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SMA Actuated Low-Weight Bio-Inspired Claws for Grasping and Perching Using Flapping Wing Aerial Systems

A.E. Gomez-Tamm[1,*], V. Perez-Sanchez[1,*] , B.C. Arrue[*] and A. Ollero[*]

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Abstract— **Taking inspiration from nature, the work presented in this paper aims to develop bio-inspired claws to be used for grasping and perching in flapping-wing aerial systems. These claws can be 3D printed out of two different materials and will be capable of adapt to any shape. Also, they will be soft for avoiding undesired damages on the objects when performing manipulation. These claws will be actuated by shape memory alloys (SMA) springs to get rid of the weight of traditional servos. The design of all the components will be explained in this work. Also, the challenges of being able to control SMA using only a LiPo battery on an aerial vehicle will be exposed. The solutions applied and electronics used will be also described. Lastly, experiments made both in test bench as on flight will be summarized.**

UAS, Bio-inspired, Soft Robotics, SMA, Aerial Manipulation, Flapping Wing

I. INTRODUCTION

Aerial manipulation has been a trend in the last years. Strictly related to the exponential increase of the use of unmanned aerial systems (UAS) the capability of performing manipulation with those systems, especially with multirotors, has been evolving over the years in research and industry. Additionally to multi-rotors and fixed wings systems, flapping wings have gained prominence. However, flapping wings have important payload limitations. Therefore, using traditional actuation methods for performing manipulation is nearly impossible

Looking in the state of art, it can be seen that the first publications related to aerial manipulation started at the beginning of the second decade of the 21^{st} century.

As multirotors were too limited in terms of payload for this type of early manipulators, helicopters where used. In [1], [2] it can be seen how these systems were used for carrying some customized end-effectors. Even big industrial robotics arms [3] where loaded in these big sized aerial systems. These made it possible to add many degrees of freedom (DoF) to the systems [4]. Also, some researchers studied the challenge of performing manipulation with multiple aerial systems [5].

The problem with the helicopters was their large size and weight. They are dangerous for being used in reduced space environments or co-working tasks with humans. So, reducing the size and weight was an aim from the beginning of this research field.

[1]A.E. Gomez-Tamm and V. Perez-Sanchez contributed equally to this work

[*]GRVC Robotics Laboratory, University of Seville. Avenida de los Descubrimientos S/N 41092 Spain agtamm@us.es, vicpersan@alum.us.es, bcarrue@us.es, aollero@us.es

One example can be seen in works like [6] where the intention was to develop actuators for mini UAV. Other works did similar approaches, like [7] trying to develop mechanical designs for unmanned aerial vehicles (UAV). Also, the reliability [8] and control [9] of these actuators where studied. So, some robotic arms like [10] could be developed.

This has allowed the development of some lightweight applications, trying to reduce the payload embedded at the UAV like [11], an aerial manipulator with the goal of achieving more miniaturization of these devices. Doing so, the risks for human operators is reduced and the systems can be used in environments with limited space for performing aerial maneuvers, like indoor industrial environments.

Optimizing the design, it has been possible to develop robotic arms with several DoF, while minimizing the weight [12]. However, the traditional actuation systems, normally servomotors, are reaching mechanical limits that make them impossible to reduce more in terms of size and weight without losing most of the force they can exert.

It can be seen in some surveys [13], [14] how the evolution of aerial manipulators (AM) for industrial applications always looks to increase in maneuverability and safety, principally by reducing weight and size.

Thus, as the limit of traditional actuators has been reached, alternatives should be studied. Continuing with multirotors, some projects have tried to develop landing gears for performing landing on the structure where the manipulation has to be performed so that energy can be saved [15], [16].

However, when speaking about flapping wings, the payload restriction made it impossible to even use these optimized low weight systems. Performing manipulation, even grasping an object or perching, is nearly impossible using traditional servomotors, as the weight/force ratio is limited. For that reason, some alternative actuation systems, based in different materials properties and mostly related to soft-robotic applications have been studied [17], [18].

