

Article

The UC Softhand: Light Weight Adaptive Bionic Hand with a Compact Twisted String Actuation System

Mahmoud Tavakoli *, Rafael Batista and Lucio Sgrigna

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Institute of Systems and Robotics, University of Coimbra, 3030 Coimbra, Portugal; rafaeljcb@hotmail.com (R.B.); lucio.sgrigna@gmail.com (L.S.)

* Correspondence: mahmoud@isr.uc.pt; Tel.: +351-968-397-681

Abstract: In this paper, we present the design and development of the UC-Softhand. The UC Softhand is a low cost, Bionic and adaptive hand that takes advantage of compliant joints. By optimization of the actuation strategy as well as the actuation mechanism, we could develop an anthropomorphic hand that embeds three actuators, transmission mechanisms, controllers and drivers in the palm of the hand, and weighs only 280 g, making it one of the lightest bionic hands that has been created so far. The key aspect of the UC Softhand is utilization of a novel compact twisted string actuation mechanism, that allows a considerable weight and cost reduction compared to its predecessor.

Keywords: twisted string; prosthetic hand; soft robot; soft hand; soft bionics

1. Introduction

Anthropomorphic hands, which have been developed so far for industrial and prosthetic purposes can be roughly categorized as highly dexterous hands with many actuators [1–3] and minimally actuated hands (see for instance [4,5]). The former group has many actuators, placed on the forearm or in the hand itself, by sacrificing the weight and the size of the hand and/or the actuation power. These hands can grasp and manipulate a wide range of objects by applying a complex control strategy. Yet, due to their electromechanical and control architecture complexity, they are not the best option for many applications that demand simplicity, lightness and low cost.

Here, we call the latter group as the minimally actuated hands, referring to bionic hands that contain one to six actuators (compared to the 34 muscles of a human hand). These hands can be fully actuated or under-actuated. In both cases, their advantages over the former group include:

- Simpler electromechanical structure
- Lower weight, size and cost
- Simpler control architecture

A recent and comprehensive analysis was performed in [6], where authors recorded 7:30 hours of daily activities of two housekeepers and two machinist. They showed that out of the total 33 grasps that humans use in the daily tasks [7], 10 grasps for the machinists and 5 grasps for the housekeepers constituted 80% of the total grasping duration. This makes the minimally actuated hands more interesting, since it indicates that if the actuation strategy is carefully selected, these hands may not be very inferior than very dexterous hands with many actuators for grasping purposes.

In addition, researchers are trying to exploit as much as possible passive adaptive mechanisms and compliance in order to make bionic hands minimally actuated. For an anthropomorphic hand, compliance can result in a better adaptability to the large variety of sizes and shapes of the objects. Integration of compliance allows that several contact points being possible with the a single joint

posture. This means that for a specific design of a bionic hand, the integrated compliance can reduce the number of actuated joints, and the control complexity by taking advantage of adaptive synergies.

Compliance can be integrated in the control loop as can be seen in The DLR HAND II [8] or in the actuator by integration of compliant elements, *i.e.*, springs to the system (*i.e.*, Meka-H2 compliant hand [9]). Another approach is to directly integrate compliance into the joints. Pisa-IIT Softhand [10], the UB hand [11] and our previous development the ISR-Softhand [12] are examples of recent development of anthropomorphic hands that directly integrate the compliance into the joints. In Pisa-IIT Softhand several elements are interconnected with elastic elements, while in UB hand the joint compliance is achieved by integration of springs into the joints. Flexirigid [13] and SDM hands [14] are examples of non anthropomorphic grasping mechanisms that use elastomeric joints for a better adaptability to objects.

In addition to the compliance, there are two main research subjects that can highly contribute to the further simplification of Bionic hands, the actuation strategy and the actuation mechanism. We studied both subjects, in order to improve our previous development, the ISR-Softhand. For the first subject, the actuation strategy, we made an extensive analysis, where we showed how the actuation strategies can affect the number of different grasp taxonomies that a Bionic hand can achieve [15]. For the second subject, the actuation mechanism, we found the twisted string mechanism, an interesting subject for further exploration. We then developed a novel compact twisted string actuation system that takes advantage of an “overtwist phase”, to increase the contraction ratio [16].

