Implementation and Control of the Velvet Fingers: a Dexterous Gripper with Active Surfaces.

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***Abstract*— Since the introduction of the first prototypes of robotic end-effectors showing manipulation capabilities, much research focused on the design and control of robot hand and grippers. While many studies focus on enhancing the sensing capabilities and motion agility, a less explored topic is the engineering of the surfaces that enable the hand to contact the object.**

In this paper we present the prototype of the Velvet Fingers smart gripper, a novel concept of end-effector combining the simple mechanics and control of under-actuated devices together with high manipulation possibilities, usually offered only by dexterous robotic hands. This enhancement is obtained thanks to active surfaces, i.e. engineered contact surfaces able to emulate different levels of friction and to apply tangential thrusts to the contacted object. Through the paper particular attention is dedicated to the mechanical implementation, sense drive and control electronics of the device; some analysis on the control algorithms are reported. Finally, the capabilities of the prototype are showed through preliminary grasps and manipulation experiments.

I. INTRODUCTION

The first two prototypes of End Effector that demonstrated manipulation capabilities are the Salisbury's three-fingered robotic hand [1] and the Utah/MIT hand [2]. Since their introduction, many different designs have been proposed, from very simple devices [3], to multi-fingered hands such as the UB Hand IV [4], to very sophisticated fully actuated devices that incorporate the ultimate advancements in robotic actuation, such as [5] (for extensive surveys on robot hands see [6] and [7]). Since the proposal of those two prototypes much research developed to improve robotic hands hardware. In particular many studies focused on enhancing robot hand sensorization and actuation technology. A possible direction for further improvement of end-effector design for grasping and manipulation, that we started exploring in [8], is the introduction of *active surfaces*. The idea of using active surfaces at the finger-pads is prompted by the successful developments in adhesive surface engineering, as the bio-inspired designs, such as Cutkosky's Stickybot ([9], [10]).

The idea of active surfaces aims at controlling adhesion between the fingers and the object in different manipulation phases. Controlling adhesion implies being able to regulate it from very high "sticky fingers" to very low "slippy fingers", thus enabling nimble manipulation with "velvet fingers". It is even conceivable, through the use of a suitably shaped surface adhesion wave, to apply tangential forces on the manipulated object to relocate it on the finger-pad.

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Fig. 1. Prototype of the "Velvet Fingers" smart gripper implemented at the University of Pisa, while grasping a ball.

The idea of active surfaces, culminates in [8] with the design of the Velvet Fingers dexterous gripper, which prototype (see Fig. 1) is presented in this paper, but the idea can also be found in at least other four implementations. For sake of precision we have to mention that, unfortunately, the few information about their design and functioning can be found in web pages, technical brochures or patents rather than in scientific publications.

The first of such device, shown in [11], is an hybrid between a forklift and a gripper. Actually composed of two rigid plane forks with an actuated belt each, located on the inner side and on the tip, which can be moved independently. A proximity sensor and a presence sensor are used to detect objects to be forked and conveyed. Moreover the distance between the forks can be varied according to the dimension of object to be grasped. They can also be rotated around their own axes to reach a configuration where the gripper works as a standard two finger gripper with additional capabilities thanks to the active belts.

The Traction Gripper [12] consists of a series of active rubber cylinders, arranged on two perpendicular planes, and used as conveying units. Each conveying unit has a separate drive chain and traction belts that exert a friction force allowing the grasping of goods of several shapes. The inward conveying motion of the traction belts causes friction between the active surfaces and the grasped object, the object is thus pulled toward the gripper corner and firmly held in position. Very similar to the traction gripper is the "Rack n' Roll" [13]. As the Traction Gripper, it is a two finger gripper without closure actuation. It has two independent belts on the fingers which are shown to be able to manipulate a wheel until it is properly positioned.

A slightly more complex structure is that patented by Robin Read [14] where a twin gripper uses two interlinked belts, maintained in constant tension, as active surfaces. The length of the belts within the jaws can be varied to modulate the gripping forces. Moreover, proper belt motions allow the grasped object to be rotated in-hand.

The Velvet Fingers dexterous gripper, which is a preliminary attempt to add dexterity to simple, under-actuated grippers through the adoption of active surfaces, is presented in this paper with particular attention to the mechanical implementation and to the complementing electronics and control. The outcome is a very simple gripper with very high manipulation capabilities, which ensure an enveloping grasping around the objects and allows to control the displacement of the contact points between the fingers and the piece and their friction conditions.

