Motor-less and Gear-less Robots: New Technologies for Service and Personal Robots

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Abstract: In the last years, we have been working on exploring alternative actuation technologies for the future service and personal robots. These shall allow designing lighter and safer robots, devoid of conventional mechanical transmission mechanisms i.e. *motor-less* and *gear-less* robots. Here, we summarise our work with Shape Memory Alloys. We show that, despite their known limitations, by finding suitable niches of application, dedicated mechatronics design, and ad-hoc control strategies, SMAs can effectively be used as an alternative actuation technology for robotic systems.

1 INTRODUCTION

The current state of the art on actuation technology is essentially based on hydraulic/pneumatic and electromagnetic technology (servo-motors, gearboxes etc.). Although current commercial actuators have reached a notable degree of refinement, such technologies have their foundations in the mid nineteenth century, and still rely on the same basic principles. We believe that such technology faces several fundamental limitations and may not be suited for the future generations of service robots. Future robots will come out of the factories and work in close co-operation with humans, in small workshops as well as in domestic environments, as co-workers and home assistants (see Box 1)[1]. In this context, it is difficult to imagine a clockwork-like system made of several motors and hundreds of gears. If the robotic device is to operate in close relationship with humans, the safety of the system will be a central issue. Furthermore, current technology hardly allows creating robots whose aspect (”look and feel”) can raise social acceptance.

The need for different actuators for safe human-robot interaction is widely acknowledged. Currently, a growing research activity addressing this issue. In fact, industrial robots need stiff actuators, (see Box 2)[2]. However, most of such systems still adopt classical mechanics technology, in complex mechanical devices. As such, current robots are electro-mechanical devices that are hard-bodied, usually heavy, bulky and complex. In fact, even the most advanced robots move in extremely clumsy and often dangerous ways.

New Robotic Applications
- Cooperative manipulation tasks
- Domestic applications
- Entertainment
- Personal Assistance
- Rehabilitation
- Teleoperation
- Human augmentation
- Haptic exoskeletons
- Mixed environments

Box 1: Examples of new applications.[1]

In our view, a radical change in actuation technology is essential for building the smaller, lighter, simpler and safer robots that can share living and working space with humans.

New actuation technology in functional or ”smart” materials has opened new horizons in robotics actuation systems. Materials such as piezo-electric fiber composites, electro-active polymers and shape mem-

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[1] Source of Box 1: Antonio Bicchi, University of Pisa, URAI Conference, 2011

[2] Source of Box 2: Raffaella Carloni, Univ. of Twente, RoboNed Conference, 2011.

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Industrial Robots
-High accuracy in position
-High speed
-Not safe: "far from humans"
-Stiff actuation (tracking of a predefined trajectory whatever external forces)

New Robotic Applications
-Low accuracy in position
-Low speed
-Safe: close contact with humans
-Compliant actuation (allow a deviation from the equilibrium position)

Box 2: Comparison between needs in industrial and new robotics applications.[2]

ory alloys (see Tab. 1) are being investigated as promising alternatives to standard servomotor technology (Pons, 2005).

Recent research at out Laboratory, the Bioinspired Systems Lab[3] of Centre for Automation and Robotics UPM-CSIC, has focused on the use of SMAs for building muscle-like actuators. SMAs are extremely cheap, easily available commercially[4] and have the advantage of working at low voltages.

SMAs are used in many different application fields (M. Hashimoto et al., 1985),(Kuribayashi, 1986),(Raynaerts and Brussel, 1991),(Ikuta, 1990),(Hunter et al., 1991),(Waram, 1993). They can be used to generate and sense movement and even for storing energy. Their applications cover many sector, like, e.g., in deployable satellite antennas, sensors, machinery, robotics to materials for the construction of suspension bridges or anti-seismic devices.

SMAs are also being used in many non-invasive surgery devices (Liu et al., 2011),(Hashimoto et al., 1999),(Shi et al., 2011),(Ho et al., 2011),(Li et al., 2006) and biomedicine, in devices such as stents and tubular prosthetic devices.