We applied these studies on the actuation strategy and mechanisms. This helped us to develop a novel fabrication method and to enhance the Mechatronics system of the previously developed ISR-Softhand. This resulted in the novel UC-Softhand that embeds twisted string actuators inside the palm of the hand. Altogether we achieved a considerable reduction in the hand’s complexity, weight and cost compared to its ancestor, the ISR-Softhand.

A twisted string actuation system converts the rotational motion of a motor’s shaft into a linear motion. It offers some advantages over conventional systems, like a rack and pinion, or a lead screw and nut system, such as being lighter, simpler and less expensive. The actuator is also not completely rigid due to the strings elastic behavior. This can make it harder to control, but it should be safer to operate around humans, due to the natural compliance of the entire system.

Some of the earliest applications of the twisted string systems in robotics were reported by M. Suzuki *et al.*, where they were used to drive a six-legged robot [17], an articulated arm that includes an anthropomorphic robotic hand [18,19] and an elbow exoskeleton based on twisted-string actuators [20]. Also impedance controlled twisted string actuators was reported, where researchers integrated a spring with a twisted string scheme and reported a position holding controller for both directions [21]. Mathematical modelling of the twisted string actuators were also presented in [22,23].

As reported in [19], actuators of the anthropomorphic hand are placed in the forearm of the system outside the hand itself. The same concept was applied in the DEXMART hand [24,25], where several actuators with twisted string systems are placed outside the palm and in a relatively large forearm. While placing the actuators at a remote distance from the driven object is advantageous for some applications, it is not desired in many others. Godler *et al.*, presented a five fingered robotic hand, that uses 15 twist drives to control the fingers [26]. In this case the actuators are placed in the fingers. To do so and in order to increase the joints’ motion range with a limited stroke of the twisted string system, the coupling point of the tendon was shifted from the joint at the cost of making the fingers larger. All above examples demonstrate a common problem in the twisted string systems. That is, twisted string systems suffer from a low contraction to length ratio (the ratio of the actuator stroke to the total string length). In all of the previous research works, the contraction ratio never exceeded 25%. In our recent study, we showed that it is possible to use an “overtwist phase”, to increase the contraction ratio to as much as 80% [16]. Integration of such system, resulted in the current version of the UC-Softhand, that weights only 280 g, which is probably one of the lightest functional bionic hands with electrical motors, that have been introduced so far.

2. ISR-Softhand

Here, we briefly describe the ISR-Softhand. ISR-Softhand is an adaptive bionic hand that embeds elastic joints and soft elements. For more information, readers are invited to see [12]. Figure 1 shows the bones and name of the joints of a human hand that will be used further in this paper. Figure 2 depicts the conceptual design of the hand. As can be seen in Figure 2, in the ISR-Softhand each finger is composed of MCP and PIP joints and does not include the DIP joint. The thumb is composed of CMC and MCP joints. Thereby the hand has a total of 10 joints.

Figure 3 shows the first prototype of the ISR-Softhand. Except the thumb abduction-adduction joint, all other joints are composed of elastic materials. Each finger has a single tendon, which drives the MCP and PIP joints simultaneously in order to perform the finger flexion. The PIP joint is designed with a higher stiffness compared to the MCP joint. In this way, if the MCP joint is blocked (meaning that the first contact with the object is established) the tendon force is applied to the PIP joint and thereby the PIP closes until surrounding the object.

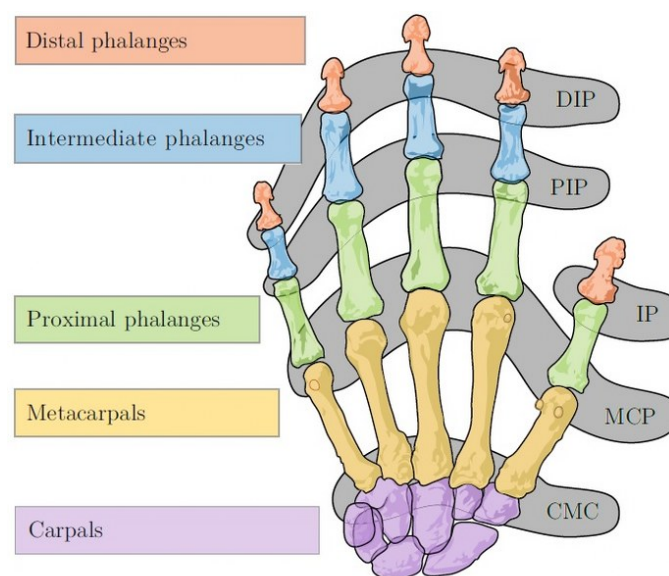


Figure 1. Bones and joints of the human hand, DIP—Distal Interphalangeal joint; PIP—Proximal Interphalangeal joint; IP—Interphalangeal joint; MCP—Metacarpophalangeal joint; CMC—Carpo-Metacarpal joint [27].

