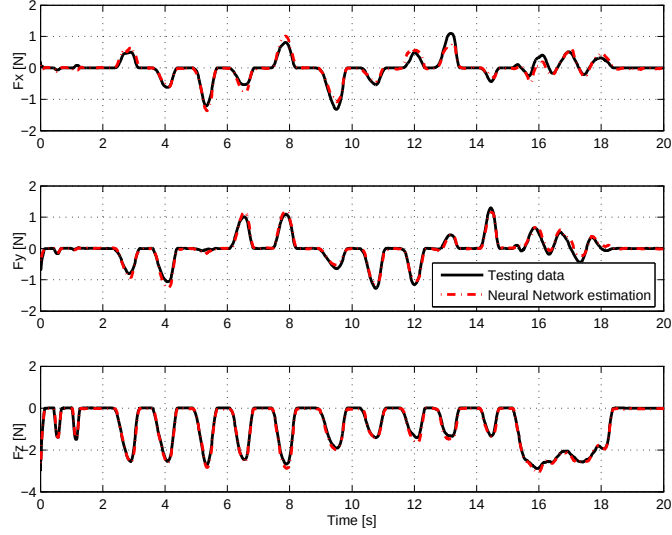


FIGURE 19. CAD drawing (a) and picture (b) of the tactile sensor integrated into the fingertip.

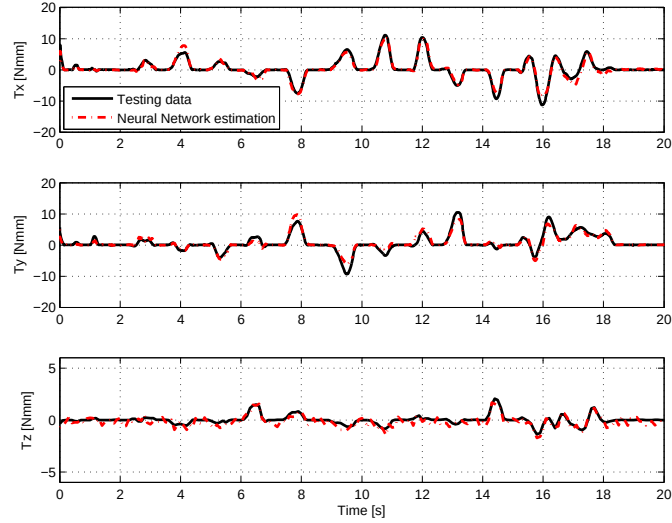
of the deformable layer. In particular, as detailed in D'Amore et al. [2011], the relation between the sensor full scale and the silicone hardness is quite linear, e.g., by using a silicone with a hardness two times higher, also the sensor full scale is practically doubled. Each taxel of the sensor is composed of an infrared LED (code SFH480), and a silicon NPN phototransistor (code SFH3010). The digital interface has been implemented by means of the AD7490, which is a 12-bit high-speed, low-power, 16-channel, successive-approximation ADC with a maximum sample rate of 1 MHz. It also presents versatile serial input/output ports, supporting several communication protocols (SPI/QSPI/MICROWIRE), including the one (SPI) used in the DEXMART Hand. The overall power consumption of the tactile sensor is about 100 mW, and the estimated cost is much lower than any commercial 6-axis F/T sensor.

5.3.2. Sensor Calibration. Aiming at using it as a six-axes force/torque sensor, the proposed approach for the calibration of the tactile sensor is based on the use of a neural network used to model the relationship between the applied forces and torques and the phototransistors measurement. The sensor has been mounted on a six-axes load cell used as reference sensor, i.e., FTD-Nano-17 manufactured by ATI. An operator carried out various experiments, using a stiff plane, applying different external forces and torques and simultaneously acquiring all the voltage variations on the phototransistors and all the forces and torques components measured by the reference load cell. These data, acquired at a sample rate of 100 Hz, have been organized in a training set and a validation set to be used as input data (voltage variations) and target data (forces and torques components) of the neural network. A standard two-layer feed-forward neural network f_{NN} trained with the Levenberg-Marquardt method has been used to fit training data. Figure. 20 shows the accuracy of the tactile sensor in reconstructing the force and torque components. The reader can refer to De Maria et al. [2012] for details about tactile sensor characterization.

5.4. The Angular Sensor. Each joint of the DEXMART Hand integrates a miniaturized angular position sensor based on commercial optoelectronic components [Palli and Pirozzi, 2013]. The angular measurement takes place by modulation of the radiation light power that goes from a LED to a PD by means of a variably



(a) Force Reconstruction.



(b) Torque Reconstruction.

FIGURE 20. Reconstruction of the force and torque components by means of the tactile sensor.

shaped channel that moves together with the joint. The main advantage of this solution is that the light path is entirely enclosed within the joint itself, so the sensor is insensitive to disturbances caused by adjacent sensors or external infrared sources.

5.4.1. *Working Principle.* To describe the working principle of the angular sensor, the interaction between the LED and the PD has been schematized in Fig. 21. In

particular, according to Kasap [2001]: the LED is approximated as a point source positioned at a point A that generates light in all directions with an intensity that depends on the emission angle according to the LED radiation pattern; the PD is modeled as a finite surface $\overline{CD}$, whose midpoint is indicated with B , with a sensitivity that varies with the receiving angle according to the responsivity pattern of the PD. Due to the axial symmetry of the optical components and their corresponding radiation and responsivity patterns, the dependence of the model on the spherical coordinate ϕ can be omitted. As a consequence, the design of the sensor can be addressed using a 2D coordinate system instead of a 3D system without loss of generality. The optoelectronic components are mounted at a fixed relative position with the optical axes aligned to maximize the signal level.

In the initial condition, i.e. without any occlusion as reported in Fig. 21(a), the PD measures an optical power P_1 . If a mechanical component is partially positioned between the two optical devices, see Fig. 21(b), a certain amount of the light emitted by the LED is occluded and, as a consequence, the PD measures an optical power P_2 smaller than P_1 . With reference to Fig. 21(a) where the case of no occlusion is shown, the distance between the emitter and the midpoint of the receiver is defined as d_0 , the segments $\overline{AC}$ and $\overline{AD}$ delimit the light flux impacting on the PD and γ_0 is the angle between these segments.

Figure 21(b) shows a generic case with partial occlusion, where the occlusion is defined as a variable δ that assumes values between 0 (no occlusion) and 1 (total occlusion). Note that the occlusion is assumed to be symmetric with respect to the optical axes of the optoelectronic components to maintain the symmetry of the system. The LED emits light in all directions but, due the occlusion, the PD receives only the amount of light with an emitting angle $\gamma < \gamma_0$. A proper mechanical design allows to obtain an occlusion δ of the light flux proportional to the physical variable to be measured: the angular position of the robotic joint.

5.4.2. Sensor Design and Calibration. Each joint is composed of a first link on which the LED and the PD are mounted and a second link where a variable width channel is implemented. On the first link two sockets for the optoelectronic components are realized so that the two devices are mounted face to face with the optical axes aligned and the light beam is entirely enclosed inside the joint itself (see Fig. 22(a)). The channel in the second link is designed in order to obtain a variable occlusion for the light emitted by the LED and received by the PD according to the working principle presented above. The dimensions of the channel are fixed so that the relationship between the occlusion and the joint angle is linear for the entire range of angle variations (see Fig. 22(b)).

