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Adaptive Synergies: an approach to the design of under-actuated robotic hands.

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Abstract— **To match the richness and complexity of the sensory and motor functionalities of a human hand with a robust and economically reasonable robotic device remains one of the hardest challenges in the field. Previous work has explored the possibility to exploit insight from neuroscientific results on postural correlation patterns (synergies) taming the sensorimotor complexity of hands. The postural synergy model has been recently extended to account for grasp force control through a model of "soft synergies" which incorporate hand compliance.**

In this paper we propose a first translation of such principles in the design of a robot hand. It so turns out that the implementation of the soft synergy model in an effective design is not obvious. The solution proposed in this paper rests on ideas coming from under-actuated hand design. We give a synthesis method to realize a desired set of soft synergies through the principled design of adaptive under-actuated mechanisms, which we call the method of *adaptive synergies*. This approach leads to the design and implementation of a prototype modular hand capable of accommodating an arbitrary number of synergies. The effectiveness of the design is shown in grasping simulations and experiments.

I. INTRODUCTION

Neurosciences studies suggest that the brain uses the hand as an organized and ordered ensemble. Particular patterns of muscular activities form a base set analogous to the concept of *basis* in theory of vector spaces [1]: a minimal number of linearly independent elements that under specific operations generate all members of a given set, in this case, the set of all movements. Such basis is referred to as the space of postural synergies, or the eigengrasp space [2], [3].

Recently, different approaches in robotics tried to take advantage from the idea of synergies, aiming to reproduce the same "coordinated and ordered ensemble" of human hand motion. A first approach to re-create this system implements, by control, *software synergies* on fully actuated robotic hands. This approach, suggested by [3], has the important advantage of largely simplifying the design phase of a grasp, especially when it is performed by a human operator.

A second and dual approach consists in building under-actuated (UA) robotic hands, which embed, in their mechanical structure, one or more *hardware synergies*. One example of this approach, is the hand design by Asada [4], where two interchangeable set of pulleys are used to close the hand with different types of grasping.

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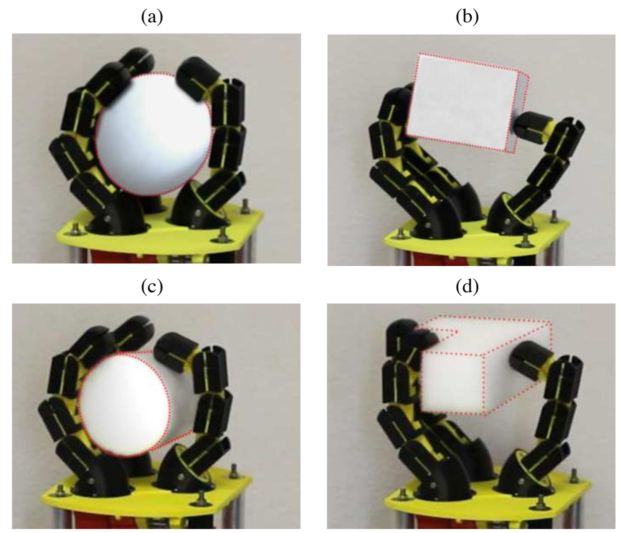

Fig. 1. The second hand developed within the EU project "THE Hand Embodied" (hereby on THE Second Hand), an under-actuated hand with 9 degrees of freedom and 4 degrees of actuation, which is implemented following the proposed method of adaptive synergies. In this picture, only the first synergy is used to grasp four test objects, thanks to its adaptivity.

Both former approaches use the idea of exploiting only a subset of all the synergies to generate grasp actions. Indeed, as shown in [5] and [2], most of the whole hand positional and force behavior is encompassed by the set of the first few synergies. Both [3], [4] are confronted with the gap between the number of hands DOFs (Degrees Of Freedom) and actuated synergies. In fact, the simple projection of a generic grasp configuration on the lower-dimensional subspace spanned by only few synergies would imply some error in achieving the desired pose. The software synergy approach of [3] faces the problem by constraining the motion of each finger when it comes in contact with the grasped object, while a parallel actuation system, realized with memory-shape alloys, was proposed in [6] by the same authors of [4] to integrate the (rigid) hardware synergy they implemented before. An improvement over the former solutions is the introduction of *soft synergies*.