The paper is organized as follows: Sec. II briefly recalls the general design of the Velvet Fingers, Sec. III presents some important details of the mechanical implementation of the system, sec. IV presents the system dynamics, along with the algorithms adopted to control both the active surface and the adaptive gripper. Sec. V shows some photo sequences extracted from the attached video content that display the grasping and manipulation capabilities of Velvet Fingers. Finally, Sec. VI presents the conclusions and sketches the future work.

II. DESIGN

Recent advances in nano-manufacturing and bio-inspired technologies led to the development of nano-structured surfaces inspired by the animal world like gecko skin and other adaptable surfaces. The real future challenge is to create real active surfaces able to change their friction coefficient and exert tangential propulsive actions thanks to nano-structured arrays of selectively controlled adhesive elements.

In [8] it has been shown how smart skins with active surfaces would empower robotic hands with greater ability in the manipulation of objects. In particular the variation of the friction coefficient can be exploited to switch between different grasping configurations, while propulsive actions would allow to actively manipulate objects in hand.

Even though nano-structured active surfaces are not yet available at the present time, their effects with respect to robotic hands can be, to some extent, reproduced by implementing smart conveyor belts on the hand contact surfaces. This, along with proper control, allows to emulate friction variation, thus controlling the force resisting to sliding, and to exert propulsive tangential actions.

Since such controlled conveyor systems need additional motors mounted on the hand, with increased weight, volume, cost and complexity, an underactuated actuation system can in principle be adopted for the movement of the links in order to keep the total number of motors unvaried.

To assess the effective advantage of this modification to a gripper design a manipulability analysis has been presented in [8]. It compared two robotic hands with same mechanical structure and same total number of motors but distinguished by the fact that the first adopts full actuation and traditional contact surfaces, while the second combines under-actuation and active surfaces. This comparison showed a considerable advantage of the second hand with respect to the first, in terms of dimension of the manipulability ellipsoids.

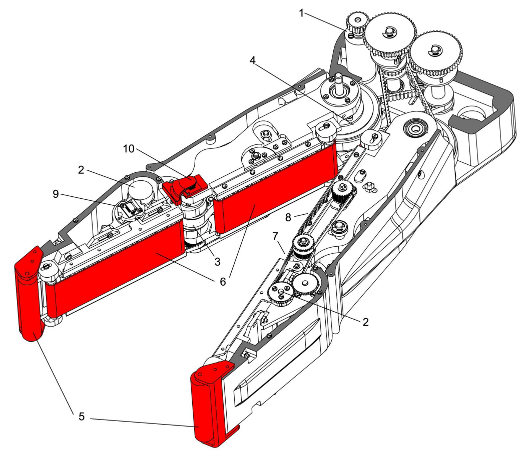

Fig. 2. Section view of the Velvet Fingers smart gripper. Parts colored in red are variations with respect to the design presented in [8].

This led to the design of a novel planar underactuated gripper with two fingers and controlled conveyor belts mounted on the inner fingers to implement active surfaces. Each one of the two fingers of the gripper is a planar RR manipulator with two coupled conveyor belts on each link. Each finger has one degree of actuation (DoA) for the movement of the belts. The whole gripper has one more DoA for opening and closing.

In the next section the real mechanical implementation of the Velvet Fingers, based on the design presented in detail in [8], is described with specific attention to the belts and the driving and control electronics and sensors.

III. IMPLEMENTATION

Fig. 2 shows an overall view of the real mechanical implementation of the Velvet Fingers. During the realization phase, some small refinements were introduced in the design of the gripper. In particular (i) two idle rollers were added to the fingertips to reduce friction, (ii) two additional sensors were added to completely reconstruct the hand position, and (iii) the belts used to implement the active surfaces were modified. These modifications are highlighted in Fig. 2 by red color. Some details about these and other aspects of the prototype implementation follow.

A. Mechanical implementation

Referring to Fig. 2, actuator (1) is used for the closure movement of the fingers; it is a 6W Maxon RE-MAX brushed DC motor with nominal torque $6.82 mNm$ (peak torque $27.8 mNm$) with a $316:1$ gearbox able to exert a maximum continuous force of $12.6N$ on the tip of the finger (about $50N$ in peak torque condition). Hence the hand is able to grasp a mass of about $1kg$ and lift it with an acceleration of $1g$.