For each finger of the DEXMART Hand three identical sensors (from the mechanical point of view) have been used for the DIP joint, the PIP joint and the second axis of the MC joint. The same sensor is used also in the MP and IP joints of the thumb. For these joints, compatible with their size, the distance between the optoelectronic components has been selected to $d_0 = 7$ mm. These three joints differ only by the angle ranges of the variable-width channel, which are $[0, 110]$ deg, $[0, 90]$ deg and $[0, 80]$ deg for the medial joint, the proximal joint and the distal joint, respectively. Suitable PCBs (Printed Circuit Boards) have been designed and optimized to be integrated into the finger joints. For the first axis of the MC joint and the two axes of the CMC joint of the thumb, a different joint implementation has been adopted because of the different implementation of these joints due to

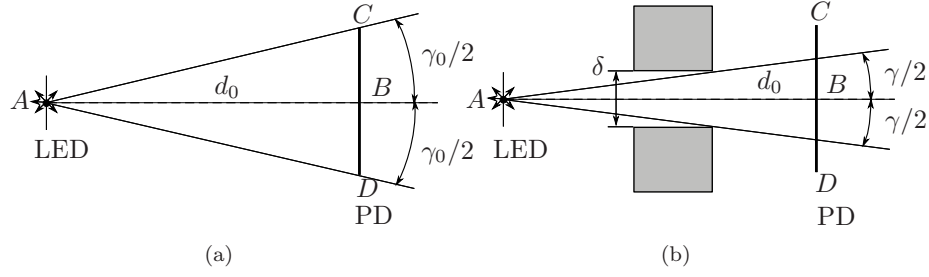


FIGURE 21. Sketch of the interaction between the LED and the PD for the angular sensor: (a) interaction in the case of no occlusion and (b) in the case of occlusion.

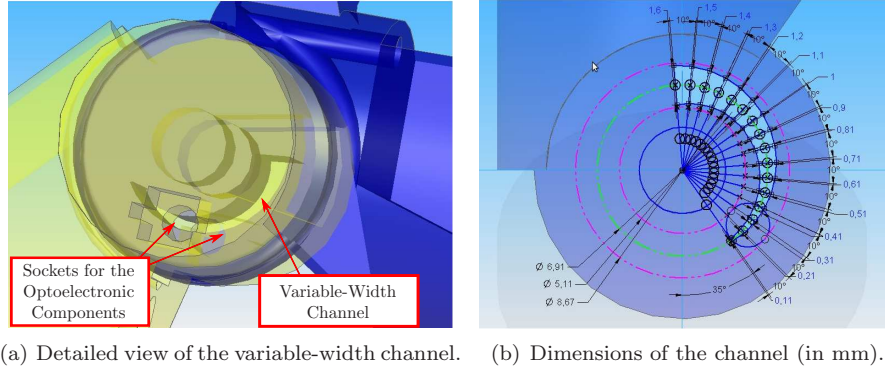


FIGURE 22. Details of the robotic joint: (a) detail of the optoelectronic component sockets and (b) detail of the variable-width channel.

the higher mechanical strength required. In these cases, the joint dimensions are greater than the previous ones and, as a consequence, the distance between the optoelectronic components has been selected $d_0 = 9$ mm. A different PCB has been designed to integrate the same position sensor concept in this joint. Figures 23(a) and 23(b) show two pictures where the two different implementations of the sensor for the two axes of the MC joint can be appreciated. These figures show the details of the different variable-width channel used for the corresponding axis and how the PCBs are assembled with the mechanical structure of the finger.

The typical calibration curves for the 4 sensors of a robotic finger are reported in Fig. 24. This characteristic is fundamental for a position sensor since it becomes attractive for the integration in complex systems such as anthropomorphic robotic hands. In fact, the linearity allows calibrating the whole system in a single step by estimating the calibration constant of each sensor on the basis of its output measured in two known positions only, e.g., the stroke limits of the joint angular motion, instead of having a long calibration phase different for each joint and always based on the use of a reference sensor. Also in this case, the sensor output variations as shown in Fig. 24 are large enough to allow a direct digitalization of

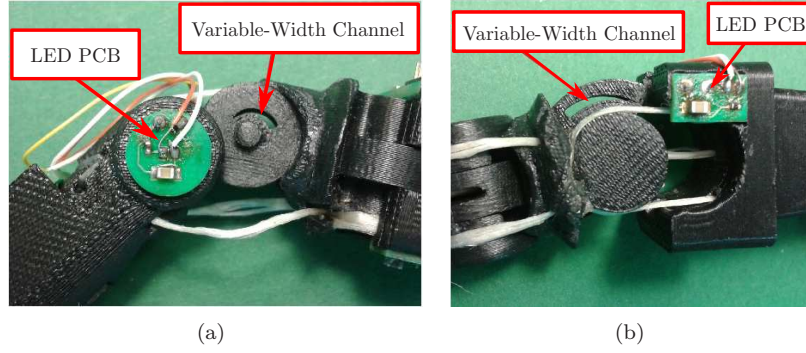


FIGURE 23. Detailed picture of the second (a) and first (b) axis of the MC joint with the corresponding channel and PCB.

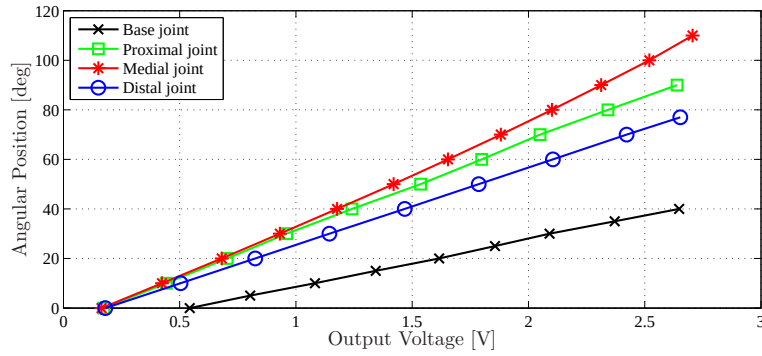


FIGURE 24. Calibration curve of the finger angular position sensor.

the measurement signals, without any additional amplification/filtering stage. As a consequence, the sensor signals are directly connected to the ADC on the finger embedded electronics and transmitted to the DEXMART Hand controller through the SPI bus. Another important feature of this sensor is that, in case of joint dislocation, the output signal of the position sensor will likely reach a value very close to zero, which means full occlusion, or close to the power supply voltage (3.3 V), which means no occlusion at all. Since these values are outside the working range of a properly assembled sensor (and joint), as can be seen from Fig. 24, they can be used by the hand control logic to detect joint dislocation and then react in a proper way, e.g., by stopping the system to allow reassembly of the joint before restarting the task.

The use of FDM for the manufacturing of the variable-width channel of the position sensors imposes several tests and design adjustments, a suitable selection of the printing directions and the separate manufacturing of some parts constituting the position sensors, in particular for the thumb and the wrist, to achieve the linear sensor response shown in Fig. 24. Finally, the polishing of the channel surfaces allows the measurement noise to be reduced. Probably the adoption of a different

and more precise manufacturing method may simplify these operations, but will probably increase the sensor prototyping and the robotic hand production costs.