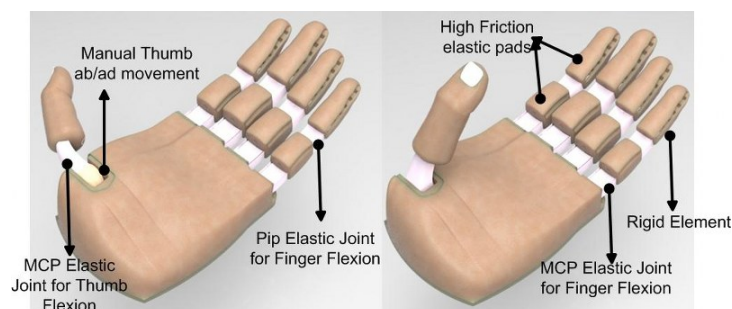


Figure 2. Conceptual design of the Softhand: Each finger is composed of MCP and PIP joints and does not include the DIP joint. The thumb is composed of CMC and MCP joints. Except the non/actuated thumb abduction/adduction joint, all other joints are fabricated with elastic materials.

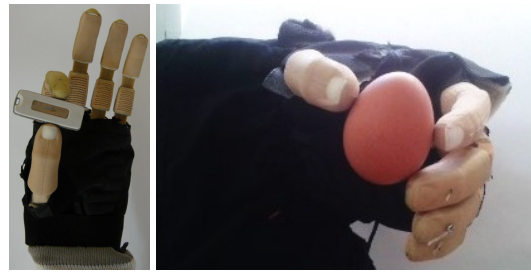


Figure 3. ISR- Soft hand performing a tip pinch grasp and a tripod grasp.

In terms of actuation, ISR-Soft hand has three actuators, one actuator (Actuator 1) is dedicated for flexion of the index finger and another actuator (Actuator 2) was integrated for flexion of the thumb. A third actuator (Actuator 3) is considered to simultaneously drive the flexion of the resting three fingers. The rotation movement of the thumb is performed manually by the user, meaning that the thumb can stay at two rest positions at both extremes. Figure 3 shows the prototype of the ISR-Soft hand.

3. The UC Hand

The kinematics of the UC-Soft hand is similar to the ISR-Soft hand (Figure 2). The thumb is composed of the CMC and MCP joints. However, the ab/ad movement of the thumb is not manual anymore and is actuated. The fabrication process of the fingers was slightly modified, but the actual kinematics maintains same.

The UC-Soft hand differs from the ISR-Soft hand in four subjects

- The design and fabrication of the fingers
- The actuation Strategy
- The actuation mechanism
- The Mechatronics and the control architecture

3.1. Design and Fabrication of the Fingers

In the ISR-Soft hand, MCP and PIP joints are composed of elastic joints as can be seen in Figure 4. For the objectives of the project, such as anthropomorphic appearance, a finger similar to the one of the human, is highly desirable. It is desired to have

- An anthropomorphic appearance, *i.e.*, the fingers look like a human finger
- Continuous contact area
- Minimal lateral deflections

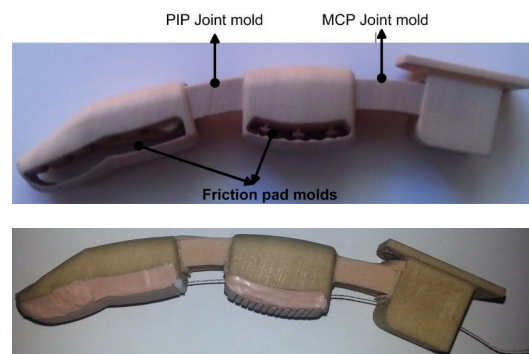


Figure 4. First fabrication methods: The 3D printed index finger before casting the Urethane rubber (**up**); the finger after casting (**down**).