In classical robotic systems, the use of SMAs as linear actuators provides an interesting alternative to the mechanisms used by conventional actuators. SMAs allow to drastically reduce the size, weight and complexity of robotic systems. In fact, their large force-weight ratio, large life cycles, negligible volume, sensing capability and noise-free operation make possible the use of this technology for building a new class of actuation devices. Nonetheless, high power consumption and low bandwidth limit this technology for robotics applications.

In fact, due to such limitations, SMAs have not raised the attention of the robotics technology for several years. Here, we claim that careful control design that takes into account the particular characteristics of the material coupled with proper mechanic design, significantly increases effectivity of SMAs as robotics actuators. In fact, It has been demonstrated that suitable control strategies and proper mechanical arrangements can dramatically improve on SMAs performance, mostly in terms of actuation speed and limit cycles. Also, from the mechatronics point of view, niches of applications can be found that greatly benefit from this technology. Bio-inspired artificial systems are one such niches.

It is clear, however, that SMAs (and smart materials in general) cannot, nowadays, be thought as a universal substitute for classical servomotor technology.

From our point of view, the limitations of SMAs represented a challenge that needed to be addressed from both mechatronics and control perspectives in order to overcome these drawbacks.

Our work of the last years has demonstrated that by (i) finding suitable niches of application, (ii) dedicated mechatronics design, and (iii) ad-hoc control strategies, SMAs can effectively be used as an alternative actuation technology in a wide spectrum of applications and robotic systems.

Several other SMAs-based robotic systems have been proposed in the literature that confirm our claim. These will be described later in this Section.

One of the advantages of SMAs is that although they are mostly used as actuators, they also have sensing capabilities. Despite most of the SMAs physical parameters are strongly related in a nonlinear hysteresis fashion, the electrical resistance varies linearly with the strain of the alloy. Because strain is kinematically related to the motion of the actuator (either linear motion or rotational), the electrical resistance and the motion produced by the actuator are both linearly related. This linear relationship between resistance variation and motion is achieved because the martensite fraction is kinematically coupled to the motion, and the martensite fraction is what drives the resistance changes. This issue is an advantage for developing closed-loop position controllers that regulate the SMAs actuation. In fact, most of the applications involving position linear control of SMAs, feedback electrical resistance measurements to estimate the motion generated by the actuator. This avoids the inclusion of external position sensors for closing the control loop.

[3] http://www.disam.upm.es/crossi/Bio_Inspired_Systems_Lab

[4] NiTi (Nickel-Titanium) such as NiTinol® are the most commonly commercially available SMAs.

Table 1: Main characteristics of functional materials.

Kind	Variant	Principle	Pros	Cons
Shape memory	Shape Memory Alloys (SMAs)	Electric current	Price, availability	small strain, speed
	Magnetic Shape Memory (MSM)	Electric field	Contraction speed	High power fields
Piezo-electric	Direct	Electric field	Price, availability	Small strain
	Wave	Electric field	Price, availability	
Electro-active Polymers	Electronic	Electric field	Large strain	High voltages
	Ionic	Electric field	Large strain, low voltages	Must be kept ”wet”

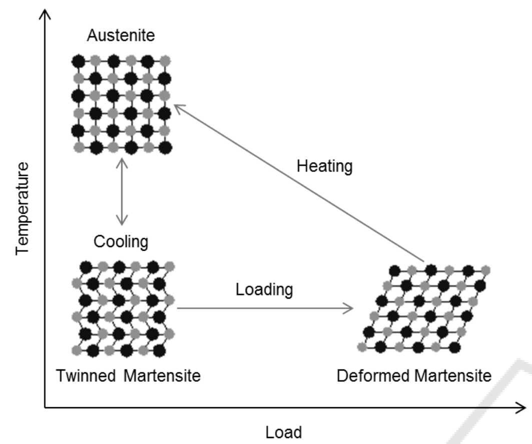

Figure 1: Microscopic viewpoint of the Shape Memory Effect.