6. SYNERGY-BASED CONTROL OF THE DEXMART HAND

In this section, a method for deriving the postural synergy configuration subspace for the DEXMART Hand from observation of human hand motions is presented. The human hand palm pose and fingertip positions have been measured for a reference set of grasping postures, chosen with the goal of covering the entire grasp variety referring to a recently proposed taxonomy [Feix et al., 2009] (see Fig. 25), by means of a commercial low-cost RGB+Depth (RGBD) camera, the Kinect from Microsoft Corp., used as a 3D motion capture system. The Kinect RGBD camera allows achieving a precision of about 1mm for the 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 precision is suitable for deriving postural synergies from human motion observation. Moreover, the large number of open-source libraries for both the use of the Kinect sensor and computer vision applications freely available on Internet allowed us to produce a customized application for the execution of the required measurements in a very easy and quick way.

To describe the configuration of the DEXMART Hand, a total of 15 joint angles are necessary (only the fingers and the thumb are considered, the configuration of the wrist is not necessary). The observation of the human actions in this paper is focused on the estimation of the corresponding angles on the human hand using the measurements of the fingertip positions and inverse kinematics. Since significant differences exist in both the size and kinematics of the human hands [Gribenstein et al., 2010], the observation of the grasps has been applied to 5 subjects, in order to generalize the approach. Moreover, suitable scaling factors have been applied to adapt the DEXMART Hand kinematics to the subject hand dimension and the measured hand configurations have been mapped to the robotic hand as described in Sec. 6.2. Then, the postural synergies of the DEXMART Hand have been computed by means of PCA, and kinematic assessments have been provided by means of graphical and numerical tools for synergy pattern evaluation. Finally, the effectiveness of the control approach has been validated by performing reach to grasp actions with the DEXMART Hand. The hand motions are planned using the three predominant postural synergies, and the grasps of selected objects within the reference set of postures used for PCA computation have been performed. A schematic representation of the whole procedure for postural synergies computation is represented in Fig. 26. It is important to mention that the information about the contact forces provided by the tactile sensors implemented on the fingertips are not used in the presented synergy-based control, but the introduction of this useful information is a subject of the current investigation on the DEXMART Hand.

6.1. Measurement of the Human Hand Configuration. The main issues in the observation and the reproduction of the human motions with a robotic hand are related to the fact that capturing the motion of all the phalanges and the position of the joints during a grasp by means of a single camera is a very challenging task because of evident occlusion problems. To solve this issue, we focused the observation of the human grasping postures on the detection of the position (not the orientation) of the fingertips with respect to the palm, since the kinematic properties of the DEXMART Hand allow to univocally reconstruct the joint angles

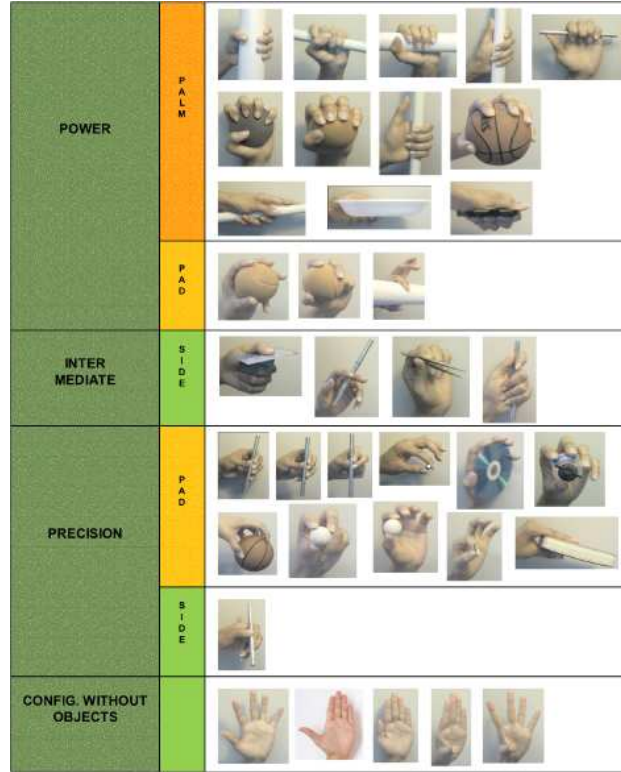


FIGURE 25. Reference set of comprehensive human grasps configurations used for PCA.

from these measurements. Then, the hand posture of the 5 subjects has been acquired through the Kinect RGBD camera that allows the reconstruction of the 3D real world coordinates (in meters) of any point in the acquired image with respect to the camera frame. The points to be measured are selected by clicking with the mouse on the RGB image and by matching the RGB and the depth data acquired by the Kinect. Since we are interested in measuring the fingertip positions with respect to the hand reference frame (the palm frame), the hand position and orientation (the palm pose) with respect to the RGBD camera must be reconstructed. As a matter of fact, during grasps the palm is often hidden by the grasped object itself. In this case, the goal of reconstructing the hand position and orientation

TABLE 3. Finger lengths (in mm) of the five subjects, of the DEXMART Hand and of the UB Hand IV.

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

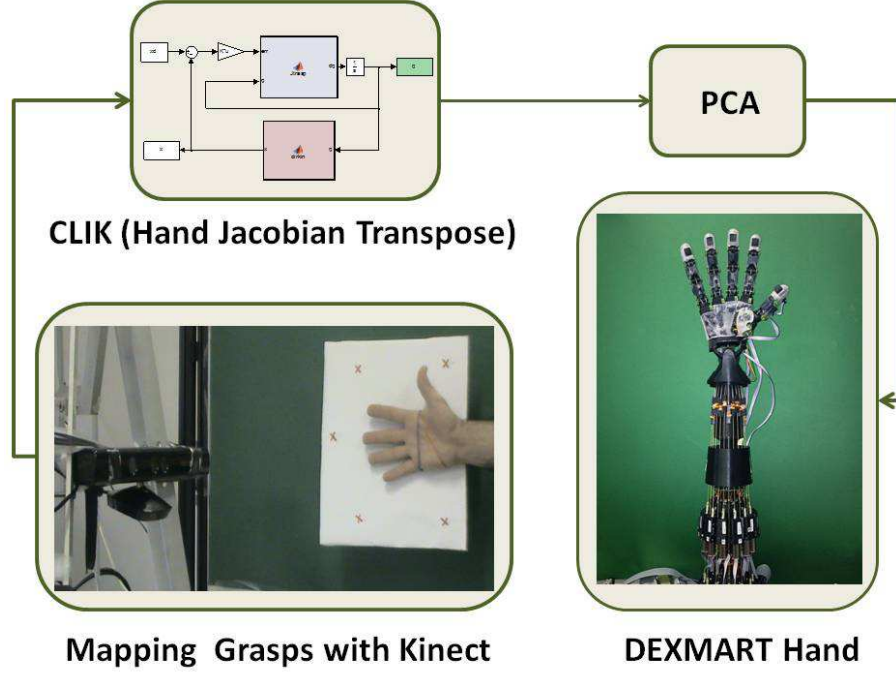


FIGURE 26. Schematic representation of the procedure for the evaluation of the DEXMART Hand postural synergies.

with respect to the camera has been achieved by measuring a set of five reference points on a rigid panel fixed to the opisthenar (the back of the hand). Thus, before starting the mapping procedure, each subject was instructed first in wearing the rigid support and then in assuming an open-hand posture (corresponding to the configuration when all the joint angles are zero in the DEXMART Hand). The distance of the fingertips from the palm base in the open-hand configuration was measured with the aim of defining suitable scaling factors between the subject hand and the robotic hand dimensions. The finger lengths of the 5 subjects and of the DEXMART Hand are reported in Table 3. In Fig. 27, the mapped open-hand configuration of one subject (the number 5) is represented in green, whereas the open-hand configuration on the DEXMART Hand is represented in red. The comparison between the mapped human hand configurations demonstrates that the mapping process ensures that the human hand palm pose matches very well that of the robotic hand.