Therefore, we created a method based on a reusable mold that resembles a human finger appearance. The new fabrication process is depicted in Figures 5 and 6. In this approach an internal endoskeleton is first fabricated by a 3D printer. As can be seen the PIP and DIP joint of the bone area actually thin elements with some reinforcement which are designed for minimizing the required force for flexion of the force, as well as minimizing the undesired lateral deflection of the fingers due to lateral forces. The bone is then filled with a low stiffness material such as sponge and then it is placed inside a mold. The mold for the middle finger was designed based on a point cloud from 3D scan of an adult human finger. The length of the middle finger is 10.5 cm. The indicator, ring and the little fingers were created as a 0.9 scale of the middle finger. The original mold from the 3D scan of the human finger had to be slightly modified for a better surface quality when 3D printed. Afterwards, the resin is cast in the mold. In this way the finger is covered with a compliant material that helps in the creation of bigger contact surfaces with different objects, and also provides a more anthropomorphic look.

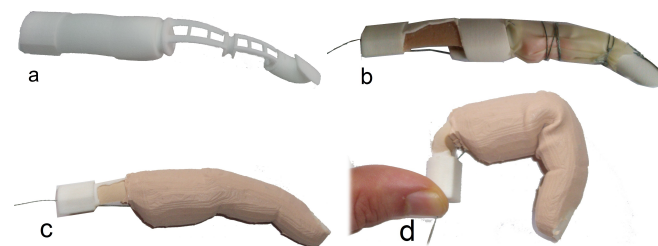


Figure 5. The new fabrication process of the fingers with the second approach—(a) A 3D printed endoskeleton embeds the elastic MCP joint (b) Then the PIP and DIP joints are filled with sponge and covered by an sealing sleeve (c) The exterior surface of the finger is formed by casting a resin in the mold (d) The finger bending.

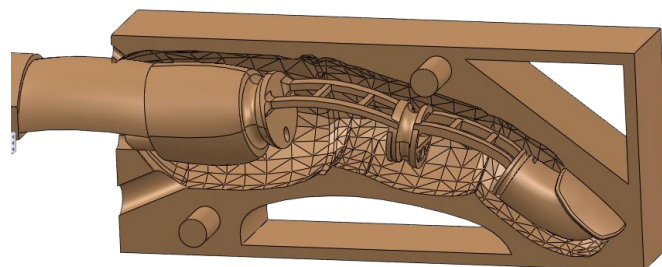


Figure 6. The internal surfaces of the mold are created from 3D scan of a human hand.

3.2. The Actuation Strategy

We performed an analysis on the actuation strategies of minimally actuated hands, *i.e.*, bionic hands with less than five actuators [28]. In that analysis we defined 15 different actuation strategies with less than five actuators and analyzed their performance against two benchmarks. The analysis was performed based on two benchmarks; The grasp diversity and the grasp functionality. The former is based on the number of achievable grasps from a comprehensive grasp taxonomy [7] that lists 33 different grasps that humans do in daily tasks. The latter benchmark is based on the grasp frequency and the highly used grasps [6]. Details of this analysis can be found in [15,28]. Based on this analysis, we found out that the actuation strategy has a very important role in increasing the number of achievable anthropomorphic grasps. For instance, we found out that the thumb's rotation movement has a very important effect on this aspect. Based on the results of that study, the actuation strategy for the UC-Soft hand was selected as below.

- Actuator 1: For rotation of the thumb
- Actuator 2: For flexion of the thumb and the index finger
- Actuator 3: For flexion of the other three fingers

Compared to the ISR-SoftHand, this means that the number of actuators kept equal, however the thumb's rotation is actuated, however the flexion of the thumb and the index finger are coupled and actuated by a single actuator. In this way, the new actuation strategy enables a higher functionality index compared to the ISR-SoftHand (64% vs. 55%). For more information on the definition of this index, the reader is invited to see [6,28].

3.3. The Actuation Mechanism

The actuation mechanism is probably the most important breakthrough in this version of the hand. As mentioned in the introduction, we studied a new version of the twisted string system with an overtwist phase, which allows development and integration of a compact system within the hand's palm. This mechanism and the Mechatronics structure of the hand will be described in the next section.

4. The Two-Phase Twisted String System

4.1. Concept

Figure 7 shows the schematic of the twisted string system used in the hand. It is composed by a motor, strings, a separator and the connection between the motor shaft and the strings. The role of the separator is to limit the zone where the strings can twist. In this way, beyond the separator there is only linear motion. The zone between the shaft and the separator (Figure 7) is called the twisting zone.