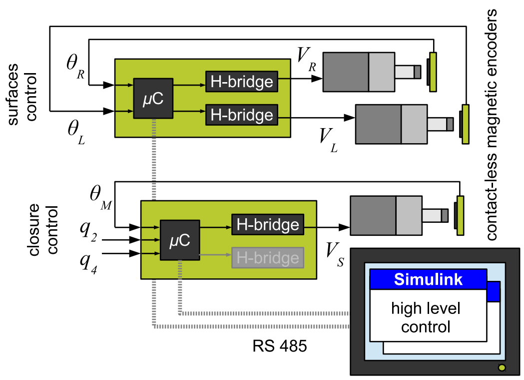

Fig. 3. Velvet Fingers general control architecture. Two custom boards, designed to drive two motors each, drive the system implementing sensor reading, lower-level loop closure and higher level communication.

Kinematic analysis, presented in detail in [8], demonstrates that a gear ratio of 3 between proximal and distal pulleys (4) and (3) in Fig. 2) ensures an enveloping grasp around the objects also when the two fingertips collide. Idle rollers (5) were added to the tip of the fingers to allow the free sliding of the distal phalanges, one on the other, in the case that asymmetric closure leads one fingertip in contact with the contact surface of the other finger.

Conveyor belts (6) are actuated by motor (2) (same as used for the movement of the fingers), placed on the distal phalanx, with gear ratio $4.4:1$, able to exert a traction force on the belts of about $30N$. The motion of the belt from the distal to the proximal phalanx is transmitted by timing belts (7) and (8).

Conveyor belts used in the prototype are composed of a synthetic tissue fixed on a polyurethane layer, with a thickness of $0.8mm$, featuring high tensile strength $30MPa$ and extensional stiffness, yet suitable to wind around $8mm$ diameter rollers.

To emulate variable friction between the objects and the fingers, high adhesion on the external side of the belts is essential. In order to achieve it, the belts are treated with a Liquid masking film produced by Talens. It is a liquefied mixture of natural rubber (latex) which, when dried, fixes on the belts. The final result is a high resistance and very flexible thin belt with high adhesion properties.

The implemented prototype overall weight is $3.46Kg$. When completely open the gripper width is $674mm$, when fully closed, it's width reduces to $150mm$, and its length is $379.5mm$. The maximum gripper depth is $116mm$.

B. Electronics

A general schematics of the power and control hardware of the Velvet Fingers hand is shown in Fig. 3. Five magnetic encoders AS5045 (Austriamicrosystem) read the rotation angles of the three motors which actuate the gripper closure and the two active surfaces.

Two custom electronics board implement motor power driving, encoder reading, low-level closed-loop control and communication with the higher level control. Each board core is a PSOC3 embedded micro-controller. It can read up to four rotary magnetic encoders through SPI bus interface. It communicates with the higher level control (a PC with Matlab/Simulink) through serial RS485 interface, implemented by a MAX1437 IC. Each board uses two ST L6206D H-bridge power drivers to command the voltage to the motors.

The first board takes care of controlling the two active surfaces, reading two encoders mounted on the motor rolls of radius r which angular displacement θ_R and θ_L can be related to the linear displacement of the conveyors x_i (refer to Fig. 4) by

$$\begin{aligned} x_1 = x_2 = r\theta_R \\ x_3 = x_4 = r\theta_L \end{aligned}, \quad (1)$$

and driving the two voltages V_R and V_L which in turn activate the DC motors actuating the two belts. The micro-controller implements the lower layers of the control loop, implementing the two control modalities defined in Sec. IV-A.

The second board takes care of controlling the motor closing the gripper. In doing so it reads the rotation angle of the motor and the two angles q_2 and q_4, thanks to which it is possible to reconstruct the total kinematic configuration of the hand, through (2) of Sec. IV-B. The second board also presents a spare power channel to operate the hand in the case that a decoupled fingers assembly is implemented (the hand design accounts for such possibility, refer to [8] for details).

IV. CONTROL

As hinted by the hardware architecture presented in the previous section, control of the Velvet Fingers smart gripper is implemented in two layers. The top layer is realized by a computer running Matlab/Simulink, and takes care of commanding the inner layer. In the inner layer there are three independent control loops, two take care of controlling the active surfaces and another the gripper motion.