1.1 SMAs Muscle-like Actuation for Robotics

The use of SMAs as artificial muscles allows for more ”natural” actuation (Hunter and Lafontaine, 1992). SMAs wires can act as muscle fibers. SMAs can provide an excellent actuation technology, in that they are activated by electrical signals, have a large pull force excellent strength-to-weight ratio.

We re fer the reader to (Coral et al., 2012) for a review of the most representative robots and structures that integrate SMAs as muscle-like actuation mechanisms.

2 RECENT WORK AT THE BIOINSPIRED SYSTEMS LAB: iTuna, BR^3 AND BaTboT

In this section, we describe our recent results on two SMAs-actuated bio-inspired robots. The iTuna and the BR^3 are fish-like underwater robot whose main feature is to use SMAs wires to bend the continuous structure that constitutes the backbone of the fish. The BaTboT is a Flapping Wings Micro Aerial Vehicle (FWMAV) capable of changing its wings' geometry by means of SMAs-based muscles.

These prototypes have been conceived and designed specially in order to exploit the particular features of SMAs-based actuation. In fact, as mentioned earlier, in order to make the best of SMAs-based actuation, we do not have to think at them as substitute of other actuation techniques in already existing mechanical setups. Specific application niches and mechanical needs exist where SMAs are not only a valid alternative, but even outperform classical actuation means.

2.1 iTuna: A Bending Structure Swimming Robotic Fish

The iTuna (Rossi et al., 2011) is a swimming fish-like robot imitates some key features fish biomechanics.

Its actuation system takes inspiration from the arrangement of the red or slow-twitch muscles. In real fishes, such muscles are used for bending their flexible backbone. Alike, the main mechnical structure of the iTuna robot is a continuous flexible backbone, composed of polycarbonate of $1mm$ thickness.

Three antagonistic pairs of SMAs-based actuators, parallel to the body produce the independent bending of three body segments of $8.5cm$ length. This actuation is similar to the one produced by fish red muscles. This antagonistic configuration of the SMAs wires has the advantage that both directions of motion (contraction and elongation) can be actively controlled.

In the iTuna, NiTi SMAs wires with a diameter size of $150\mu m$ were adopted. These have a pull force of $230grams - force$ at consumption of $250mA$ at room temperature, and a nominal contraction time of 1 second.

Under nominal operation such SMAs could bend the body segments up to 28 degrees, even if SMAs wires only contract approximately 4% of their length. By increasing the input electrical current and including a suitable control that handles the overheating of the SMAs, contraction time of $0.5s$ was achieved, and strain could be increased up to 6%.

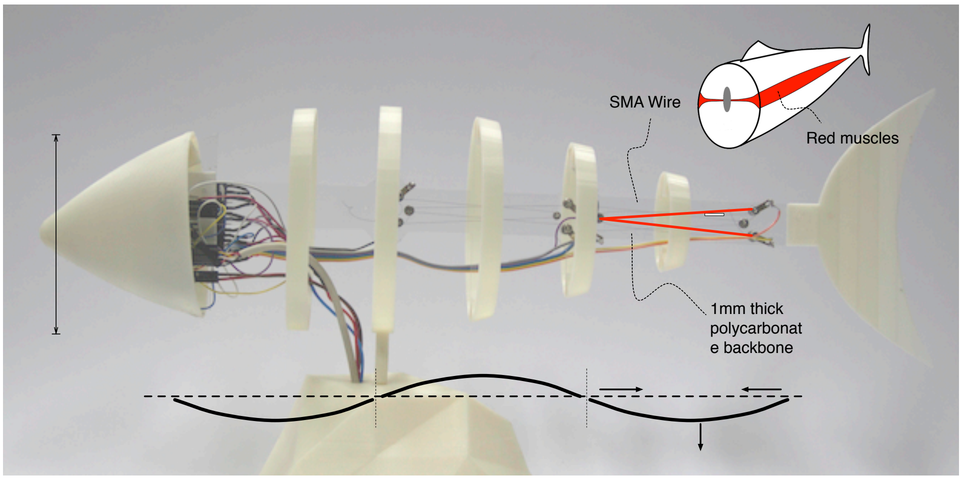

Figure 2: Main structure of the iTuna robot fish.