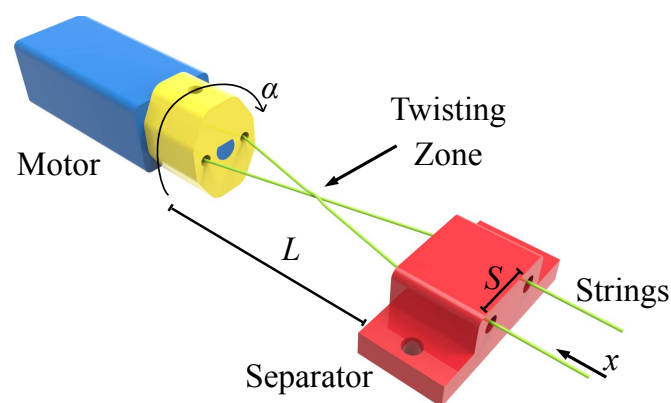


Figure 7. Twisted string system. With an electric motor (blue), strings (green), connection between motor shaft and strings (yellow) and separator (red). Where L is twisting zone length, α is the rotational angle of the motor shaft, x is the linear displacement of the strings and S is the distance between the holes of the separator.

In [16], we proposed a system with two twisting phases, an initial phase where the strings twist around each other, and a second phase, called the overtwist phase, where the strings form a bundle and twist together. In this way we achieved contraction percentage as high as 81% without having untwisting problems (Figure 8). The contraction percentage is defined as the amount of the total linear contraction on the overall system length (without actuators). This means that in order to be able to achieve a linear displacement of 20 mm, the twisted zone can be as small as 5 mm, which makes the overall system length equal to 25 mm (excluding the actuator). In addition we achieved extensive life cycle tests and showed that for a constant load, the total linear displacement of the twisted string actuator is almost constant. That means that using the overtwist phase reduces the total number of cycles as it also results in a higher displacement, however it does not accelerate the string wearing [16].

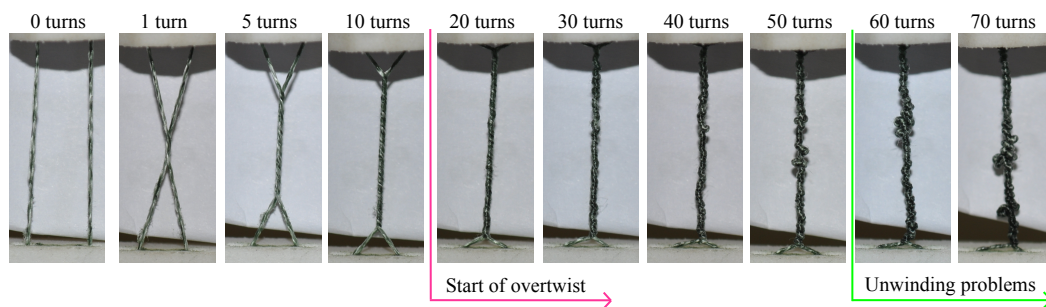


Figure 8. Twisted string system with an overtwisting phase.

4.2. System Requirements, Design and Integration

It should be also noted that the twisted string system, can only insert the pulling force that closes the fingers. Opening of the finger is achieved automatically when there is no external force applied to them. This is due to the elastic properties of the endoskeleton and the form of the elastic skin around it. Both these are easily customizable. The original shape of the endoskeleton and the shape of the mold determines the default position of the fingers when no external force is applied. Moreover, since the twisted string system is non-backdrivable, if the motors are turned off in any state of the finger closure, the fingers will hold their shape. Fingers do not return to their default shape if we solely turn off the motors in a close status. For the fingers to be able go back to their default position, the gear motor should untwist the strings.

Figure 9 shows the model of the integrated hand. It is composed of three gear motors, two for the twisted string systems (Pololu 30:1 Micro Metal gear motor HP), and another one for the thumb’s rotation (Pololu 298:1 Micro Metal gear motor HP). We have also integrated two absolute magnetic encoder (AS5045 12 bit Rotary Sensor with digital interface-Resolution 0.088°) on the pulleys of the twisted string system and another absolute magnetic encoder on the output shaft of the gear motor for the thumb. Being a single turn absolute encoder installed on the output shafts, this encoder eliminates error sources in the transmission mechanism and provides an accurate position feedback for the position control loop of the gear motors. One of the twisted string actuators drives the flexion of the index finger and the thumb, while the other system is connected to the tendons of the other three fingers. Figure 10 shows the implemented prototype of the system. The palm and all plastic parts were 3D printed.