According to the model proposed in [7], Synergies are used to define motions of a virtual (reference) hand, which attracts the physical hand. The latter is also subject to repelling forces generated by contact with the grasped object, and thus reaches an equilibrium grasp configuration, defined by the system compliance. In other words, physical properties of the grasped object and of the hand concur with

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the controllable soft synergy gains to determine the overall compliant behaviors of the system.

A similar approach is implemented in [8] on the DLR HAND II, through the means of a suitable impedance controller. In this implementation, the soft-synergy solution still requires full hand actuation.

A different approach for hand design simplification is the so-called under-actuation (UA). The approach of UA hands offers many advantages to the designer: saving of space, weight and cost, all derive from using a lower number of motors. This, over the years, led to the design of a large number of hands and adaptive grippers (for a complete review refer to [9]). One particularly investigated aspect of robotic and prosthetic UA hands is *adaptivity*. Hands, as those proposed in [10] and [11], and grippers, such as in [12], are characterized by many DOFs but just one degree of actuation (DOA). They are designed to allow passive movements which are used to adapt the hand shape to the grasped object. These passive movements are determined by the equilibrium of the contact forces with passive elements as springs or, less often, clutches or brakes (see [13] and [14]).

In this paper we propose the extension of the *soft synergies* framework with the introduction of *adaptive synergies*. They integrate the viewpoint of soft synergies with that of adaptive UA hands.

Adaptive synergies move a step past soft synergies by enabling a method to effectively exploit synergies for the design of UA hands, compensating for the adoption of a reduced number of synergies with the possibility to adapt to the shape of the objects to be grasped. On the other hand, we go beyond traditional adaptive hands, by proposing a technique to combine multiple DOAs on the same UA hand, in a way that each DOA globally actuates the whole hand and DOAs are hierarchically ordinated by a functional bio-inspired relationship.

Our approach leads to the design and implementation of an experimental prototype hand, with 3-fingers. The prototype comprehends easily interchangeable phalanx modules, which can be connected in series, and a stack of distribution mechanisms, in order to be easily customized and expanded. It can be mechanically set-up to implement up to four adaptive synergies on fingers with an adjustable number of DOFs. Functionality of the prototype is demonstrated in some grasping simulations and experiments with some differently shaped objects (see Fig. 1).

The paper is organized as follows: section II introduces the problem and presents the soft synergies and the adaptive synergies approaches. Section III presents some practical implementation advantages of adaptive synergies, while section IV shows some of the grasping results obtained with the designed experimental prototype. Finally, conclusions are drawn in section V.

II. SYNERGIES FOR UNDER-ACTUATION OF HANDS

The kinematic configuration of a hand is univocally defined by a vector of n joint angles, $q \in \mathbb{R}^n$. A (linear) synergy base is an orthogonal base of the joint space, described by a matrix $S \in \mathbb{R}^{n \times n}$. Thanks to this the hand configuration is described by the vector $\sigma \in \mathbb{R}^n$ as

$$q = S\sigma. \tag{1}$$

Each of the columns of S is a synergy, by consequence the amount of movement of the hand along the i-th synergy is represented by the value of the i-th element of σ.

Specifying only a subset $\sigma^{(k)}$ of the components[1] of the synergy representation, and setting the value of the other $n-k$ components zero, as in

$$\begin{aligned} q &= S\,[\sigma_1 \cdots \sigma_k | 0 \cdots 0]^T = \\ &= S^{(k)}\sigma^{(k)} + S^{(k+1,n)} 0_{n-k} = S^{(k)}\sigma^{(k)}, \end{aligned} \tag{2}$$

is the basic idea behind the use of synergies for under-actuation. The matrix $S^{(k)} \in \mathbb{R}^{n \times k}$ is obtained by the first k columns of S, while $S^{(k+1,n)} \in \mathbb{R}^{n \times (n-k)}$ by the remaining $n-k$. This under-actuation pattern is that implemented by [4], with $n = 17$ and $k = 2$. Fig. 1(a) shows a schematic of the proposed implementation mechanism for the simplified case $n = 3$ and $k = 2$.

A drawback of this approach arises because the reduction of DOAs comes at the cost of reducing the overall hand DOFs. This, during a grasping task, could result, in general, in a grasp configuration with a very limited number of contact points.