A. Active Surfaces Control

Each pair of conveyor belts implementing the two active surfaces can be controlled in two modes: (i) tangential push and (ii) friction emulation. The combination of these two control modalities confers to the system the maximum flexibility, making it capable to range over a lot of configurations with a several number of intermediate behavior between two extreme, ”sticky fingers” and ”slippy fingers”. Moving the system inside this range is not easy and is a work that require a deeper analysis that is out of the aim of this work. This approach will be discussed comprehensively in future works. In this work only the ”sticky fingers” control behavior is taken into account, in order to demonstrate the effectiveness and the manipulation capabilties of the system. It can be implemented under some simple conditions: infinite contact friction coefficient between the actuation roller and conveyor belts, high friction in the contact between active surfaces and grasped objects, and, finally, the conveyor system can be considered rigid. From a control point of view this kind

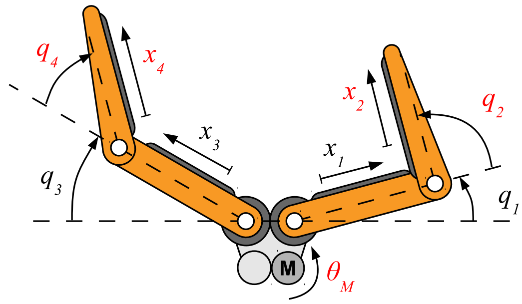

Fig. 4. Kinematic scheme of the Velvet Fingers hand. Variables highlighted in red are measured.

of behavior can be implemented with a simple PID control loop, closed on the angle rotation of the motor actuating belts. With other words we can consider them actuated with a conventional servo-motor unit. With this approach most of the gripper features can be exploited to obtain an advanced manipulation capability and to performs some advanced grasps, as Sec.V shows.

B. Gripper Control

The kinematics of the gripper, shown in Fig. 4, is that of a pair of RR robots. Moreover the under-actuated mechanism driving the two fingers determines the constraints

$$r_1 q_1 + r_2 q_2 = r_3 q_3 + r_4 q_4 = s, \tag{2}$$

where r_1, r_3 and r_2, r_4 are the radius pulleys on the first and the second joints respectively and s is the displacement of the motor belt winding on the motor pulley of radius r_1 and r_4.

The dynamics of the gripper can be described as:

$$\begin{cases} B(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + A^T\lambda = \\ \quad = J(q)^T w_e + M^T\tau_M + \tau_e = \tau \\ A\ddot{q} = 0 \end{cases}, \tag{3}$$

which, with the augmented formulation technique, can be explicitly solved as

$$\begin{cases} \ddot{q} = & (I - A_B^+ A)B^{-1}[\tau - C(q,\dot{q})\dot{q} - G(q)] \\ \lambda = & (A_B^+)^T[\tau - C(q,\dot{q})\dot{q} - G(q)] \end{cases}, \tag{4}$$

where

$$A_B^+ = B^{-1}A^T(AB^{-1}A^T)^{-1}. \tag{5}$$

In the previous equations q are the joint variables $B(q)$ the inertia matrix, $C(q,\dot{q})$ the Coriolis matrix. Matrix A is the constraint matrix, which takes into account the constraint realized by the coupled actuation of the two fingers. It can be derived by the first two members of (2), as

$$A = \begin{bmatrix} r_1 & r_2 & -r_3 & -r_4 \end{bmatrix}. \tag{6}$$

M is the transmission matrix linking the motor displacement s and the joints displacement q, which can also be derived from (2), as

$$M = \begin{bmatrix} n_t & n_t r_2/r_1 & 0 & 0 \end{bmatrix}, \tag{7}$$

where n_t is the gear ratio between the pinion of the motor shaft and the motor pulley. Of the remaining variables, $J(q)$ is the Jacobian matrix of the contact points, w_e is the array of the external wrenches on the links, τ_M is the torque exerted by the motor opening and closing the fingers and τ_e is a vector of elastic forces accounting for the springs which couple first and second phalanges of each fingers, and for the mechanical stops (refer to Fig. 5). Finally λ is a Lagrange multiplier which represents the internal force acting on the constraint. Values of the matrices $B(q)$ and $C(q,\dot{q})$ are calculated from data presented in Appendix.