As shown in Fig. 28, ten points have been detected by the vertices of the line depicted in the figure in the open-hand configuration: the fingertips of the fingers and the thumb and the five points on the support attached to the palm. The obtained fingertip positions, expressed in the camera frame, have then been matched with the ones of the robotic hand (whose kinematics has been scaled by the ratio between the human and the robotic finger length) expressed in the robotic hand reference frame (the palm frame), obtaining in this way the affine transformation T_i between the camera and the hand reference frame for the i -th subject. The

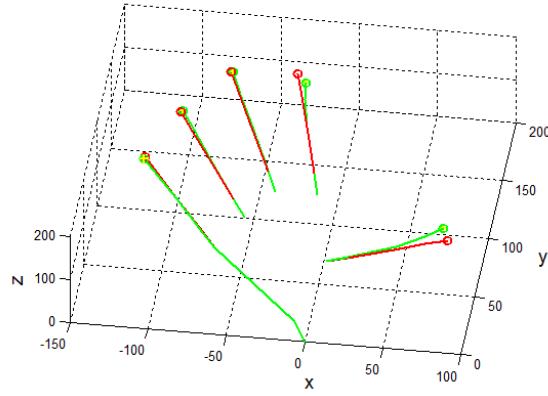


FIGURE 27. Mapping between the open-hand configuration of Subject 5 (in green) and of the DEXMART Hand (in red).

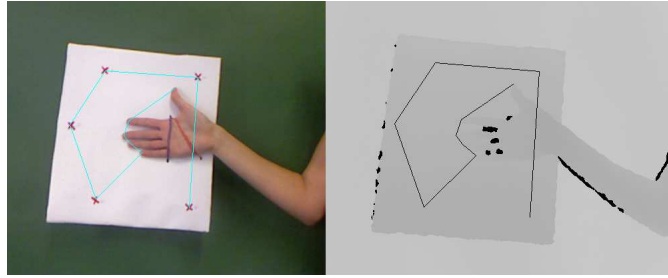


FIGURE 28. Measurement of the open-hand configuration of the human subject.

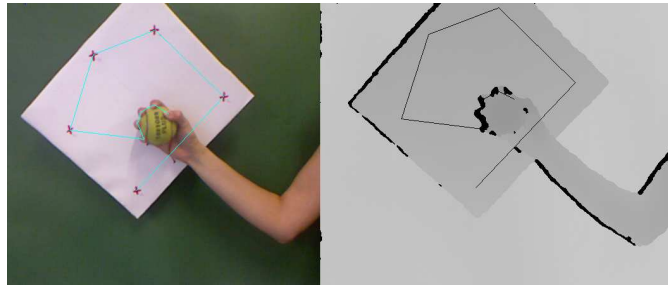


FIGURE 29. RGB and depth image from Kinect.

position of the panel reference points $p_{i,j_{\text{ref}}}$, $j = 1, \dots, 5$ with respect to the hand frame has then been computed on the basis of the transformation T_i . Once T_i and $p_{i,j_{\text{ref}}}$ have been determined, each subject has been asked to reproduce each of the 36 reference postures in Fig. 25 using the right hand. The fingertip positions and the position of the panel reference points have been acquired as shown in Fig. 29. By matching the position of the panel reference points measured by the Kinect with

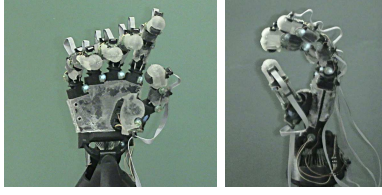


FIGURE 30. Mean position of the DEXMART Hand configuration.

$p_{i,j_{\text{ref}}}$ the new affine transformation $T_{i,k}$, $k = 1, \dots, 36$ between the camera and the hand reference frame during the execution of each grasp can be computed together with the position of the subject fingertips $p_{i,j}$ expressed in the hand frame.

6.2. Mapping Postures Between the Human and the Robotic Hand. The reconstruction of the human hand joint angular positions implies the knowledge of its kinematics, that is not completely coherent in anatomical literature [Kapandji and Honoré, 2007, Drenckhahn and Benninghoff, 1994], moreover the difference between the kinematics of the human and the robotic hand may cause problems in mapping the acquired information. Then, the mapping of the fingertip positions $p_{i,j}$ from the human hand to the robotic one has been performed by scaling the robotic hand link dimensions to fit with the human subject. To this purpose, the robotic hand kinematics has been inverted through a Closed-Loop Inverse Kinematics (CLIK) algorithm [Siciliano and Khatib, 2008] for computing the robotic hand joint positions (this implies that the robotic hand kinematics is used as reference model for the measurement performed on the human hand). For each subject, the robotic hand kinematics is differently scaled for each finger by multiplying the linear Denavit-Hartenberg parameters (a and d in Tab. 1) for the ratio between the human finger length and the corresponding robotic finger length, see Tab. 3. For each grasp of the reference set (Fig. 25), the average value of the five robotic hand configurations $\mathbf{c}_i \in \mathbb{R}^{15}$ mapped from the five subjects performance has been computed and stored in a configuration matrix $\mathbf{C}$.

6.3. Control by Means of Postural Synergies. Once the matrix $\mathbf{C} = \{\mathbf{c}_i \mid i = 1, \dots, 36\}$ of the DEXMART Hand configurations has been built, the vector $\bar{\mathbf{c}}$ representing the mean hand configuration (the zero-offset position) and the matrix $\mathbf{F} = \{\mathbf{c}_i - \bar{\mathbf{c}} \mid i = 1, \dots, 36\}$ of the grasp offsets with respect to the mean configuration have been computed. The PCA has then been performed on the matrix $\mathbf{F}$ and a base matrix $\mathbf{E} = \{\mathbf{e}_1 \ \mathbf{e}_2 \ \mathbf{e}_3\}$ of the postural synergy subspace has been found selecting the three predominant components of the configuration space decomposition through PCA, see Ficuciello et al. [2012a] for additional details on the procedure.

The synergy-based control relies on the fact that each hand grasp posture $\mathbf{c}_i$ can be approximated by a suitable selection of the postural synergy coefficients $[\alpha_1 \ \alpha_2 \ \alpha_3]^T \in \mathbb{R}^3$, as the projection $\hat{\mathbf{c}}_i$ on the postural synergy subspace

$$(17) \quad \hat{\mathbf{c}}_i = \bar{\mathbf{c}} + \mathbf{E} \begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix}.$$

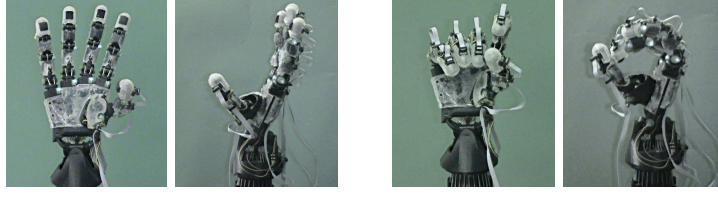


FIGURE 31. From left to right, front and lateral view of the first postural synergy in the minimum and the maximum configuration.