A. Hands with soft synergies

A solution to this problem is proposed by [7], with the introduction of *soft synergies*. The geometric configuration of hands actuated with soft synergies is not defined by the truncated synergy vector $\sigma^{(k)}$ alone, but depends on the force equilibrium between the contact forces and the elastic forces of an introduced joint compliance, which is *in series* with the synergistic actuation system. This translates in having a virtual hand configuration defined by the truncation of the synergy vector, as

$$q_r = S^{(k)}\sigma_r^{(k)}, \tag{3}$$

and a joint space stiffness matrix K. Within this framework, the effective hand configuration is determined by solving the equation

$$J^T f_c = K(q_r - q), \tag{4}$$

where J is the grasp jacobian and f_c is the wrench associated with the contact forces. The differences between (2) and (4) highlight that a soft synergy hand retains all its kinematic DOFs. Consequently the number of contact points it can acquire during a grasp is, potentially, the same of a fully actuated hand with equal DOFs. The hand of Fig. 1(b) is the soft synergy equivalent of the one shown in Fig. 1(a).

[1] The superscript (k) indicates, in $\sigma^{(k)}$, truncation to the set of first k components.

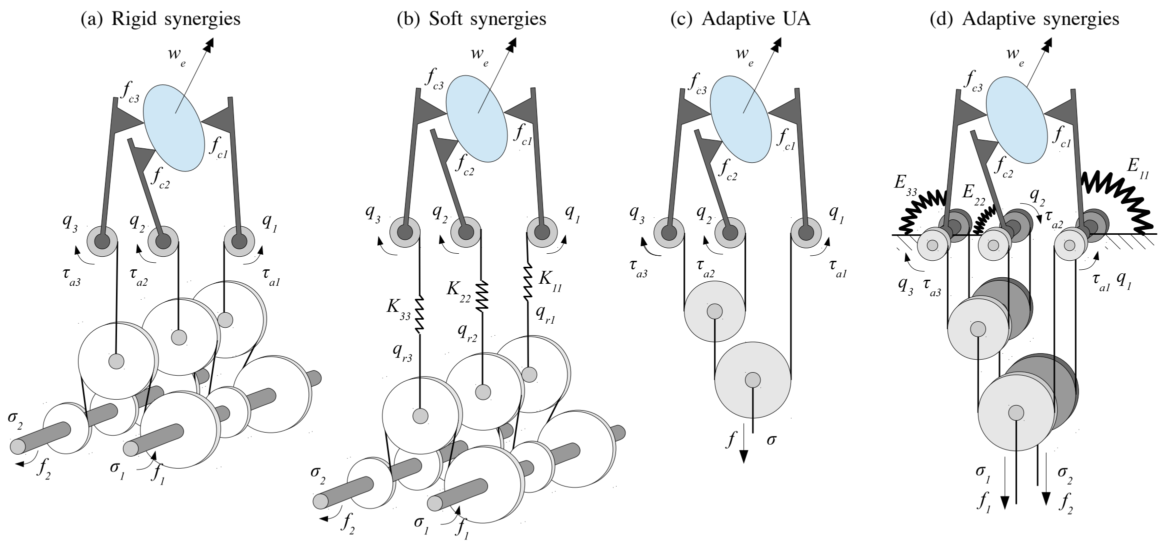

Fig. 2. One simple UA hand made of three fingers, powered by (a) rigid synergies, (b) soft synergies, (c) adaptive under-actuation and (d) adaptive synergies. The implementation of (a) is similar the one proposed in [4], implementation of (b) is the same of (a) extended with springs for soft synergies, while scheme (c) is a reduce version of that proposed in [10]. All the system rely on differential transmission, but schemes (a) and (b), on one side, and schemes (c) and (d), on the other, rely on a dual distribution policy.

B. Hands with adaptive synergies

Adaptive UA hands, such as that proposed in [10] and [11], exploit a dual approach to under-actuation, in which the joints are actuated along some directions of the configuration space and left free along the remaining others. To obtain such behavior, Adaptive UA hands implement a differential transmission system, as that shown in Fig. 1(c), which, through suitable gear ratios, actuates a linear combination of q, as in

$$rq = s, \tag{5}$$

where s is the displacement commanded by the actuator and the row vector r is the vector of the transmission ratios from the actuator to joints.