In this work, the decision was to use shape memory alloys (SMA) springs as linear actuators. As studied in [18] there are many possible actuators in the state of art. However, the requirements for the application presented needs some specific properties.

Firstly, a low weight is required so that the flapping wing system is capable of takeoff with the payload. Secondly, enough force for performing the actuation of the designed claws. Lastly, the actuation performed should have enough displacement for closing the actuator around the desired object and keep it closed. So, SMA seems to be the ones that cover these requirements.

These materials have been studied over the last decades, starting in the last years of the 20^{th} century [19], [20], [21], [22]. In these works, the behaviour of these materials where characterised. Also, the materials they were made from where presented and the different properties of the different material combinations where summarized. The most used material combination is an alloy of nickel and titanium, named Nitinol. However, this alloy can be reinforced with a low percentage of other materials (for example Cooper, Aluminium or Zinc) to increase some specific properties.

Nevertheless, one of the most interesting conclusions of the above work is the existence of two different types of SMA. The one-way and the two-way SMA. The difference between them is that one-way SMA tends to regain its original shape when heated and maintain that shape when cooled down so that an external force is needed to deform them. Two-way SMA recovers their original shape when heated, but regain their deformed shape when cooled down.

Regarding potential applications of SMA, many types of research have been done. Starting with potential medical applications [23] but also for non-medical [24]. Although the main objective of this work is to use them as actuators, where different researches have been done [25].

Recently works like [26] have presented SMA potential and in [27] it is proved how they can be used in a high-frequency application, reaching up to 35Hz frequency movement.

The use of SMA as actuators has been presented in many kinds of research. In [28] thin-film shapes of SMA for developing micro-grippers and micro-valves were presented.

But also bio-inspiration and soft robotics have involved the use of SMA. In [29] Nitinol springs are used for developing a mesh worm prototype. This work has been improved over the years in several publications [30], [31].

Focusing on aerial applications, some work has used SMA for performing fixed wings morphing. Several works have been developed like [32] using SMA ribbons, [33] a review of potential uses for wing morphing and others like [34], [35]. In [36] also winglets are controlled using SMA. Lastly, landing gear was developed in [37] for small UAS, actuated by SMA. However, no aerial actuators and end-effectors are using SMA for performing manipulation and perching from aerial systems, like the one presented in this work.

The rest of the paper is structured as follows. Section II will present the system overview, describing the aerial system where the actuators will be embedded and also the bio-inspired end-effectors developed for performing the different manipulation tasks. Section III will focus on the electronics used for being capable of making use of these actuators on the flight. In Section IV the experiments developed for validating the use of these actuators will be summarized and explained. Finally, Section V will show the conclusions of this work and the future research lines that can be developed from this point.

II. SYSTEM OVERVIEW

This section presents the hardware used for performing the experiments that will be described in Section IV. In particular, the ornithopter used will be presented and their characteristics will be enumerated. After that, the designed bio-inspired end-effector and the rest of the hardware components will be presented. Their manufacturing process and characteristics will be detailed thoroughly.

A. Aerial platform

The aerial system consists of a commercial ornithopter from the company CarbonSail. It consists of a carbon fiber frame with a realistic eagle shape. The front tip is reinforced with three-layered carbon fiber to increase durability. The wings are attached to the frame with a 4mm carbon fiber rod using a lock made out of Aluminum. The tail is also supported by carbon fiber plates and actuated with two tiny servomotors. The wingspan is 1.5 meters. The wings are actuated with a gearbox made out of plastic and powered by a brushless motor.

Fig. 1: Complete aerial system with bio-inspired claws

This ornithopter has enough payload capabilities, due to his wingspan, to embed the small manipulators to be used in this work. Also, their robust design ensures reliability and sturdiness in case of crashes. However, due to its low aspect ratio, as shown in Table I, the maneuverability is reduced. Despite that, the size is small enough for considering it a medium-sized aerial system, capable of performing flight in reduced spaces.