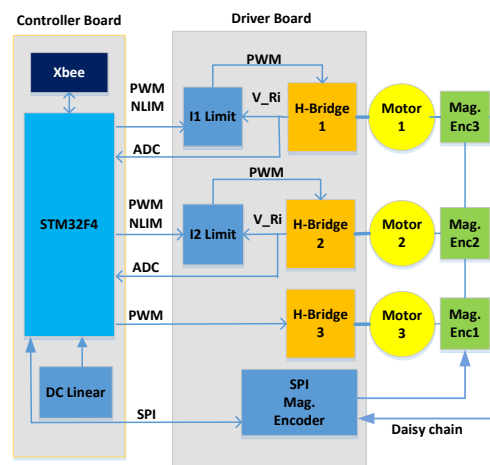


Figure 9. The schematics of the mechatronics system of the UC-Soft hand is composed of drivers for gear motors with current measurement and current limiter, a Daisy chain of magnetic encoders and an ARM Cortex-M4 STM32 Microcontroller.

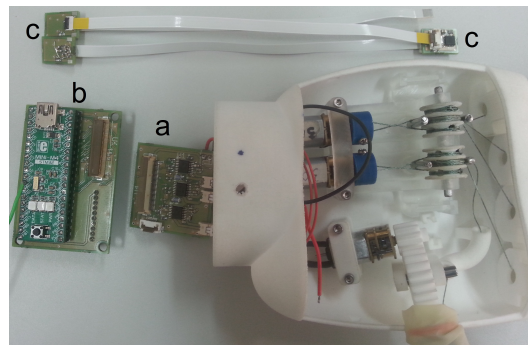


Figure 10. The home made miniaturized electronics. (a) The drivers PCB, composed of motor drivers and input for magnetic encoders (b) The control PCB composed of a STM32 ARM Cortex-M4 STM32 Microcontroller, and a X-bee communication (on the back of the board); (c) The daisy chain magnetic encoders boards.

4.3. The Mechatronics and the Control Architecture

Figure 9 shows the block diagram of the Mechatronics system integrated in the soft hand. This includes a driver board and a control board (Figure 10). In order to fit inside the palm of the hand, the driver board was designed and assembled in our lab with the objective of minimizing the overall dimensions. The driver board contains the circuits to power the motors, measure and limit the motor's current and the encoder's comparators. This board is placed on the inside of the artificial hand (next to the motors). The control board is designed to be placed near the elbow of the amputee along with the battery and is connected through a thin flat cable to the inner board. It contains an ARM Cortex-M4 STM32 Microcontroller and the regulated power supply. Currently, this board communicates through a X-bee unit with a PC, which is used to send the control commands to the hand. In the future development this unit will not be necessary and instead signals from EMG sensors that are installed on the forearm of the amputee will be sent and processed in the external board. We also designed, developed and integrated three magnetic encoder boards that contain a sensor which detects absolute angular orientation of the pulleys that are used for flexion of the fingers or rotation of the thumb. Taking into account that none of the pulleys rotate a full turn, the absolute magnetic encoder can report the absolute position of the shafts at any time.

Two of the drivers that are dedicated for flexion of the fingers can measure and limit the current in order to resemble a force control loop. Figure 11 depicts the current measurement and limiting procedure. This feature can be used both as force limiter and motor protector. As depicted in Figure 11, the current measurement circuit outputs a voltage proportional to the motor current to a comparator circuit which compares it to the current limit. Then a secondary circuit cuts the power from the motors when needed. This enables a fast response of the limiter because the implementation is done by hardware.

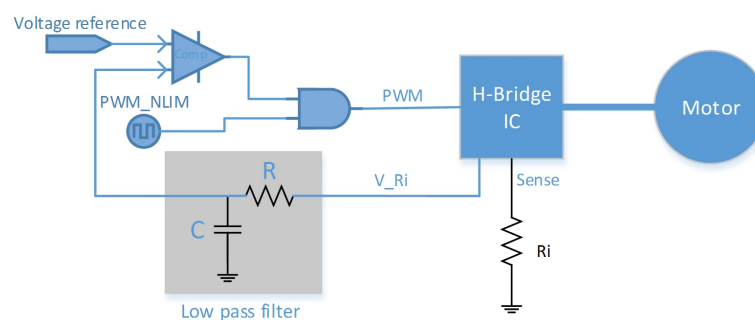


Figure 11. The current measurement and limiting diagram.