This approach suggests the implementation of *adaptive synergies*. The desired behavior of an adaptive synergies hand, is actuated in the direction of the first k synergies, and is passively free in the complementary directions. This translates in

$$q = S^{(k)}\sigma^{(k)} + N^{(k)}\lambda, \tag{6}$$

where the matrix $N^{(k)}$ is a kineto-static complement to $S^{(k)}$, such that $N^{(k)} \in \mathcal{N}(S^{(k)T})$ and λ is a vector accounting for the movement of the hand in the directions spanned by $N^{(k)}$ (thus not spanned by $S^{(k)}$). To attain this, multiple distribution system as that described in (5) can be layered in parallel to actuate a custom number of synergies. Indeed, collecting the transmission ratios of all layers in a matrix $R = [r_1^T, .., r_k^T]^T$, the system becomes

$$Rq = \mathbf{s}. \tag{7}$$

Choosing the matrix $R \in \mathbb{R}^{k\times n}$ with complementary rows allows for independence of the k values of $\mathbf{s}$. By virtue of this a design where $\mathbf{s} = \sigma^{(k)}$ can be found.

From the kineto-static dualism, R relates the force f applied by the k actuators to the torque τ_a on the n joints by

$$\tau_a = R^T f. \tag{8}$$

Given that the desired synergistic motion is that specified by equation (2) (i.e. with $\lambda = 0$), the movement of the unperturbed hand is assured by the introduction of elastic elements *in parallel* with the mechanical actuation system, characterized by the joint space stiffness matrix E. As a consequence, the hand configuration is specified by the balance of the contact forces f_c, the spring torques Eq and the actuation force f, as in

$$J^T f_c = R^T f - Eq. \tag{9}$$

Actuating the adaptive synergistic hand by direct control of the reduced synergy vector $\sigma^{(k)}$, leads to the system

$$\begin{bmatrix} -E & R^T \\ R & 0 \end{bmatrix} \begin{bmatrix} q \\ f \end{bmatrix} = \begin{bmatrix} J^T f_c \\ \sigma^{(k)} \end{bmatrix}. \tag{10}$$

Exploiting the Schur-complement block matrix inverse formula, leads to the solution

$$\begin{aligned} q &= \left(-E^{-1} + E^{-1}R^T(RE^{-1}R^T)^{-1}RE^{-1}\right) J^T f_c + \\ &\quad + E^{-1}R^T(RE^{-1}R^T)^{-1}\sigma^{(k)} \qquad (11) \\ f &= (RE^{-1}R^T)^{-1}RE^{-1}J^T f_c + (RE^{-1}R^T)^{-1}\sigma^{(k)}. \qquad (12) \end{aligned}$$

Suitable choices for R and E are sufficient to implement a desired synergy matrix $S^{(k)}$ as long as

$$S^{(k)} = E^{-1}R^T(RE^{-1}R^T)^{-1}. \tag{13}$$

In the simplifying case that $E = \alpha I$ and R is orthogonal, equation (13) simplifies to

$$S^{(k)} = R^T. \tag{14}$$

C. Dualism between soft and adaptive synergies

An interesting property of adaptive synergies, is that if the actuator are driven in force mode, with constant force $f = \hat{f}$, equation (9) holds, which can be re-written

$$J^T f_c = E\left(E^{-1} R^T \hat{f} - q\lambda\right). \tag{15}$$

Comparing it with (4), it can be noticed a parallelism in the behavior of the two hands. In particular the behavior of an adaptive synergy hand can match that of a soft synergy hand as long as $E = K$ and $\hat{f}$ solves

$$R^T \hat{f} = E S^{(k)} \sigma_r^{(k)}. \tag{16}$$

Once again, in the simplifying hypotheses that $E = \alpha I$ and $RR^T = I$, since $R = S^T$, the solution becomes $\hat{f} = \alpha\sigma(k)_r$.

III. ADVANTAGES OF ADAPTIVE SYNERGIES

Equation (16) gives an effective method to implement the behavior of a soft synergy hand on the hardware of an adaptive synergy hand. In this section some design issues are considered to hint that the physical implementation of adaptive synergies can have some practical advantage.