In [38] the authors characterized the physical and kinematic data of the above ornithopter, which can be summarized in Table I.

Parameters	Values
Mean chord length of each wing	0.455m
Aspect ratio of each wing	1.42
Mass of the ornithopter	450g
Flight speed of the ornithopter	10-25km/h
Range of wing-beat frequency	3.5-4.5Hz
Reynolds number based on tip speed	5.8-7.5 m/s: 174.641-225.829

TABLE I: Physical and kinematic data of the ornithopter

The data in Table 1 were used in the design and positioning of the hardware and also for valuing the performance of the developed applications.

B. Handling Claw

The design of the end-effector takes inspiration from the design of eagle claws. So, the design consists of a claw with four fingers disposed of in a configuration imitating one of the birds.

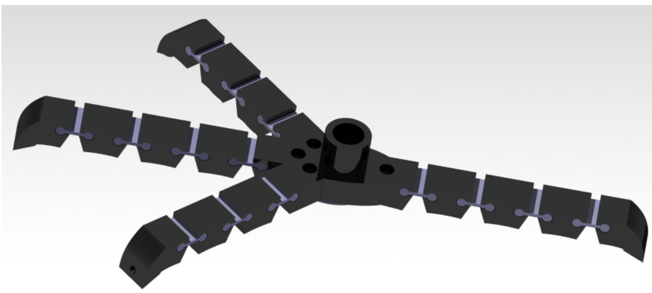

Fig. 2: Four finger bio-inspired model

The materials used to manufacture this claw are polylactic acid (PLA) and thermoplastic polyurethane (TPU). The first one, very used in 3D printing, adds stiffness to the rigid parts of the claw, the phalanges and the base of the claw. The second one is much more elastic and allows large deformation without breaking and recovering their original shape when the external force disappears. So, it is ideal for making the unions that will link the phalanges. This adds elasticity and makes the system compliant. It also reduces the rigidity of the claw and allows it to easier adapt to different shapes.

Taking advantage of the TPU properties, it was also decided to add fingertips out of this material to the base of the phalanges. Consequently, more friction is achieved due to the elasticity of this material, compared with leaving only a PLA fingertip. This makes it easier to grasp objects and adapt to the shape like a real hand o claw, deforming the fingertips. To add even more friction to the claw, a thin layer of Ecoflex, a viscous elastomer, was added over the TPU fingertips.

The idea is to move the four fingers with tendons located inside the phalanges and that is actuated directly with SMA. Concerning the four-finger configuration, it is important to remark that the two central ones are longer than the two on the side. This decision is not arbitrary and takes again inspiration from birds. Normally, this four fingers configuration uses the two central fingers for performing the grasping or perching and the two exterior fingers are used to keep the equilibrium of the grasp, avoiding the bird to fall when perching or to drop an object when grasping it. So, the design also intends that the fingers fulfill this in the designed end-effector.

Related to that, the modular design of the claws allows it to easily add phalanges for allowing the grasp of larger objects and also to change phalanges with different closing angles for better adaptation to the desired aim.

Fig. 3: Ornithopter center of mass and hardware distribution

Regarding the location of the claw in the ornithopter, taking the work of [38] into consideration, the most favorable position of the claws in the system is near to the center of mass. In Figure 3 the best center of mass position can be observed. This position is in the aerodynamics center of the wings. In this position, the claw needs to perform the minimum efforts to keep the equilibrium. This situation is very important in two cases. Firstly, during the flight, where it can hold different objects having the minimum disturbances. Secondly, in pre-flight or post-flight situations, where it needs to keep the equilibrium of the system on different landing platforms.

The shape memory alloys are located under the ornithopter. The claws are aligned vertically with the center of mass so that the horizontal efforts are minimal. Another advantage is that SMA is actively refrigerated due to the forced convection with the air. This situation makes it possible to perform faster actuation cycles.