2.1.1 SMAs Control in the iTuna

In order to address the two main limitations of SMAs (slack in the fibers, and limited actuation speed) we deigned a low-level PID controller. Slack issues are due to a two-way memory effect during operation (Featherstone, 2008), while actuation speed is limited by to the switching time between cooling and heating phases. To address the first problem, a pre-heating mechanism was developed. The pre-heating prevents the inactive alloys from complete cooling, thus shortening the heating phase (fiber's contraction). Additionally, the antagonistic arrangement provides an external stress to the cooling wire by the active antagonistic wire, that sums to the stress provided both by the elastic backbone. Working with an already-warm wire allows for a faster stretch and slack issues are avoided. Resistance measurements were used as a feedback signal for closed-loop control. We refer the reader to (Rossi et al., 2011) and (Rossi et al., 2010) for more details.

The control developed also allowed overloading the SMAs with up to 350mA peak current accelerating the heating phase, but preventing it from overheating that could cause physical damage of the SMAs. Overloading has allowed for achieving a 1Hz oscillation time (i.e. 0.5 seconds contraction and cooling times) and a bending angle of 36 degrees of each body segment.

The iTuna experience showed that an ad-hoc mechatronics design and a suitable control (together with a deeper understanding of the SMAs physics) allow taking advantage of SMAs and overcoming some of their limitations.

2.2 Black Bass: The Evolution of iTuna

Then a second version of iTuna was created under the name "Bioinspired and Biomimetic Black Bass Robot" (BR^3) (Coral et al., 2018). This was based on a new design, but still used to move the same working principle of iTuna. It also included many significant improvements related to mechatronic design and control algorithms. The main purpose was to get closer to a commercial version of a robot fish that could be used in the agro-alimentary sector. The robotic bass is inspired by the Sea Bass due to its relevance because this is the second most important species (in production volumes) in Mediterranean aquaculture.

Similarly with the iTuna, the BR3 has a backbone made of flexible polycarbonate structure of 1 mm thick and 263 mm long, but it differs from it since it has two rectangular holes along where the SMAs are located. This allows us to reduce the effective cross section of the structure by 50%, thus reducing the force required to bend it and optimizing the force made by the SMAs. These holes also prevent SMAs from overstretching when the backbone is bent. Considering that the SMAs only contract 4% of their total length, this overstretching causes the loss of contraction for which the bending angle is smaller and consequently the thrust will be smaller. For this reason these holes were one of the great improvements in the BR3 with respect to the iTuna. Another of the improvements to the backbone was to include 20 spines along the structure that support the solid ribs that were printed using ABS plastic. These ribs increase the mass of the robot and provide support to the skin allowing obtain smoother body curves.

In order to obtain more precise bending angle measurements, the BR^3 was equipped with four flex sensors (see Fig. 3) distributed along the backbone.

Figure 3: **Left:** Backbone and flex sensor used to control the bending angle and frequency; **Centre:** Complete structure printed with a 3D printer and ABS plastic; **Right:** Complete structure wearing our own fabricated microfiber lycra mesh between two silicone layers, that we called skin.

These provide a less noisy signal with respect to the current sensors used in the iTuna to compute SMAs contraction. Current sensors were also used in the BR^3 as a safety measure to prevent high currents on the SMAs and avoid damaging them. Due to the use of flex sensors the control of the SMAs is now based on the measurement of the bending. Thus in the BR^3 we have a high level control that generates the swimming patterns and a low level control that measures the bending of the backbone and controls the amount of electric current that is sent to the SMAs.

In order to determine if the BR3 can trace an accurate trajectory we have tested in three different configurations: Air/Backbone without ribs, Air/Backbone Ribs and Skin, and Water/Backbone Ribs and Skin. For each one we set different amplitude and frequency values. Figure 4 shows one of these tests including the thrust generated by the fish in the water. We made a Particle Tracking Visualisation (PTV) to trace the trajectory of the tail by using a reference spot placed at the top of the tail.