A. Economy of differential systems

One of the strong motivations behind hand under-actuation is the inherent gain of space and weight derived by the smaller number of motors. This comes at the cost of a slight loss in terms of mechanism complication, which is usually well balanced. Nevertheless the introduction of synergies in a robotic hand could imply an excessive complication of the mechanism due to the potentially high number of differential systems needed to mechanically implement a synergic motion.

The implementation of synergies proposed by [4], requires a number of differential systems d_s equal to:

$$d_s = n(k-1). \tag{17}$$

This is also the number of differential systems required by the implementation of soft synergies, following the scheme of 1(b). This number, which is equal to zero in the case of the implementation of one synergy, grows with k and can, potentially, become large enough to render the hand design complex and bulky.

If adaptive synergies are accounted for, the number of differential systems is

$$d_a = (n-1)k. \tag{18}$$

At a first glance this solution is even worse: differential systems are needed even in the case that only one synergy is implemented. Despite this number growing slower than d_s, both d_s and d_a grow linearly up to $n^2 - n$, so there is no value of k for which the number of differential systems in the adaptive synergies case is smaller than in the soft synergies one.

Nevertheless, a clever implementation of fingers, as that proposed in [15] and shown in Fig. 3, exploits serial tendon

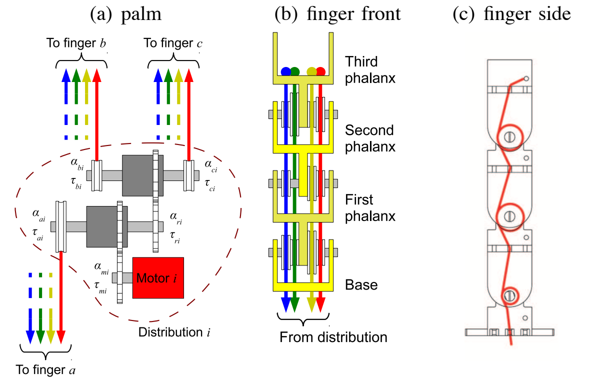

Fig. 3. Enhanced distribution tree to implement adaptive synergies, as implemented in THE Second Hand. Notice that the pulleys mounted on the finger (panel b and c) are idle, to allow a differential effect.

actuation of joints to obtain a differential behavior. This allows to reduce the number of differential systems to

$$d_{a*} = (n_f - 1)k, \tag{19}$$

where $n_f << n$ is the number of fingers in the hand. This facilitation is possible just for adaptive synergies implementation, where the differential distribution system goes from one actuator to many joints, and not from many actuators to the single joints as in the soft synergies implementation.

Given that $k < n$ and $n_f << n$, the relationship

$$d_{a*} < d_s < d_a \tag{20}$$

holds, which concludes in favor of adaptive synergies.

B. Superposition of synergies

As requested by the definition, synergies are orthogonal. This allows for application of the superposition effect to the different synergistic movements. Each actuator can move its synergistic component independently from the others, while this is true for all the proposed synergies implementation patterns, one important difference arises between the implementation as soft synergies and that as adaptive synergies that can be understood comparing the schemes of Fig. 1(b) and 1(d). In the soft synergies implementation (see Fig. 1(b)) the motors actuating different synergies are coupled together by the action of the differential systems: this implies that when one motor is actuating its synergic movement, all the other motors have to hold their position with the same torque. On the other side, in the adaptive synergies implementations (see Fig. 1(d)), each motor actuates all the joints in parallel with the other motors: this allows the use of differently sized motors to actuate synergies based on the amount of force expected to be needed on it (for example following the findings of [2]).

IV. EXPERIMENTAL PROTOTYPE

To validate the above findings, a proof-of-concept rapid prototype hand was designed. The prototype has three fingers and it is modular with respect to: a) the number of phalanxes

(a) Four adaptive synergies (b) One ad. synergy

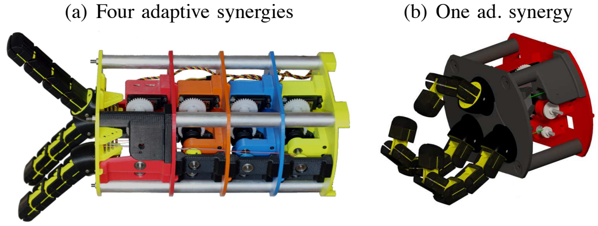

Fig. 4. THE Second Hand prototype. Left panel shows a picture of the prototype in a configuration with 3-phalanxes per finger, with four adaptive synergies assembled. Right panel shows a render of prototype, assembled with two 4-phalanxes fingers, a 2-phalanxes thumb and one adaptive synergy.