C. Shape memory alloys configuration

The characterization of the behaviour of the SMA is precisely described in [39]. The equation that describes the relationship between the mechanic variables of the material and the martensitic transformation degree can be observed on it. This is significant, as the change from martensitic to the austenitic configuration of the Nitinol is the reason for the SMA properties of changing their shape when heated. This can be expressed as:

$$\begin{aligned} \sigma &= D\epsilon + \Omega\xi + \theta T \\ \sigma - \sigma_0 &= D(\epsilon - \epsilon_0) + \Omega(\xi - \xi_0) + \theta(T - T_0) \end{aligned} \tag{1}$$

Where σ is the Stress, D is the Young Modulus, ϵ is the strain, Ω is the Phase transformation tensor, ξ is the degree of martensitic transformation, θ is the thermoelastic tensor and T is the temperature.

As described in the previous Section, SMA comes in different shapes (threads, springs, sheets, rods, etc.) and even present different properties depending on the materials they are made from (one-way or two-way SMA). Therefore, one of the first steps in this work was to decide which shape and type of SMA should be used. The desired properties for being capable of actuating the claw are high force and high displacement. As the force directly depends on the diameter of the SMA, it was clear that the thickest thread possible should be used, so that the force that could be applied was maximized. To ensure high displacement, the best option was spring, as not only the payload but also space is limited on the ornithopter. A spring allows high displacement in a compact shape.

A typical actuation cycle of a Nitinol spring is described in [29]. This behavior can be expressed as:

$$\begin{aligned} \delta_{effective} &= \delta_M + \delta_L - \delta_H \\ \delta &= \frac{8FD^3n}{Gd^4} \\ \delta_M &= \frac{\pi\gamma D^2 n}{d\kappa} \end{aligned} \tag{2}$$

Where F is the load, D is the spring diameter, d is the wire diameter, n is the number of active coils of the spring and G is the shear modulus after annealing. For calculating the change of free length,δ_M, of the spring when it changes from austenite to martensite phase, the variables needed are γ which is the shear strain of the spring, τ which is the shear stress and κ which is the stress factor. So, to get the effective displacement $\delta_{effective}$ the following equation is used.

$$\delta_{effective} = \frac{\pi\gamma D^2 n}{d\kappa} + \frac{8FD_{eff}^3 n}{G_M d^4} - \frac{8FD^3 n}{G_A d^4} \tag{3}$$

The coil diameter is reduced when the spring is extended in the martensite phase. For this reason, an effective spring diameter D_{eff} is used.

It is also interesting to remark that the force exerted by the spring is dependent on the elongation of the spring. Being so, it is important to keep an elongation enough for performing the force desired. Figure 4 shows the relation between temperature and strength with different pre-elongations (increased length from the compressed shaper) of two different springs.

The SMA used in the graphic on the top of Figure 4 has a smaller size than the one used on the bottom. The first one was used in a previous version of the claw. Regarding the information on the graphic, the second one can exert a higher strength than the first one. It is also interesting to remark that the second spring is capable of reach higher forces with much less temperature applied. In terms of weight, the second spring is only twice heavier but can apply almost ten times the force of the other. The difference in size can be seen in Figure 5.

The size of the springs is one of the most important parameter in order to characterize the actuation. The size includes the undeformed length and the diameter of the spring and also the diameter of the wire. In Table II the size parameters of the Nitinol springs are presented.

Concerning the type of SMA used, in the case of the application developed in this work, the objective is that the claw keeps closed or open with the minimum energy