2.3 BaTboT: a Biologically-inspired Bat-like Aerial Robot

BaTboT was one of the first a bio-inspired bat robot that SMAs as artificial muscles for changing the geometry of the wings (Colorado et al., 2012). Wing geometry control is what makes biological bats capable of extremely agile maneuvering at low flight speed. Biological studies (Swartz et al., 2005), (Hedenström et al., 2009), (Iriarte-Díaz et al., 2011), (Riskin et al., 2010) have revealed that real bats are able to maneuver because of the inertial forces and torques produced by the changing the wings' shape during flapping. Such features are highly desirable in Micro Aerial Vehicles (MAVs).

With the BaTboT project we attempted to mimic bats maneuvering system, reproducing the biomechanical design of the wings, and tackling the challenge of controlling their shape. In Micro Aerial Vehicles, the weight of the components is clearly a critical issue. This is why "classical" actuation technologies were considered not suitable for the purpose. SMAs were adopted because of their extremely low (actually negligible) weight, and high force-to-weigh ratio.

In the BaTboT, the SMAs actuators used are the commercial Migamotor NanoMuscle model RS-70-CE (Migamotors, 2019). Each NanoMuscle consists of several short strips of SMAs NiTi wire with a thickness of 150μm attached to opposite ends of six metal strips stacked in parallel. Each SMAs segment pulls the next strip about 0.67mm relative to the previous strip, and the relative movements sum to make a stroke of 4mm. Two Migamotors muscles have been arranged into an antagonistic configuration working as artificial biceps and triceps that provide the rotation motion of the wing elbow's joint. The range of motion of the joint is about 60°. Figure 5 shows the detail of the BaTboT's wing.

In (Colorado et al., 2012) we presented the prototype and the results of the experiments carried out, focused at evaluating the use of SMAs as artificial muscles to change of wing's morphology. Simulations and experiments wern carried out aimed at quantifying the Power-to-Force tradeoff of the SMAs muscles working under two operation modes: nominal and overloaded. Nominal-mode implies an input heating current between 175mA and 350mA, and overloaded-mode, between 400mA and 600mA.

AS for the iTuna, overloading allows for reducing the heating-time of the SMAs, therefore increasing the contraction speed and the overall actuation frequency. Again, overloading was monitored to avoid overheating issues that could cause physical damage of the fibres.

In the work presented in (Colorado et al., 2012), we also investigated SMAs fibers *fatigue* issues, and how overloading can accelerate their appearance, which causes a loss of performances as far as both pull force and contraction speed is concerned. We found that after approximately 5 minutes of continuum SMAs *overloaded* operation, actuation speed drastically decreases about 56%. This limitations in SMAs bandwidth conducted us to investigate how to achieve Batbot maneuvers while flapping and morph-