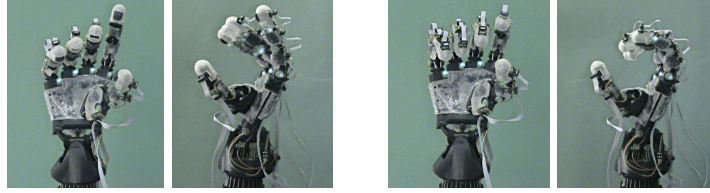


FIGURE 32. From left to right, front and lateral view of the second postural synergy in the minimum and the maximum configuration.

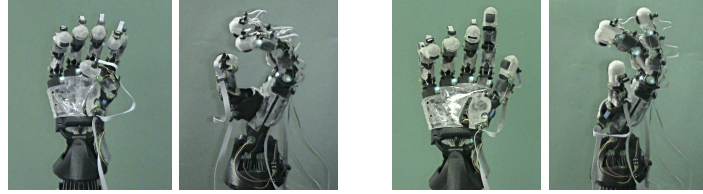


FIGURE 33. From left to right, front and lateral view of the third postural synergy in the minimum and the maximum configuration.

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

$$(18) \quad \begin{bmatrix} \alpha_{1,i} \\ \alpha_{2,i} \\ \alpha_{3,i} \end{bmatrix} = \mathbf{E}^\dagger (\mathbf{c}_i - \bar{\mathbf{c}})$$

where $\mathbf{E}^\dagger$ is the Moore-Penrose pseudo-inverse of the base matrix $\mathbf{E}$. In the following, we refer to the minimum and maximum configuration of each synergy as the robotic hand configurations spanned by $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ (the postural synergy vectors) by means of, respectively, the minimum and maximum value of the corresponding synergy coefficients without violating the joint limits. When the weights of the synergies are zero, the hand posture corresponds to the zero-offset position (mean position) $\bar{\mathbf{c}}$, see Fig. 30 where a frontal and a lateral view of the robotic hand mean position are shown. In Figs. 31, 32 and 33 the minimum and maximum configurations in frontal and lateral views of the three postural synergies are represented.

The value of the coefficients α_1 , α_2 , α_3 during grasp operations has to be chosen in such a way that, starting from the zero-offset position $\bar{\mathbf{c}}$ (i.e. $\alpha_1 = \alpha_2 = \alpha_3 = 0$),

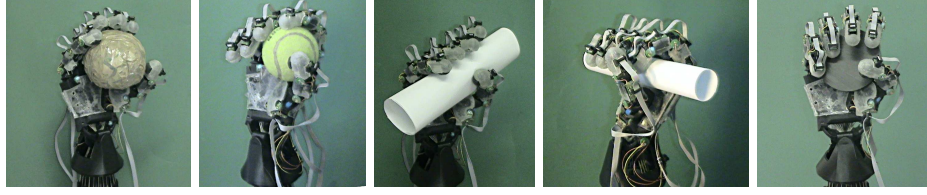


FIGURE 34. Reproduced power grasps from the reference set of postures.

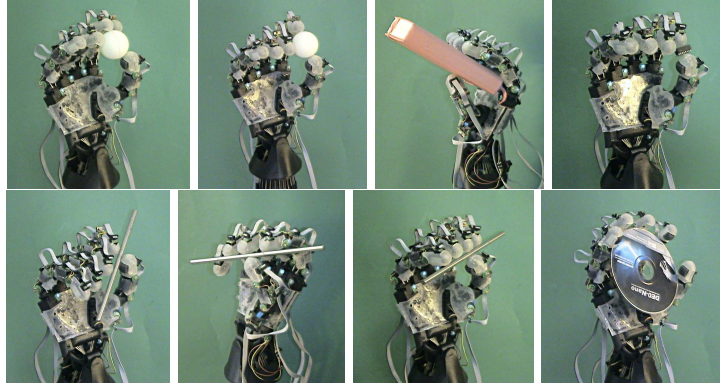


FIGURE 35. Reproduced precision grasps from the reference set of postures.

the hand opens during the reach in preparation for object grasp, and then closes reaching a suitable shape determined from (18) and depending on the original grasp configuration $\mathbf{c}_i$. In the open-hand configuration, namely $\mathbf{c}_0$, all the flexion joint angles are close to zero, and the corresponding values of α_1 , α_2 and α_3 can be determined from (18) by posing $\mathbf{c}_i = \mathbf{c}_0$. The intermediate values of the synergy coefficients have been determined by assuming a suitable time interval for the grasp operation (six seconds for the whole reach to grasp phase, three seconds for both the opening and closing phases) and by linear interpolation of the values α_1 , α_2 and α_3 in the three reference configurations $\{\bar{\mathbf{c}}, \hat{\mathbf{c}}_0, \hat{\mathbf{c}}_i\}$ that are, respectively, the zero-offset (initial), the open-hand and the final configurations. The object can be then released by reversing the configuration sequence.

The experimental evaluation of the DEXMART Hand synergies has been obtained by using an open-loop control strategy to perform reach to grasp actions on selected objects. A linear combination of the first three predominant synergies has been achieved by means of linear interpolation of the synergy coefficients computed in the three reference configurations. In Fig. 34 it is possible to see that the linear combination of the three synergies allows a power grasp of both cylinders and spheres of different dimensions by means of suitable opposition of the thumb. The performance corresponding to precise grasp operations considering both prismatic and circular objects and grasps involving from two to five fingers are reported in Fig. 35, whereas the reproduced intermediate side grasps from the reference set of postures are depicted in Fig. 36.

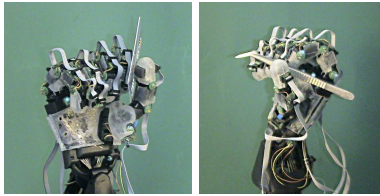


FIGURE 36. Reproduced intermediate side grasps from the reference set of postures.

6.4. DEXMART Hand Synergies: Assessments and Comparison. The circular graphs in Fig. 37 are a graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ and identify the joints whose rotations are more involved in each synergy. From left to right, the unitary variation of joints position is represented for the first, the second and the third synergy, respectively.

- *First Synergy:* With reference to the first postural synergy, in the minimum configuration the proximal and medial flexion joint angles of all the fingers are all almost zero and increase their value during the motion toward the maximum configuration. The adduction/abduction movements of the four fingers are not significantly involved in this synergy.
- *Second Synergy:* The second postural synergy is characterized by a movement in opposite directions of the proximal and medial flexion joints. The adduction/abduction movements of the four fingers are not significantly involved also in this synergy.
- *Third Synergy:* In the third postural synergy the movement involves especially the index and the thumb. The movement of adduction/abduction of the thumb and of the index increases with respect to the first two synergies. This characteristic is important for correct index/thumb opposition that allows increasing the grasp accuracy, and thus achieving more stable grasps.

The circular graphs highlight that the kinematic patterns of the first two synergies are in accordance with the results of the studies conducted on the human hand in Santello et al. [1998]. It confirms the validity of the mapping method and the good level of anthropomorphism of the DEXMART Hand.

7. CONCLUSION

The design of currently available anthropomorphic robotic hands is mainly based on conventional mechanics and commercially available actuators and sensors. This fact is in contrast with the need in terms of integration among the components, simplification of the overall structure, reduction of the cost and of the power consumption, to name a few. What can be learned from this situation is that new approaches should be identified for the design of anthropomorphic dexterous robotic hands.