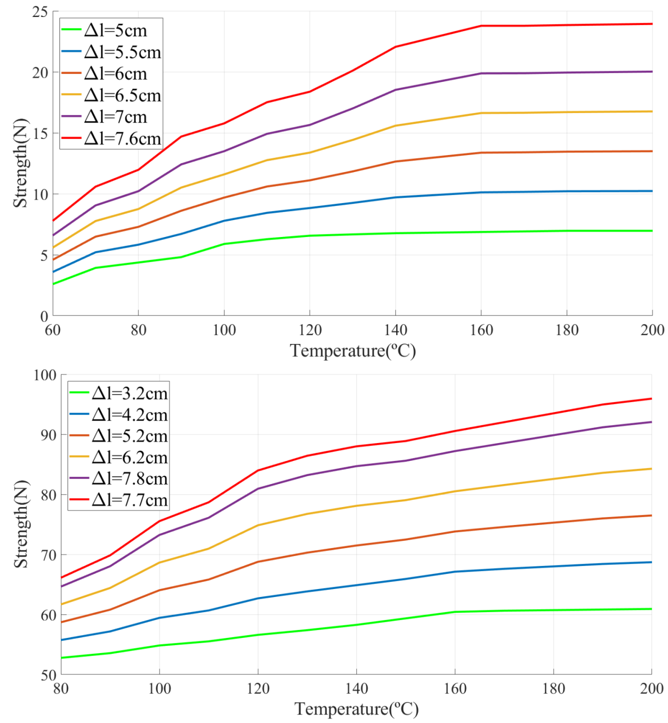

Fig. 4: Comparative between Strength, Initial Deformation and Temperature. The variable Δl is the difference between the elongated and compressed length

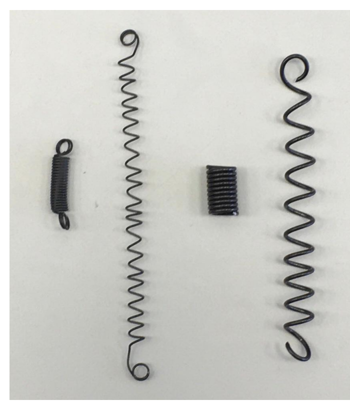

Fig. 5: Size comparison of two different Nitinols springs in compressed and elongated shape

Parameters	Spring 1	Spring 2
Undeformed length(cm)	2	1.7
Spring Diameter(mm)	6	10
Wire Diameter(mm)	0.75	1.5

TABLE II: Size parameters of the Nitinol springs

consumption. So, the use of one-way SMA is the logical decision, as it will not recover the deformed shape when cooled. However, as the claw should also be opened for being capable of dropping objects or regain flight after perching, a muscle antagonist configuration is used. This, taking also inspiration from the placement of muscles of real animals, allows to open and close the claw heating the antagonist muscle spring.

Due to the high temperatures reached by the SMA springs, it is necessary to use tendons that can resist the heat and also the force produced by this type of actuator. Therefore, the decision was to use Kevlar threads, that provide high tensile strength and thermal resistance.

Also, a finger tension adjuster was designed so that it could be possible to easily adjust the tension of each finger, making it easier to adapt to different grasping configurations and hold very different objects.

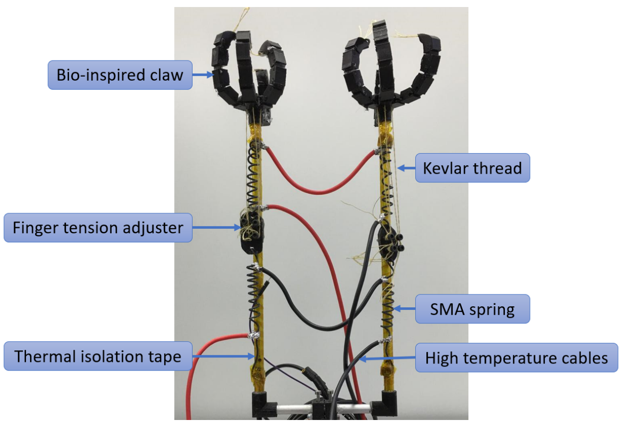

Fig. 6: Embedded system description

The springs are located on a leg out of aluminum and isolated from each other with a non-conductive and thermal resistant insulating tape, to avoid overheat and electrical conduction.

Figure 6 shows the disposal of all the above-described components.

The next Section will introduce the electronics used for controlling the actuation of the SMA and the claws.