To control this under-actuated mechanics a PID control loop is closed on the value of the variable s, i.e. the rotation of the motor actuating the hand closure. This approach leads to the control scheme reported in Fig. 6, which has been tested through Matlab/Simulink simulations.

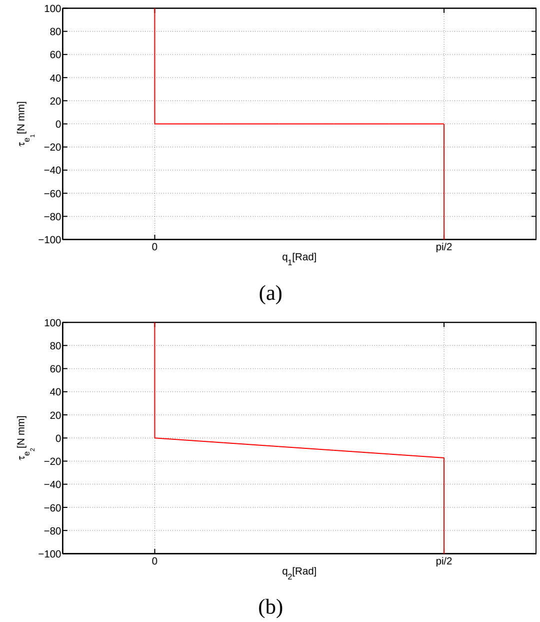

Fig. 5. Elastic force-deformation characteristic equal to a non-linear springs accounting for the springs which couple first and second phalanges of each fingers, and for the mechanical stops on joints q_1 and q_3 (a) and joints q_2 and q_4 (b).

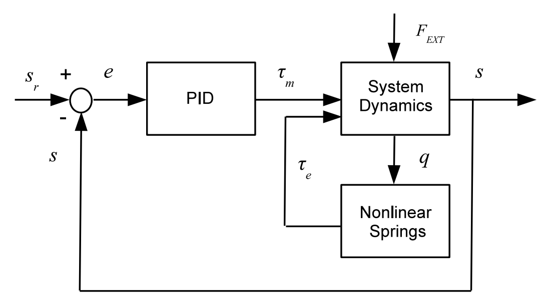

Fig. 6. The figure shows the smart gripper control scheme implemented in Matlab/Simulink. Block *SystemDynamics* contains the equations 3. The *NonlinearSprings* represents the force-deformation characteristic of the non-linear springs on joints q_1, q_3 and joints q_2, q_4.

V. EXPERIMENTAL VALIDATION

Several experiments were conducted in order to demonstrate and validate the capabilities of the system. Experiments were organized in two sessions: the first focuses on grasping performance, while the second shows the enhanced manipulation features of the Velvet Fingers smart gripper.

All trials were performed in the following experimental setup: the gripper is placed horizontally and is fixed on a frame, while some test objects are placed on a table lying under the gripper. The relative position between the plane of the gripper and the table is adjusted according to the object shape and the particular task.

All the experiments show preliminary results, carried out with a simplified version of the control. Both the fingers and the active surfaces are controlled with a PID implemented in the embedded electronics, without resorting to any kind of impedance control or friction emulation. Most of the experiments resort to the system possibilities as described in [8].

All the experimental results are reported in the attached video footage, but for ease of fruition all figures in this section present the results through a series of snapshots extracted from the video.

A. Grasp

Fig. 7 shows the grasping configuration of several different kinds of objects, demonstrating the effective adaptation capabilities of the designed under-actuated mechanism.

Fig. 8 shows the closure of the gripper in absence of any kind of external forces; in this situation the fingers are straight and angles q_2 and q_4 are equal to zero. The system presents a very different behavior when external forces due to contact act on the first phalanxes. Fig. 9 shows a sequence where the gripper performs a grasp on a sphere of about 150*mm* of diameter, guaranteeing a good winding on the shape of the object. In some grasps, as in Fig. 10, the small dimensions of the grasped objects, can cause fingertips to come into contact, (see frame (d)). Nevertheless (as shown in frames (e) and (f)) proper closure is always guaranteed thanks to the design of the transmission ratios in the system. Fig. 11 shows how combining the control of the closure with the action of the active surfaces allows for in-hand reconfiguration of the grasped object. In the particular example the grasp switches from a configuration with only two contact points (Fig. 11(a)) to a configuration with four contact points (Fig. 11(b)).