In this paper, possible solutions and innovative technologies and sensors developed for the DEXMART Hand have been presented. The results of this research activity show that it is possible to achieve a significant simplification of the design, enhancing its reliability and performance and reducing the costs of robotic hands by means of alternative approaches based on non-conventional structures and on

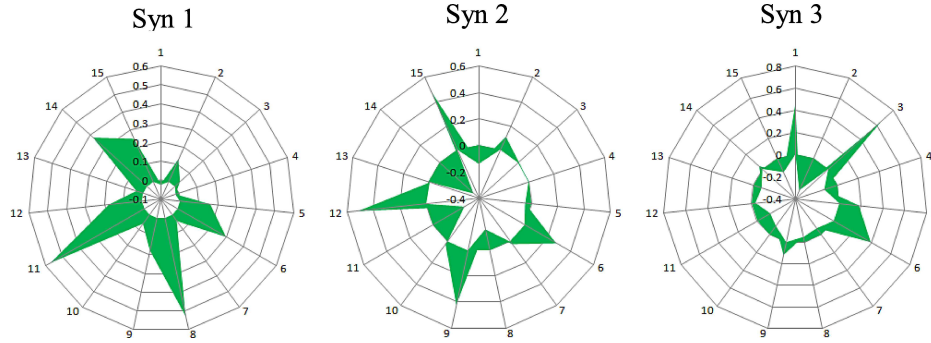


FIGURE 37. Graphical representation of the postural synergy vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$ of the DEXMART Hand. The two axes of CMC joint and the MP joint are indicated from 1 to 3 for the thumb, whereas the two axes of MC joint and the MP joint are indicated from 4 to 6 for the index finger, from 7 to 9 for the middle finger, from 10 to 12 for the ring finger and finally from 13 to 15 for the little finger.

the study of the biological model. The developed actuators and sensors, purposely conceived for integration into the DEXMART Hand, are fundamental achievements toward the general goal of improving the reliability and the functionality of the device, reducing its complexity and the overall costs for developing and producing a robotic hand. Moreover, a model-based method for mapping grasps from the human hand to the DEXMART Hand has been presented in this paper. The method comprises fingertip detection by means of the Kinect RGBD camera and a CLIK algorithm. The robotic hand kinematics is linearly scaled according to the hand dimensions of five subjects involved in the experiments. The kinematic patterns of the first three postural synergies of the DEXMART Hand are computed. Experimental evaluation of the computed synergy subspace has been performed testing the synergy-based control during reach to grasp. The results of the experiments reveal that the designed robotic hand succeeded in grasping various objects throughout a complete taxonomy.

ACKNOWLEDGMENTS

This research has been funded by the EC Seventh Framework Programme (FP7) under grant agreement no. 216239 as part of the IP DEXMART (DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition).

REFERENCES

- DEXMART Project website. <http://www.dexmart.eu/>.
 G. Berselli, G. Borghesan, M. Brandi, C. Melchiorri, C. Natale, G. Palli, S. Pirozzi, and G. Vassura. Integrated mechatronic design for a new generation of robotic hands. In *Proc. IFAC Symp. on Robot Control*, volume 9, Part 1, pages 105–110, Gifu, Japan, 2009.

- G. Berselli, M. Piccinini, G. Palli, and G. Vassura. Engineering Design of Fluid-Filled Soft Covers for Robotic Contact Interfaces: Guidelines, Nonlinear Modeling, and Experimental Validation. *IEEE Trans. on Robotics*, 27(3):436–449, 2011a.
- G. Berselli, M. Piccinini, and G. Vassura. Comparative evaluation of the selective compliance in elastic joints for robotic structures. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 4626–4631, Shanghai, China, 2011b.
- L. Biagiotti, F. Lotti, C. Melchiorri, G. Palli, P. Tiezzi, and G. Vassura. Development of UB Hand 3: Early results. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 4488–4493, Barcelona, Spain, 2005.
- A. Bicchi. Hands for dextrous manipulation and robust grasping: a difficult road towards simplicity. *IEEE Trans. on Robotics and Automation*, 16(6):652–662, December 2000.
- A. Bicchi, G. Tonietti, M. Bavaro, and M. Piccigallo. Variable Stiffness Actuators for Fast and Safe Motion Control. In P. Dario and R. Chatila, editors, *In Robotics Research*, volume 15 of *Springer Tracts in Advanced Robotics*, pages 527–536. Springer Berlin / Heidelberg, 2005.
- L. Birglen and C. Gosselin. On the force capability of underactuated fingers. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 1139–1145, 2003.
- L. Birglen, T. Laliberté, and C. Gosselin. *Underactuated Robotic Hands*, volume 40 of *Springer Tracts in Advanced Robotics*. Springer Berlin / Heidelberg, 2008.
- G. Borghesan, G. Palli, and C. Melchiorri. Design of tendon-driven robotic fingers: Modeling and control issues. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 793–798, Anchorage, AK, 2010.
- G. Borghesan, G. Palli, and C. Melchiorri. Friction compensation and virtual force sensing for robotic hands. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 4756–4761, Shanghai, China, 2011.
- C. Brown and H. Asada. Inter-finger coordination and postural synergies in robot hands via mechanical implementation of principal components analysis. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 2877–2882, 2007.
- J. Butterfass, M. Grebenstein, H. Liu, and G. Hirzinger. DLR-Hand II: Next generation of a dextrous robot hand. In *Proc. IEEE Int. Conf. on Robotics and Automation*, 2001.
- A. Caffaz, G. Cannata, G. Panin, and E. Massucco. The DIST-hand, an anthropomorphic, fully sensorized dextrous gripper. In *In First IEEE-RAS Int. Conf. on Humanoid Robots*, 2000.
- M. C. Carrozza, C. Suppo, F. Sebastiani, B. Massa, F. Vecchi, R. Lazzarini, M. R. Cutkosky, and P. Dario. The spring hand: Development of a self-adaptive prosthesis for restoring natural grasping. *Auton. Robots*, 16:125–141, March 2004.
- M. C. Carrozza, G. Cappiello, G. Stellin, F. Zacccone, F. Vecchi, S. Micera, and P. Dario. On the development of a novel adaptive prosthetic hand with compliant joints: Experimental platform and EMG control. In *Proc. IEEE Int. Conf. Intelligent Robots and Systems*, pages 1271–1276, 2005.
- M. C. Carrozza, G. Cappiello, S. Micera, B. Edin, L. Beccai, and C. Cipriani. Design of a cybernetic hand for perception and action. *Biological Cybernetics*, 95:629–644, 2006.
- G. C. Causey and R. D. Quinn. Gripper design guidelines for modular manufacturing. In *Proc. Int. Conf. on Robotics and Automation*, volume 2, pages 1453 –