III. ELECTRONICS AND CONTROL

This section presents the electronics chosen for being capable to control the actuation of the SMA spring using as a power source a LiPo battery that can be carried by the ornithopter. First, the electronic components will be presented and described. After this, the electronic schematic will be presented and the control system explained.

A. *Electronic components*

Firstly, a micro-controller for activating or deactivating the actuation cycle was chosen. For test bench experiments, any could be used, but due to the payload limitations at the ornithopter, the best decision was to choose an Arduino Nano. Thanks to their very small size and weight and their easy programming framework.

Despite that, the biggest problem encountered is that the energy source for heating the SMA should be a LiPo battery that can be carried by the UAS. As the resistance of the SMA is dependant from the temperature, changing from 0.5 Ohms in room temperature to 0.05 Ohms, or even lower when nearing 180 ºC. The Ohm law shows that $V = IR$ and knowing that the tension of the LiPo batteries are multiples of 3.7 Volts, using, for example, a 2S battery with 7.4 Volts the max current generated would be around 128 Amps. Knowing that the power is $P = VI = I^2R$ this would imply a power of nearly 800 Watts. Obviously, this is impossible for a small LiPo battery. The battery selected for being embedded in the UAS is a 2S of 600mAh and a discharge rate of 50-100C. Even with these good specifications, the maximum peak current it could resist would be 60 Amps. So, connecting the battery directly to the springs with a switch and closing the circuit would immediately contract the actuator, as the battery would try to give the maximal power possible, but would heavily damage the battery after few cycles and even cause it to explode.

For this reason, some components are needed for controlling the energy output. A power limitation that restricts the power given by the battery and an electronic switch that opens and closes the circuit that feeds the actuators. The switch must be duplicated for actuating the muscle and the muscle antagonist.

There are some commercial solutions for regulating the power output. However, the payload limitations do not allow the use of any kind of high power elements commercially available. This is due to the dissipation components needed for these circuits, which add an unaffordable load.

Therefore, the decision was to measure the resistance needed for limiting the output power and to use high power resistors capable of enduring up to 100W of continuous voltage. As the activation cycles are limited to a few seconds, this resistance can resist even higher power outputs and save weight, as the time is short enough for not overheating the system. Due to the high dissipation efficiency of these components, the heat dissipation is similar to one of the commercial current regulators. To control the actuation cycle, a low weight relay activated by a micro-controller was chosen. The relay will be limited by the maximum load current supported.

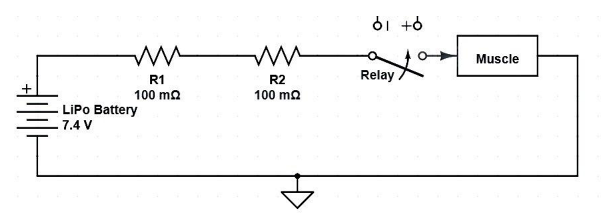

Fig. 7: Electrical schematic

Nevertheless, the power applied to the muscles must be calculated in a range that the SMA contracts quickly enough, so that the claws are closed and opened rapidly while maintaining safe the batteries. So, the maximal Amps that would be allowed by the power limitation are between 30 and 40 Amps, which will be enough to offer fast actuation of the claws.

The decision was to ensure that the maximum current applied would be in the safety range even in the most unfavorable case of the muscle resistance tending to zero. The final decision was to put two 0.1 Ohms resistance in series with the muscle, ensuring a maximal discharge current in the worst case of 37 Amps. The electrical scheme is showed in Figure 7.

Lastly, the radioreceptor, normally used for controlling the ornithopter flight, will be also used to remotely activate the muscle and muscle antagonist for closing or opening the claw.

B. Control system

As shown in Figure 8 the control schematic consists of a micro-controller connected to the electronic relay. When the radio input commands the micro-controller program to activate the actuators, a signal is sent to the relay for activating the actuation cycle.