B. Enhanced Manipulability

Tincani et al. in [8] showed the enhanced manipulability of the Velvet Fingers with respect to a conventional two finger (four phalanx) gripper. In particular the combination of an under-actuated main structure with the presence of active surfaces on fingers makes it possible to perform tasks as shown in Fig. 12 and Fig. 13. Fig. 12 shows that while controlling the active surfaces in order to push the object in the same direction, it is possible to obtain a translation of the grasped object inside the hand. On the other hand, controlling the surfaces in order to push in opposite direction it is possible to confer a rotary motion to the object (Fig. 13). During the execution of these two kind of

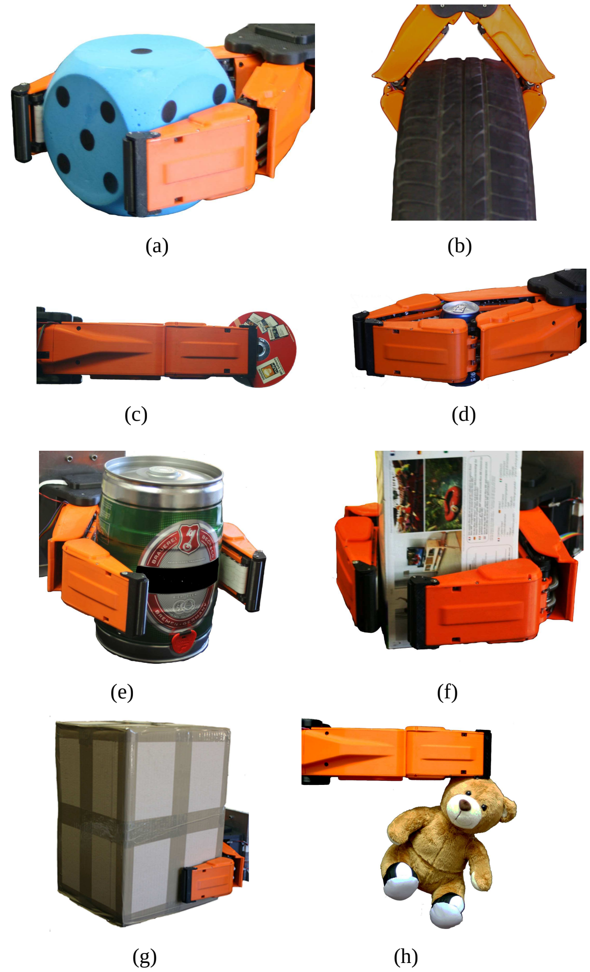

Fig. 7. Grasping of several objects. The Velvet Fingers dexterous gripper is used to grasp some of the objects which constitute part of the scenario of the EU founded project ROBLOG (`www.roblog.eu`), for which this EE has been designed. The objects grasped are: a cube with an edge of 200*mm* (a), a tire P195/55R16 85H (b), a CD-ROM (c), a can (d), a small beer keg (e), a small box 376*x*149*x*122*mm* (f), a big box 390*x*290*x*270*mm* (g) and a Teddy bear (h).

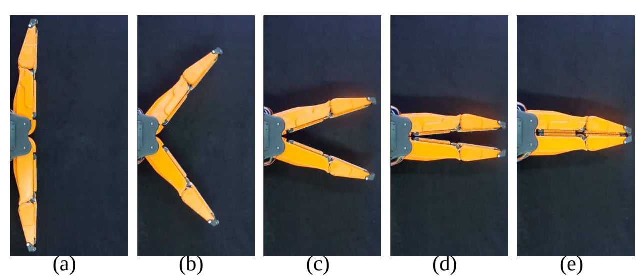

Fig. 8. Free closure movement. When closing without external forces applied, the device moves in a V-shaped feature, both the second joint variables, q_2 and q_4, are equal to zero.