- 1458, Leuven, Belgium, May 16-20 1998.
- P. C. Chou and B. Hannaford. Measurement and modeling of McKibben pneumatic artificial muscles. *IEEE Trans. on Robotics and Automation*, 12(1):90–102, Feb. 1996.
- M. T. Ciocarlie and P. K. Allen. Hand Posture Subspaces for Dexterous Robotic Grasping. *The Int. Journal of Robotics Research*, 28(7):851–867, 2009.
- S. Dalley, T. Wiste, T. Withrow, and M. Goldfarb. Design of a Multifunctional Anthropomorphic Prosthetic Hand With Extrinsic Actuation. *IEEE/ASME Trans. on Mechatronics*, 14(6):699–706, Dec. 2009.
- A. D’Amore, G. De Maria, L. Grassia, C. Natale, and S. Pirozzi. Silicone-rubber-based tactile sensors for the measurement of normal and tangential components of the contact force. *Journal of Applied Polymer Science*, 122(6):3757–3769, 2011.
- G. De Maria, C. Natale, and S. Pirozzi. Force/tactile sensor for robotic applications. *Sensors and Actuators A: Physical*, 175:60–72, 2012.
- A. M. Dollar and R. D. Howe. A robust compliant grasper via shape deposition manufacturing. *IEEE/ASME Trans. on Mechatronics*, 11(2):154–161, april 2006.
- A. M. Dollar and R. D. Howe. The SDM Hand: A Highly Adaptive Compliant Grasper for Unstructured Environments. In O. Khatib, V. Kumar, and G. Pappas, editors, *In Experimental Robotics*, volume 54 of *Springer Tracts in Advanced Robotics*, pages 3–11. Springer Berlin / Heidelberg, 2009.
- D. Drenckhahn and A. Benninghoff. *Anatomie: Makroskopische Anatomie, Embryologie und Histologie des Menschen. Zellen-und Gewebelehre, Entwicklungsbiologie, Bewegungsapparat, Herz-Kreislauf-System, Immunsystem, Atem-und Verdauungsapparat*. Anatomie: Makroskopische Anatomie, Embryologie und Histologie des Menschen. Urban & Schwarzenberg, 1994.
- T. Feix, R. Pawlik, H. Schmiedmayer, J. Romero, and D. Kragic. The generation of a comprehensive grasp taxonomy. In *Robotics, Science and Systems, Workshop on "Understanding the Human Hand for Advancing Robotic Manipulation"*, Washington, 2009.
- F. Ficuciello, G. Palli, C. Melchiorri, and B. Siciliano. Planning and control during reach to grasp using the three predominant UB Hand IV postural synergies. In *Proc. IEEE Int. Conf. Robotics and Automation*, pages 1775–1780, Saint Paul, MN, 2012a.
- F. Ficuciello, G. Palli, C. Melchiorri, and B. Siciliano. Postural synergies and neural network for autonomous grasping: a tool for dextrous prosthetic and robotic hands. In *Proc. Int. Conf. on NeuroRehabilitation*, Toledo, Spain, 2012b.
- V. Frati and D. Prattichizzo. Using kinect for hand tracking and rendering in wearable haptics. In *IEEE World Haptics Conference*, Istanbul, 2011.
- N. Fukaya, S. Toyama, T. Asfour, and R. Dillmann. Design of the TUAT/Karlsruhe humanoid hand. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 13–19, 2000.
- T. Geng, M. Lee, and M. Hulse. Transferring human grasping synergies to a robot. *Mechatronics*, 21(1):272–284, 2011.
- G. Gioioso, G. Salvietti, M. Malvezzi, and D. Prattichizzo. Mapping synergies from human to robotic hands with dissimilar kinematics: An object based approach. In *Proc. IEEE Int. Conf. on Robotics and Automation, Workshop on Manipulation Under Uncertainty*, Shangai, 2011.

- M. Grebenstein and P. v. d. Smagt. Antagonism for a highly anthropomorphic hand-arm system. *Advanced Robotics*, 22(1):39–55, 2008.
- M. Grebenstein, M. Chalon, G. Hirzinger, and R. Siegwart. A method for hand kinematics designers 7 billion perfect hands. In *Proc. of 1st Int. Conf. on Applied Bionics and Biomechanics*, Venice, Italy, 2010.
- M. Grebenstein, M. Chalon, W. Friedl, S. Haddadin, T. Wimböck, G. Hirzinger, and R. Siegwart. The hand of the DLR hand arm system: Designed for interaction. *The Int. Journal of Robotic Research*, 31(13):1531–1555, 2012.
- H. Huang, L. Jiang, Y. Liu, L. Hou, H. Cai, and H. Liu. The mechanical design and experiments of HIT/DLR prosthetic hand. In *Proc. Int. Conf. on Robotics and Biomimetics*, pages 896–901, Kunming, China, dec. 2006.
- H. Iwata and S. Sugano. Design of human symbiotic robot TWENDY-ONE. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 580–586, May 2009.
- S. C. Jacobsen, R. B. Jerrard, D. Knutti, and J. Carruth. The ladd actuator as a prosthetic muscle. In *Proc. of 5th Int. Symp. on External Control of Human Extremities*, Dubrovnik, Yugoslavia, Aug 1975.
- S. C. Jacobsen, J. E. Wood, D. F. Knutti, and K. B. Biggers. The UTAH/M.I.T. dextrous hand: Work in progress. *The Int. Journal of Robotics Research*, 3(4): 21–50, 1984.
- M. S. Johannes, J. D. Bigelow, J. M. Burck, S. D. Harshbarger, M. V. Kozlowski, and T. van Doren. An overview of the developmental process for the modular prosthetic limb. *Johns Hopkins APL Technical Digest*, 30(3):207–216, 2011.
- M. Kaneko, M. Wada, H. Maekawa, and K. Tanie. A new consideration on tendon-tension control system of robot hands. In *Proc. IEEE Int. Conf. on Robotics and Automation*, volume 2, pages 1028–1033, Sacramento, CA, 1991.
- I. Kapandji and L. Honoré. *The Physiology of the Joints: The upper limb*. The Physiology of the Joints. Churchill Livingstone, 2007.
- S. Kasap. *Optoelectronics and Photonics: Principles and Practices*. Prentice Hall, Englewood Cliffs, NJ, 2001.
- H. Kawasaki, T. Komatsu, and K. Uchiyama. Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II. *IEEE/ASME Trans. on Mechatronics*, 7(3):296–303, 2002.
- V. Lippiello, B. Siciliano, and L. Villani. A grasping force optimization algorithm for dextrous robotic hands. In *Proc. IEEE Int. Conf. on Robotics and Automation*, pages 4170–4175, 2012.
- V. Lippiello, F. Ruggiero, B. Siciliano, and L. Villani. Visual grasp planning for unknown objects using a multifingered robotic hand. *IEEE/ASME Trans. on Mechatronics*, 18(3):1050–1059, 2013a.
- V. Lippiello, B. Siciliano, and L. Villani. A grasping force optimization algorithm for multiarm robots with multifingered hands. *IEEE Trans. on Robotics*, 29(1): 55–67, 2013b.
- V. Lippiello, B. Siciliano, and L. Villani. Multi-fingered grasp synthesis based on the object dynamic properties. *Robotics and Autonomous Systems*, 61(6):626 – 636, 2013c.
- H. Liu, P. Meusel, G. Hirzinger, M. Jin, Y. Liu, and Z. Xie. The modular multisensory DLR-HIT-Hand: Hardware and software architecture. *IEEE/ASME Trans. on Mechatronics*, 13(4):461–469, 2008.