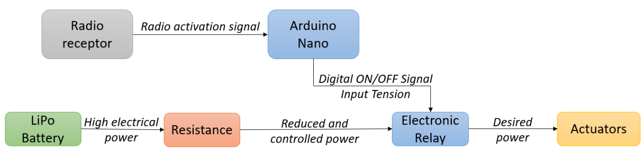

Fig. 8: Electronic control schematic

To avoid activating both muscles simultaneously, the code only allows activating one of them if the other is not activated. As the springs get a high temperature and will try to maintain the compressed shape, a fast open/close cycle of the claw is normally not possible on a test bench. However, the springs are located in front of the leg for allowing forced convection with the air, for speeding up the cooling process of the muscles when flying.

When cooled, an antagonist force of the same order must be applied to lose the compressed shape of these springs. Being so, even with the low efficiency of this type of actuators, it is possible to decrease the energy consumption of the system, as powering the actuators is only needed during small periods, specifically in the process of opening and closing the claws. To maintain them in the same state, no energy consumption is needed.

The next section will show the experiments developed for proving the capabilities of these end-effectors.

IV. EXPERIMENTAL VALIDATION

In this Section, the experiments made for validating the performance of the hardware developed is explained. First, some experiments are performed to demonstrate the performance of the claws on a test-bench, grasping some objects or perching on a rod. After that, real on flight tests are performed, where different objects are held and then released on a flight, showing possible real applications like first aid delivering. Also, a takeoff experiment is presented, using the claws for perching on an elevated structure.

A. Bench tests

For proving the performance of the claws, several grasping tests are made with different types of objects to prove the adaptability of the claw to different surfaces and materials.

So, it has been demonstrated that it is possible to grab different types of objects with the claw. Also, soft materials can be grabbed without being damaged. Thanks to being soft and compliant, the claw does not damage the objects when closing, as the claw will change their form to adapt and avoid to perform too much force on any object grasped.

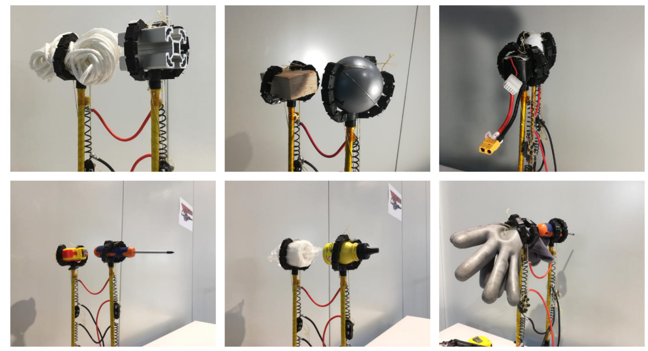

Fig. 9: Claws grasping a variety of objects

In Figure 9 it is shown how the claws grasp different objects with different weights, forms, and sizes. Also, the materials are quite different being more rigid like wood or aluminum or softer like soft plastics or fiber. Potential applications are introduced like first aid delivering or co-working with humans, delivering tools to them.

Fig. 10: Ornithopter perching on a rod

Figure 10 shows the claws being capable of holding the ornithopter on a structure performing perching, which is another application of the proposed claws. The claws are capable of holding the weight of the ornithopter, which is more than 0.5 kilograms. This is a first approach for being capable of performing landing on any surface or performing a takeoff from an elevated position.

To show the complete process of grasping objects or performing perching on a rod, the video attached to this work shows different examples.

B. On flight tests

In this subsection, the use of these claws in real flight is shown. This is a more challenging topic as all the electronics must be embedded on the ornithopter and the communications to activate the actuators must be wireless.

1) Takeoff from elevated position: In this scenario, it is showed how the flapping-wing aerial system is capable of performing takeoff from an elevated position using the claws for holding until it is capable of taking flight. In Figure 11 a takeoff sequence is shown.