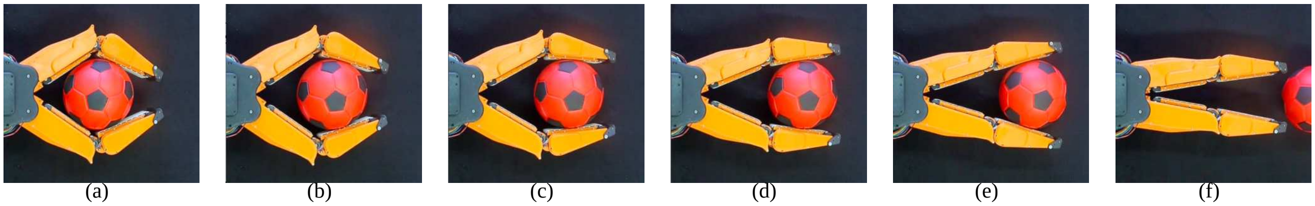

Fig. 12. Object expulsion. A grasped object (a) is completely expelled out of the hand (f) by pushing it with the active surfaces. Adaptability of the under-actuated gripper guarantees grasp stability during the whole movement (b, c, d, e).

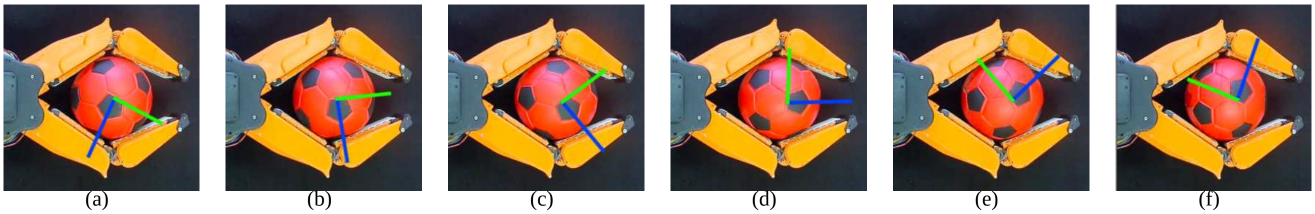

Fig. 13. In-hand object rotation. Pushing the object in opposite directions causes a pure rotation of the grasped object.

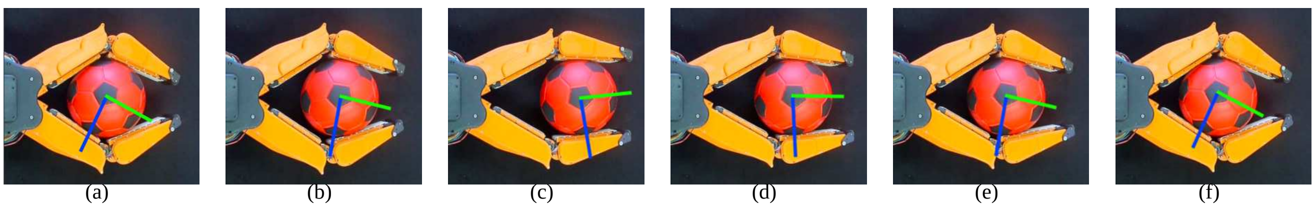

Fig. 14. In-hand object roto-tranlsation. Suitable combination of tangential pushes by the active surfaces, confer the object a movement of roto-translation inside of the hand.

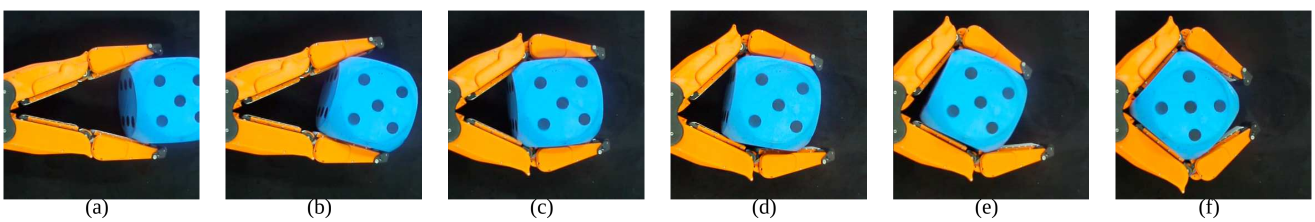

Fig. 15. Adaptive active surface grasping of a cube. The sequence shows the possibilities offered by a combination of active surfaces and under-actuation, which give the system the capabilities to reach different configurations of grasp and extend its manipulation capabilities. Pictures (a) and (c) shown, respectively, a tip-grasp and a power-grasp configuration; in the frames from (c) up to (f) a short sequence where the object is put on rotation is shown.