5. Results

Figure 12 shows the 3D model of the UC-SoftHand actuation module. Figure 13 shows the prototype of the UC-SoftHand performing some precision and power grasps. Table 1 shows the characteristics of the UC hand. As can be seen, the UC-hand is significantly lighter than the ISR-SoftHand. It weights about half of its ancestor. It includes gear motors that drive the non-backdrivable twisted string system, absolute magnetic encoder, an ad-hoc control unit that is embedded in the palm and enables the possibility of integration of torque control in the loop. Integration of a non-back-drivable actuation system is quite important since it significantly reduces the power consumption in long duration grasps. That is, once the grasp is made, motors will turn off, while the hand keeps its posture. Any change on the posture requires actuation, but maintaining each posture does not. Furthermore, by correcting the thumb's pose and integration of an actuator for the thumb rotation, it was possible to place the thumb at intermediate positions resulting in more anthropomorphic grasps. UC-SoftHand is able to grasp a bottle with a mass of 740 g. When the motors are turned off, the maximum mass that UC-SoftHand could lift reduces to 480 g. The difference between these values is due to the system elasticity and clearance on the shafts and pulleys. When turning off the gear motors, such clearance reduces the effective applied force by the hand.

Adding a small amount of slack to the tendon of a finger, helps us to adjust the closing motion of the fingers. For instance, by adding a small slack to the tendon of the thumb, we guarantee that the index finger starts bending before the thumb. In this way we can guarantee that in spite of different kinematics of the index finger and the thumb a precision grasp can be formed. This means that the two fingers reach each other at the tip.

The twisted string system is able to fully close three fingers that are actuated by the same actuator, *i.e.*, the middle, the ring and the little finger and achieves a contraction of 20 mm in less than 2 s. Based on these requirements and assumptions and the mathematical model presented in [16], we chose the gear motors that can provide the required force and a closing time of less than 2 s.

Two similar twisted string actuators are placed in the palm of the hand. Each of them can pull 52 N. In the current version, the middle, ring and little fingers that are actuated by a single actuator required a total of 36 N to fully close. However, this value reduces to 15 N in order to close up to a point that the hand is able to achieve all precision grasps and most of the power grasps. The index finger and the thumb require 29 N to fully close. Again, this value is only 12 N, for most of the grasps (without counting the grasp force).

As an indicator of how these forces are transferred to the finger tip and the object, we measured also the contact force applied by the thumb. The average force that the thumb could exert was 461.2 N, with a standard deviation of 29.1 N, obtained from 20 measurements. The force was measured for grasping an object of 49 mm (an electrical balance). This dimension is approximate to achieve a power grasp of a small bottle of water. However, it should be noted that the force varies depending on the thickness of the object, since the direction of the force applied by the tendon varies during the full course of the finger's flexion. At the fastest speed the time for full closure is slightly less than 2 s. However, most of the grasps are achieved in less than a second, since most of the grasps it is not necessary to fully close the fingers.

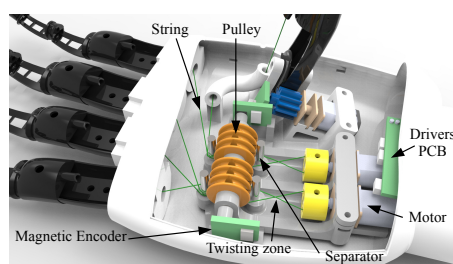


Figure 12. 3D model of the UC-SoftHand.