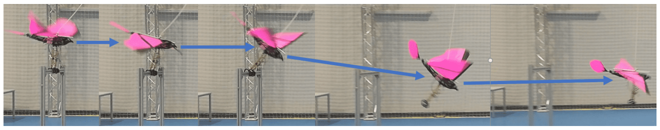

Fig. 11: Ornithopter takeoff sequence

2) Small objects delivery: This experiment shows the capability of the system of delivering small objects to inaccessible areas, grasping them and releasing them when needed. This could be used for an emergency situation where first aid kits could be brought to places using the longer time of flight of the flapping/gliding ornithopter. Also, other objects like tools or ropes could be carried. Figure 12 shows some sequences of the ornithopter dropping objects.

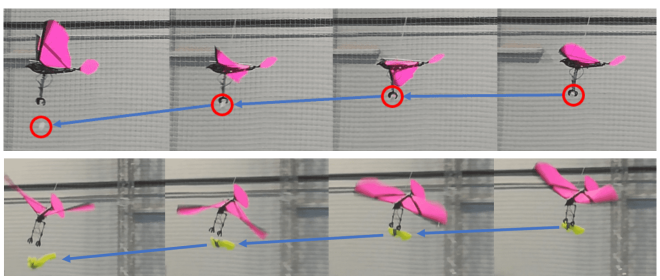

Fig. 12: Small objects delivery sequences

3) Small multirotor release: The experiment presented is the idea of combining the flapping-wing system with a micro aerial vehicle (MAV). As the autonomy of the multirotor makes it impossible to reach high distances, it seems logical to combine it with the flapping-wing system, taking advantage of his larger range. So, the experiment consists of releasing the multirotor on flight opening the claw when desired by the pilot. Due to the characteristics of the claw, it can easily adapt to the drone. The shape and tension of each finger can be easily regulated for better holding. When released, the drone is capable of performing an inspection of the surroundings and transmitting it to the operator. In Figure 13 a small sequence of the MAV release is shown.

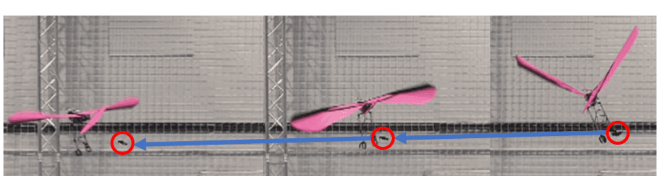

Fig. 13: MAV release sequence

V. CONCLUSIONS

This work has presented the design and development of a bio-inspired grasping mechanism that can be used on flapping-wing aerial systems. It has been demonstrated that avoiding the use of traditional servos, it is still possible to design actuators capable of generating high forces and fulfill various missions. All of that, reducing the weight that would be needed using traditional actuation systems for the same force performance.

The end-effector presented, actuated with SMA, focused its design in being modular, easy to manufacture and compliant, to adapt to several shapes and materials. This has also been proved in this work, being capable of grasping many different objects.

Regarding the SMA, it has been proven that a very low weight spring, is capable of performing several kilograms of linear force and has a good performance as an actuator.

One of the biggest challenges was to be capable of controlling the SMA actuation using small weight electronics and a small LiPo battery that could be carried on the ornithopter, even with these limitations, it was possible to complete the challenge by optimizing all the factors involved.

Therefore, the introduced system offers low weight in a compliant and soft design with a high weight/force ratio and the capability of being transported by a flapping wing system.

This design can be improved. Firstly, the optimization of the design for offering a more stable and aerodynamic flight. Secondly, the adding of one or more joints, for being capable of controlling the angle of the claw for performing perching or inspection maneuvers or for folding the legs after takeoff for improving the aerodynamics. Here, also developing a control system for the SMA, that can control the actuation of each spring for taking the claw to a specific position, will be studied.

Regarding the previously mentioned inspection, the claws' design also allows adding a camera or other sensors at the palm of the claw, so that it could be possible to give visual feedback to the claws while grasping objects, perching or detecting humans in danger for performing the delivery. The use of these sensors combined with the claws will also be a point of research in future works.

The aim is to be capable of offering fully optimized systems that can perform new tasks using flapping-wing aerial systems, applying soft robotics designs and alternative actuation solutions.

ACKNOWLEDGMENT

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