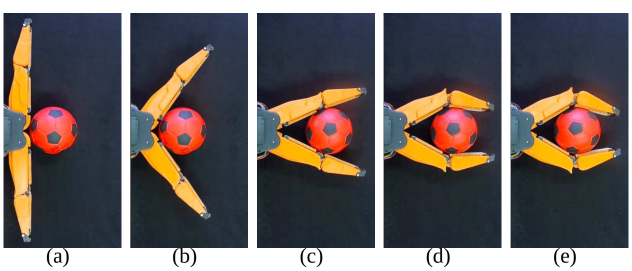

Fig. 9. Enveloping closure around a spherical object. In presence of an object, reaction forces arise due to the contact, acting on first phalanges they modify the gripper closure which in turn shows its adaptation capabilities, thanks to which it is able to reach a grasp.

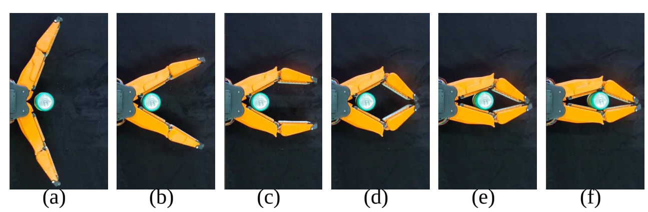

Fig. 10. Grasping with touching fingertips. This sequence shows the capability of the system to grasp an object also when fingertips come into contact. After the first contact with the object (b) the distal phalanges start bending faster than the proximal (c) until the two fingertips touch each other (d). Proper transmission design ensures that, despite the tips interference, the hand keeps squeezing the object, reaching a grasp closure.

tasks the intrinsic adaptability of the under-actuated system guarantees an enveloping grasp throughout the movement. A more complex control of the active surfaces can be adopted to realize more complex tasks, as shown in Fig. 14 and Fig. 15.

In Fig. 14 a roto-translational movement is conferred to the grasped object. The sequence shows how the sphere, which is in the starting position (a), moves to a translated and rotated configuration (c) and, afterwards, returns back to the original configuration (f). Finally Fig. 15 shows a sequence where

(a) (b)

Fig. 11. Controlled Slipping. Through the activation of conveyor belts the object is squeezed within the hand, bringing the system in a more stable grasp configuration with four contact points (b).

tangential pulling action of the active surfaces is used to grasp a cube, thanks also to the adaptivity of the under-actuated mechanism.

VI. CONCLUSIONS

This paper presents the physical prototype of the Velvet Fingers smart gripper, which design was previously introduced in [8].

It is an end-effector which adopts the novel idea of active surfaces, able to control friction and to apply tangential forces to the manipulated objects. The functionalities of active surfaces were implemented, in this prototype, through properly controlled high-friction conveyor belts.

The prototype was presented giving details concerning the mechanical implementation, sensors and electronics. Dynamic models of the system and control laws managing system under-actuation were presented, which were verified with numerical simulations and trials.

Finally the gripper functionalities were shown through preliminary grasp and manipulation experiments.

APPENDIX

A. Kinematic and Dynamics Parameters

The kinematics of the two fingers can be described by the Denavit-Hartenberg Table I. The dynamic parameters are listed in table II.

Link	l_i	α_i	d_i	q_i
1	l_1	0	0	q_1
2	l_2	0	0	q_2

TABLE I

DENAVIT-HARTENBERG TABLE OF THE RIGHT FINGER. TABLE RELATIVE TO RIGHT FINGER CAN BE OBTAINED FROM THIS ONE BY REPLACING SUBSCRIPTS 1 AND 2 WITH 3 AND 4, RESPECTIVELY.

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Parameter	Value	Unit
r_1	29.10	$[mm]$
r_2	9.70	$[mm]$
m_1	0.725	$[Kg]$
m_2	0.465	$[Kg]$
a_1	146.1	$[mm]$
a_2	132.4	$[mm]$
I_{z_1}	1961	$[Kgmm^2]$
I_{z_2}	992.2	$[Kgmm^2]$
l_1	45	$[mm]$
l_2	63	$[mm]$

TABLE II

CHARACTERISTIC LENGTHS, MASSES AND INERTIAS OF THE VELVET FINGERS. VALUES REPORTED ARE RELATED TO RIGHT FINGER, PARAMETERS FOR LEFT FINGERS ARE SAME, JUST REPLACE SUBSCRIPTS 1 AND 2 WITH 3 AND 4, RESPECTIVELY.

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