- C. Lovchik and M. Diftler. The robonaut hand: a dexterous robot hand for space. In *Proc. IEEE Int. Conf. on Robotics and Automation*, 1999.
- M. T. Mason and J. K. Salisbury. *Robot Hands and the Mechanics of Manipulation*. MIT Press, Cambridge, MA, 1985.
- C. Melchiorri and M. Kaneko. Robot hands. In B. Siciliano and O. Khatib, editors, *Springer Handbook of Robotics*, pages 345–360. Springer, 2008.
- C. Melchiorri and G. Vassura. Mechanical and control issues for integration of an arm-hand robotic system. In *Experimental Robotics II*, volume 190, pages 136–152. Springer Berlin / Heidelberg, 1993.
- G. Mennitto and M. Buehler. Ladd transmissions: Design, manufacture, and new compliance models. *Journal of Mechanical Design*, 119(2):197–203, 1997.
- T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai, and S. Ito. Anthropomorphic Robot Hand: Gifu Hand III. volume ICCAS2002, pages 1288–1293, Oct. 2002.
- J. Napier and R. Tuttle. *Hands*. Princeton Science Library. Princeton University Press, 1993. ISBN 9780691025476. URL <http://books.google.it/books?id=mNQM4jvG7hgC>.
- L. Odhner and A. Dollar. Dexterous manipulation with underactuated elastic hands. In *Proc IEEE Int. Conf. on Robotics and Automation*, pages 5254–5260, 2011.
- I. Oikonomidis, N. Kyriazis, and A. A. Argyros. Full dof tracking of a hand interacting with an object by modeling occlusions and physical constraints. In *Proc. 13th Int. Conf. on Computer Vision*, pages 1260–1264, Barcelona, 2011.
- G. Palli and C. Melchiorri. Optimal control of tendon-sheath transmission systems. In *Proc. IFAC Symp. on Robot Control*, volume 8, pages 73–78, Bologna, Italy, 2006.
- G. Palli and S. Pirozzi. A miniaturized optical force sensor for tendon-driven mechatronic systems: Design and experimental evaluation. *Mechatronics*, 22(8):1097–1111, 2012.
- G. Palli and S. Pirozzi. Optical sensor for angular position measurements embedded in robotic finger joints. *Advanced Robotics*, 27(15):1209–1220, 2013.
- G. Palli, G. Borghesan, and C. Melchiorri. Modeling, identification and control of tendon-based actuation systems. *IEEE Trans. on Robotics*, 28(2):277–290, 2012a.
- G. Palli, C. Melchiorri, G. Vassura, G. Berselli, S. Pirozzi, C. Natale, G. De Maria, and C. May. *Advanced bimanual manipulation*, chapter Innovative Technologies for the Next Generation of Robotic Hands, pages 173–218. Springer Tracts in Advanced Robotics (STAR). Springer, 2012b.
- G. Palli, C. Natale, C. May, C. Melchiorri, and T. Würtz. Modeling and control of the twisted string actuation system. *IEEE/ASME Trans. on Mechatronics*, 18(2):664–673, 2013.
- M. Piccinini, G. Berselli, A. Zucchelli, and G. Vassura. Predicting the compliance of soft fingertips with differentiated layer design: A numerical and experimental investigation. In *Proc. Int. Conf. on Advanced Robotics*, pages 1–6, Munich, Germany, 2009.
- K. L. Pottebaum and J. J. Beaman. A dynamic model of a concentric ladd actuator. *Journal of Dynamic Systems, Measurement, and Control*, 105(3):157–164, 1983.
- D. Pratichizzo, M. Malvezzi, and A. Bicchi. On motion and force controllability of grasping hands with postural synergies. In *Proc. of Robotics: Science and Systems*, Zaragoza, Spain, June 2010.

- S. Roccella, M. C. Carrozza, G. Cappiello, P. Dario, J. Cabibihan, M. Zecca, H. Miwa, K. Itoh, and M. Marsumoto. Design, fabrication and preliminary results of a novel anthropomorphic hand for humanoid robotics: RCH-1. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 1, pages 266–271, 2004.
- K. Salisbury and B. Roth. Kinematics and force analysis of articulated mechanical hands. In *Journal of Mechanisms, Transmissions and Actuation in Design*, 1983.
- M. Santello, M. Flanders, and J. F. Soechting. Postural hand synergies for tool use. *Journal of Neuroscience*, 18(23):10105–10115, 1998.
- Shadow Robot Company. Design of a Dextrous Hand for advanced CLAWAR applications. In *Climbing and Walking Robots and the Supporting Technologies for Mobile Machines*, pages 691–698, Catania, Italy, 2003.
- Y. J. Shin, H. J. Lee, K.-S. Kim, and S. Kim. A robot finger design using a dual-mode twisting mechanism to achieve high-speed motion and large grasping force. *IEEE Trans. on Robotics*, 28(6):1398–1405, dec. 2012. ISSN 1552-3098. doi: 10.1109/TRO.2012.2206870.
- M. Shoham. Twisting wire actuator. *Journal of Mechanical Design*, 127(3):441–445, 2005.
- B. Siciliano and O. Khatib, editors. *Springer Handbook of Robotics*. Springer, 2008.
- T. Sonoda and I. Godler. Multi-fingered robotic hand employing strings transmission named Twist Drive. In *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 2733–2738, Taipei, Taiwan, 2010a.
- T. Sonoda and I. Godler. A five fingered robotic hand prototype by using twist drive. In *Proc. Int. Symp. on Robotics*, pages 594–599, Munich, Germany, 2010b.
- W. T. Townsend. The BarrettHand Grasper Programmably Flexible Part Handling and Assembly. *Industrial Robot*, 27(3):181–188, 2000.
- R. Tubiana, J. Thomine, and E. Mackin. *Examination of the Hand and Wrist*. Martin Dunitz, 1998. ISBN 9781853175442. URL http://books.google.it/books?id=G1gWHR1_J9UC.
- L. Villani, V. Lippiello, F. Ruggiero, F. Ficuciello, B. Siciliano, and G. Palli. *Advanced bimanual manipulation*, chapter Grasping and Control of Multifingered Hands, pages 219–266. Springer Tracts in Advanced Robotics (STAR). Springer, 2012.
- T. Würtz, C. May, B. Holz, C. Natale, G. Palli, and C. Melchiorri. The twisted string actuation system: Modeling and control. In *Proc. Int. Conf. on Advanced Intelligent Mechatronics*, pages 1215–1220, Montreal, Canada, 2010.
- L. Zollo, S. Roccella, E. Guglielmelli, M. C. Carrozza, and P. Dario. Biomechatronic Design and Control of an Anthropomorphic Artificial Hand for Prosthetic and Robotic Applications. *IEEE/ASME Trans. on Mechatronics*, 12(4):418–429, Aug. 2007.

(G. Palli, C. Melchiorri, U. Scarcia, L. Moriello) DEI - UNIVERSITÀ DI BOLOGNA, VIALE RISORGIMENTO 2, BOLOGNA, ITALY.

E-mail address, G. Palli (Corresponding Author): gianluca.palli@unibo.it

(G. Vassura) DIN - UNIVERSITÀ DI BOLOGNA, VIA TERRACINI 2, BOLOGNA, ITALY.

(G. Berselli) DIEF - UNIVERSITÀ DI MODENA E REGGIO EMILIA, VIA VIGNOLESE 905/B, MODENA, ITALY.

(A. Cavallo, G. De Maria, C. Natale, S. Pirozzi) DIII - SECONDA UNIVERSITÀ DI NAPOLI, VIA ROMA 29, AVERSA, ITALY.

(C. May) UNIVERSITÄT DES SAARLANDES, CAMPUS E2 9, SAARBRÜCKEN, GERMANY.

(F. Ficuciello, B. Siciliano) DIETI - UNIVERSITÀ DI NAPOLI FEDERICO II, VIA CLAUDIO 21, NAPOLI, ITALY.