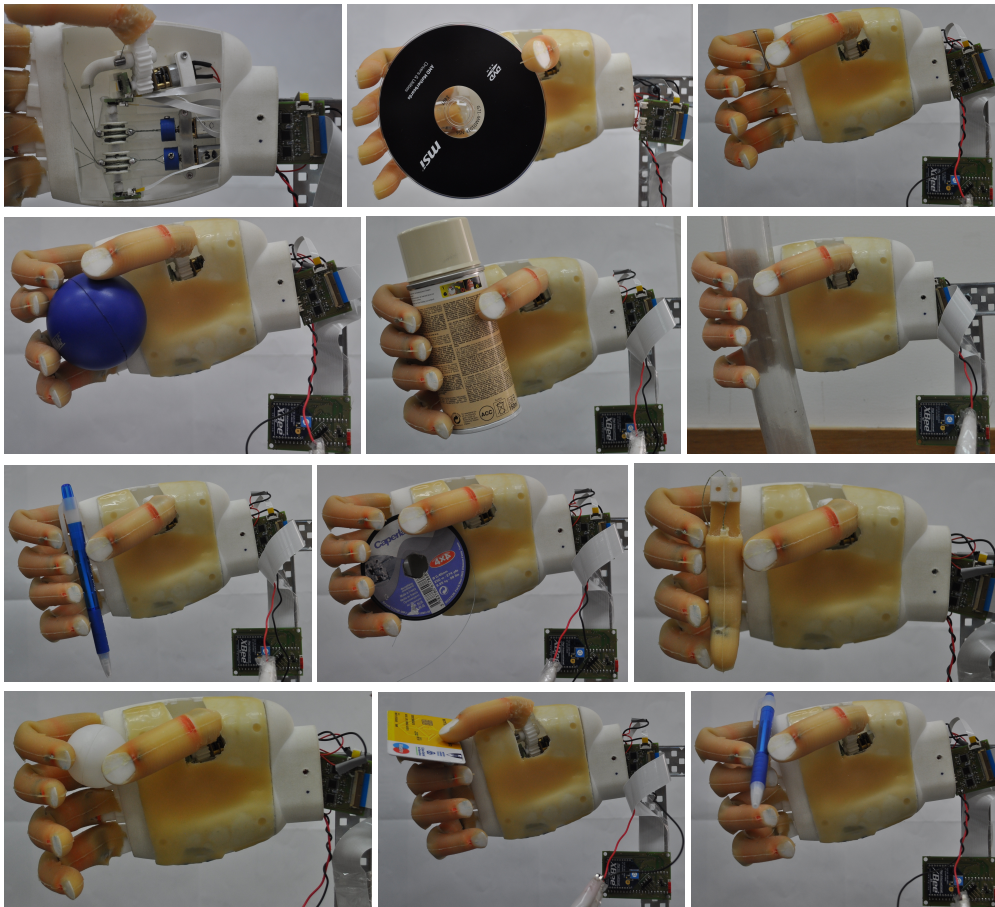


Figure 13. Prototype of the UC-SoftHand and achieving several precision and power grasps. The hand is able to grasp objects as large as a CD. Since the thumb and the index finger are operated with a single actuator, the tendon's slack is adjusted in a way that the tip of both fingers can achieve a precision grasp, such as grasping a tiny screw. The thumb's rotation enables lateral pinch grasp such as grasping a credit card.

The novel fabrication method of the fingers allowed for the integration of a compliant skin all over the fingers, which resulted in improved grasping and more anthropomorphic look compared to the previous version.

Table 1. Characteristics of the ISR-SoftHand and the UC-SoftHands.

	ISR-SoftHand	UC-SoftHand
Number of DOFs	10	10
Number of Actuators	3	3
Size (mm)	230 × 100 × 80	230 × 100 × 40
Mass [g]	530	280
Reduction Mechanism	Gears	Gears and the Twisted String System
Control	Position	Position and Torque
Non Backdrivable?	No	Yes
Actuated thumb rotation	No	Yes

6. Conclusions

In this paper, we presented the integration of a light-weight, low cost, non-backdrivable and compact twisted string system, which allowed development of the UC-Softhand with several improvements over its ancestor, the ISR-Softhand. The significant weight reduction (47%) compared to the ISR-Softhand, made the UC-Softhand, one of the lightest actuated hands that have been developed so far. Furthermore, the UC-Softhand consumes less energy due to its non-backdrivability, and finally it has a lower cost thanks to the twisted string system. The total bill of materials for this version of the hand is under 300 USD. Furthermore, the UC hand is more anthropomorphic (in terms of the appearance and the grasping posture), compared to its ancestor. We are currently focusing on two main research tasks: First, integration of tactile sensors on the fingers in order to obtain the contact force feedback and feed it into the control loop, and take advantage of the current limiting feature for control of the contact force. Second, the EMG based control of the hand.

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Author Contributions: Mahmoud Tavakoli, is the team leader and has contributed to the overall conceptual and detailed design of the soft-hand, the twisted string actuation mechanism, as well as system integration. Rafael Baptista, has contributed in the characterization and implementation of the twisted string system. Lucio Sgrigna, has contributed to the development of the dedicated electronics for the board.

Conflicts of Interest: The authors declare no conflict of interest.

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