(a) Finger exp. view (b) Palm layer

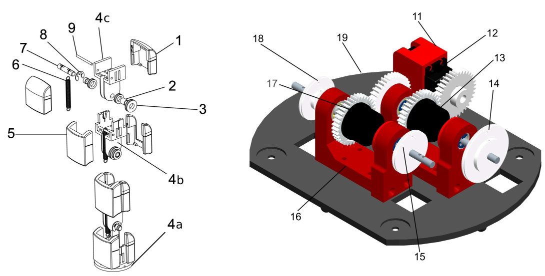

Fig. 5. THE Second hand prototype CAD: exploded view of one finger (a), render of one base module (b).

in each finger and b) the the number adaptive synergies, which goes up to four. A picture of the prototype assembled with 3-phalanxes fingers and four adaptive synergies is shown in Fig. 3(a). Another possible assembly with two 4-phalanxes fingers, one 2-phalanxes thumb and one adaptive synergy is shown, instead, in Fig. 3(b).

The prototype is composed by two main sub-systems: a palm holding three fingers, and a four layer system (one of which is shown in Fig. 4(b)), holding the servomotors and the differential systems, necessary to transmit the torque from the motors to the fingers.

A. Finger

Each finger (Fig. 4(a)) is made by a base fork (4a), a variable number (two in the figure) of middle forks (4b) and one terminal fork (4c), realized in ABS plastic. Steel axes (7) are constrained to the upper part of each fork, hosting pulleys (3), made of Derlin plastic, mounted on brass bushes (2). Each fork has a cave on its back to hosts a spring (6), which is constrained to a steel axis (9) on the upper side of the fork and to a corresponding axis of the previous fork in the chain. This solution adopts the springs to actuate a recoil movement, antagonist to the tendons. Each fork is covered on both faces with an ABS cover (1), (5).

Each finger is a serial mR robot (m depends on the number on phalanxes on the finger), on each joint a group of four pulleys hosts the four tendons that implement the different adaptive synergies (see Fig.s 2(b),2(c)). Every single finger can be easily disassembled, allowing for fast addition and removal the pulleys and phalanxes to experiment different synergies.

(a)

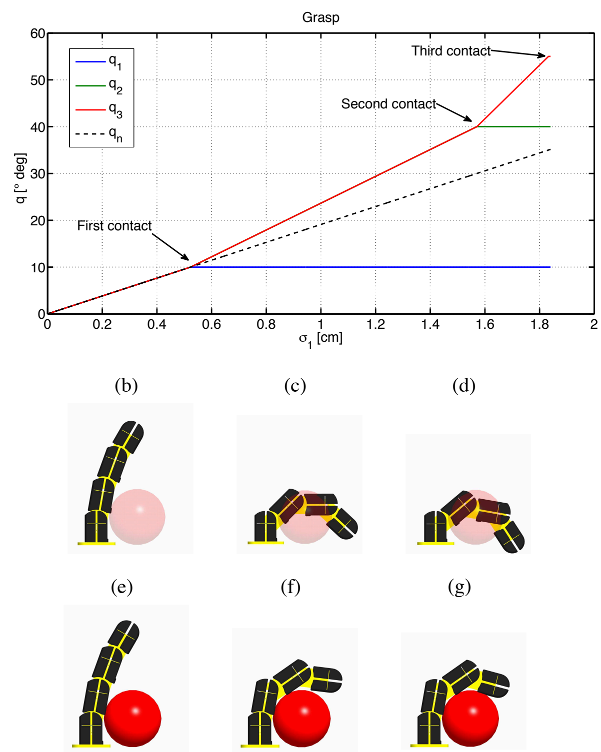

Fig. 6. Simulated interaction of the first finger and a ball during actuation on the first synergy. The graph plots joints angles in [deg] on synergy extension in [m]. As you can see Fig. 5(e), Fig. 5(f), Fig. 5(g)), once a link touches the object the angle joint stops while the forward joints continue to close until the object shape admits. Fig. 5(b), Fig. 5(c), Fig. 5(d) shows the nominal enclosure when the finger is free to move

B. Palm

In each layer of the palm (as in Fig. 4(b)) a frame (19) and some supports (16), (11) made of ABS plastic hold the differential mechanism (13) and servomotors (12). On the differentials and the motor, Derlin spur gears (17) and pulleys (14), (15), (18) are mounted, to distribute motion to the tendons.