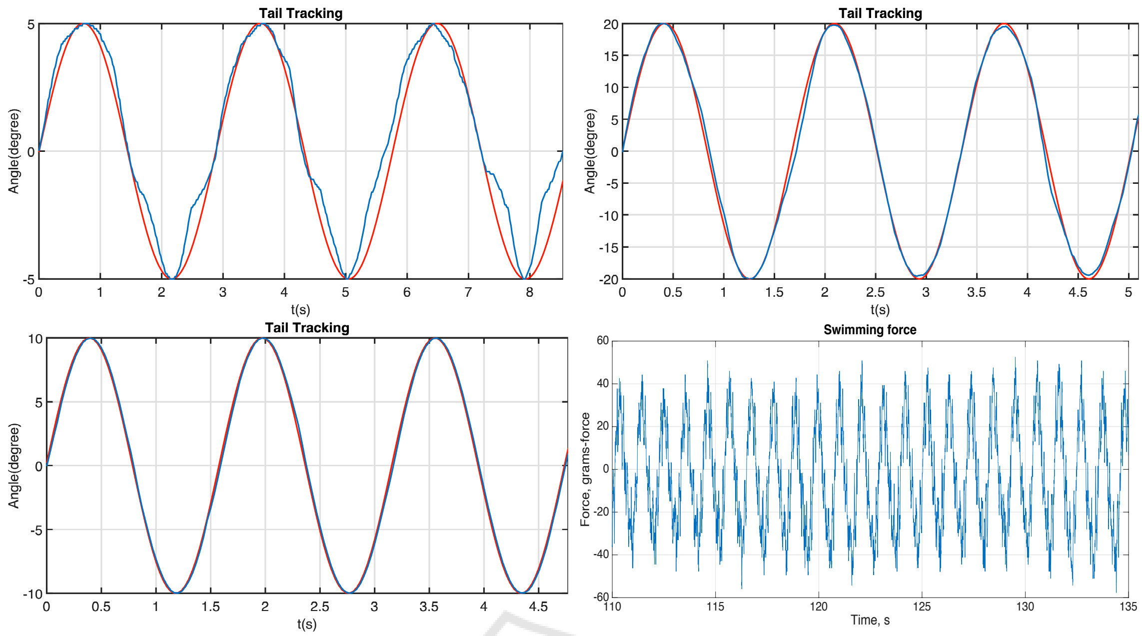

Figure 4: Carangiform swimming pattern for **Top left:**Air/Backbone without ribs at 0.34Hz and amplitude 5 degrees; **Top right:**Air/Backbone Ribs and Skin 0.6Hz and amplitude 20 degrees; **Bottom left:**Water/Backbone Ribs and Skin 0.6Hz and amplitude 10 degrees; **Bottom right:**Thrust at 1Hz and amplitude 10 degrees.

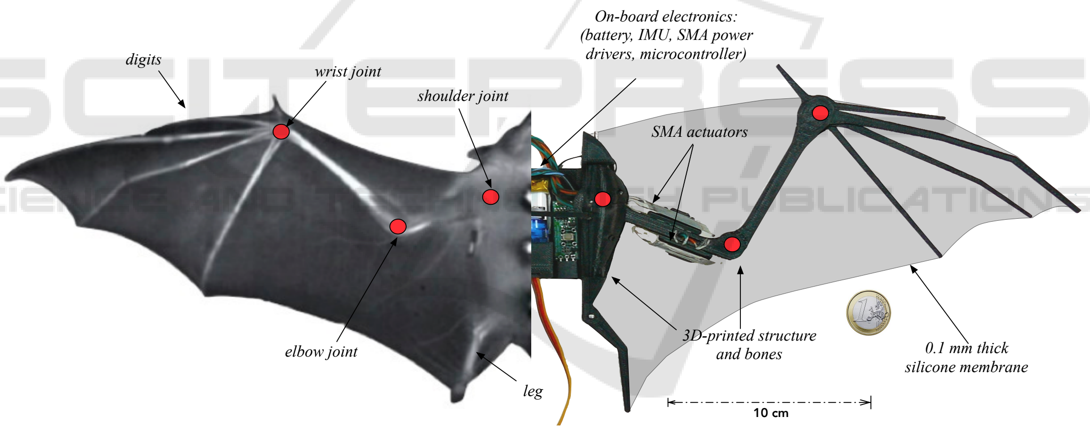

Figure 5: BaTboT mechatronics compared to its biological counterpart.

ing the wings at low frequencies. In fact, some bats are able to achieve both lifting and inertial forces by just modulating wing inertia, thus, undergoing large body accelerations. Since bat's wings have heavy muscles and bones, the inertial effect plays a significant role in a bats flying maneuvers, even more important than aerodynamic forces.

In (Colorado et al., 2013), we developed a novel inertial-based controller to properly modulate wing inertia to generate attitude movements. We investigated how to achieve forward and turning flight maneuvers by just flapping and morphing BatBot's wings at $2Hz$. Wind tunnel experiments showed that net body forces increased about 23% thanks to the bio-inspired contraction and extension of both wings during a wingbeat (morphing modulation). More importantly, thanks to the inclusion of inertial information of both wings within the control law, causing that the upstroke portion of the wingbeat cycle generates more lift and less drag due to the fact that the elbow joint contracts sufficiently to reduce the wing area at minimum span. Figure 6 shows experimental results supporting these conclusions.