C. Experimental Setup

In this section, some results are shown to illustrate the prototype functionalities, both in simulation and experiments. The prototype was assembled with 3 phalanxes for each finger, as shown in Fig. 3(a). Similar springs are mounted on all the joints, yielding for a joint stiffness matrix $E = 20 I_{9x9}\, [Nmm/rad]$.

The problem of designing the best synergies for a given, non-anthropomorphic hand is a non-trivial task, far from the scope of this paper, thus, choice of matrix S implemented for the experiments presented here was arbitrary, but for a simple heuristic that, the first synergy was designed to allow a closing movement of grasping. The other three synergies were realized but an in-depth exploration of their meaningfulness is left for future experimentations.

Given the choice of matrix S, this translates, by application of (14), into the transmission matrix R, and ultimately

(a) (b)

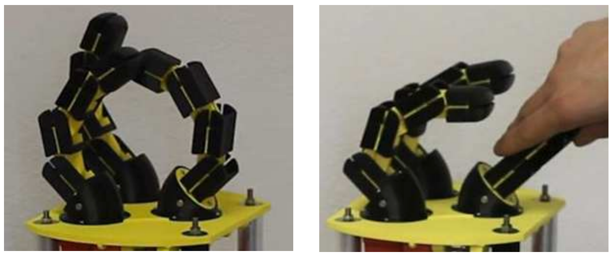

Fig. 7. THE Second hand prototype, closed by the actuation of the first synergy, $\sigma_1 = 30\%$ without external forces (left) and with external forces (right). From the right image the adaptivity warranted motions in the complementary directions can be noticed.

(a) (b) (c) (d)

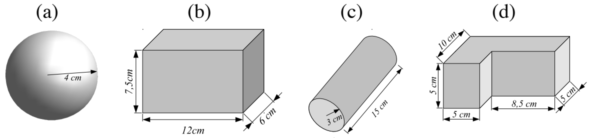

Fig. 8. Characteristic lengths of the test objects grasped in the experimental trials.

in radii of the pulleys within the fingers.

D. Grasp Simulations

Fig. (6) shows some simulation results of a finger grasping a ball with the first synergy. In this experiment the ball is fixed to the reference frame. Joint angles are plotted versus σ_1 in 5(a), compared with the virtual trajectory of the joints not contacting the object. It can be noticed that all the joints close with the same ratio as long as there is no contact. On the other side, after the first phalanx contacts the object (Fig. 5(e)), the remaining two joint keep closing at the same rate respect to each other (remaining in the synergy manifold), but at a higher rate with respect to the same change in σ_1, due to the differential effect. The same effect repeats after the second phalanx contacts the object (Fig. 5(f)), until the third contact (Fig. 5(g)), after which the movement stops.

E. Grasp Examples

Some experimental tests were performed to demonstrate the main characteristics of THE Second hand. At first the hand is closed along the first synergy without any object in it (Fig. 6(a)), to show the shape of the hand closing along the first synergy. At this point external forces are applied to the hand to show how it can move along the complementary directions λ (see Fig. 6(b).

In a second experiment, some simple grasp tests were performed to show the hand adaptivity during grasp of real objects whose dimensions are described in Fig. 8. The objects used are a ball, a cylinder, a box and a L-shaped box. Pictures of the resulting grasp positions are shown in Fig. 1

V. CONCLUSIONS

This paper presented a novel methodology to design UA robotic hands exploiting the synergies approach. The proposed method merges the concept of synergies with that of adaptivity usually found in UA hands and smart grippers, in the idea of *adaptive synergies*. The approach has been mathematically derived and compared to the approach of soft synergies. Some implementation aspects of synergic hands were discussed, leading to the design and implementation of a prototype hand with adaptive synergies. The prototype effectiveness has been shown with some grasping experiments.

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