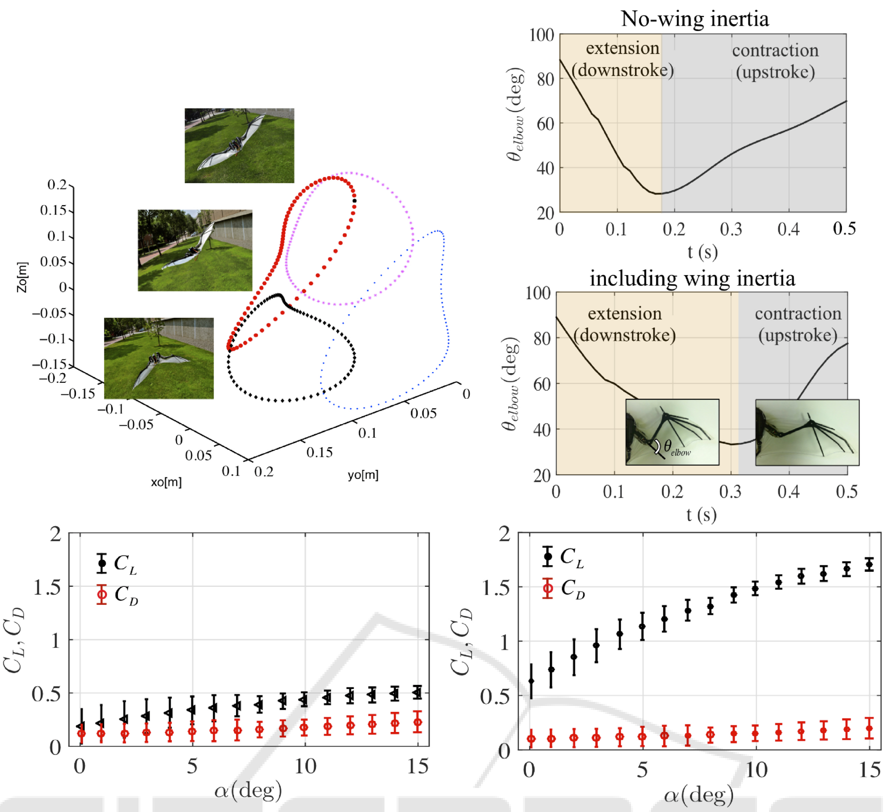

Figure 6: Different wing modulation profiles and their effect in lift and drag generation: **Top Left:** forward-turning maneuver including wing-tip Cartesian trajectories. **Top right:** The plots detail wing contraction/extension during a wingbeat cycle. In the upper plot, the wing inertial model is not considered, thus, the controller is not capable to compensate the drag payload of the wings during the upstroke. In the lower plot, the upstroke time is reduced thanks to the inertial effect included. **Bottom left:** lift and drag forces generated with the wing modulation from the upper plot in **Top right:**, wheres **Bottom right:** shows lift and drag forces generated with the modulation from the lower plot in **Top right:**. As a result, lifting forces are tripled.

3 CONCLUSIONS

New generations of service and personal robots will need new actuation technologies.

In our work, we have investigated the use of Shape Memory wires as linear actuator for this purpose. Our work has demonstrated that by

- Designing dedicated mechatronics
- Deepening the understanding of their physical behavior
- Developing ad-hoc control strategies

SMAs can provide an effective technology that allows building simpler and lighter robots. Such features that may contribute to their safety, and ultimately allow robots to share living and working space with humans.

Even if SMAs cannot substitute classical servomotor and hydraulic technology in general, we have shown that they can effectively compete with, and even outperform standard actuation technology.

We have also shown that, cleverly designed control strategies, that exploit the knowledge of the physics of the material and of its behavior over time, together with dedicated mechanic setups can help overcoming their limitations.

We ha also found that, while some of the limitations of the SMAs can be overcome, another limitation, such as *fatigue* is seldom considered in the literature, an shall be further investigated in order to obtain the best performance.

In conclusion, we can say that Shape Memory Alloys, and functional materials in general, have a great potential to be used in future robotic systems, although they need to be investigated more. In comparison with electric motors and hydraulic actuators, that have more than a century of history, functional materials are still in their infancy.

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