Current State and Trends on Bioinspired Actuators for Aerial Manipulation

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***Abstract*— Recently, several research has been developed to embed manipulators and actuators in Unmanned Aerial Vehicles (UAVs) to allow them to interact with the environment. However, there are strong limitations with these actuators which are mainly related with the weight and efficiency. This article reviews the state of art of bio-inspired solutions for aerial manipulators and presents cutting edge bio-inspired technologies that are potentially profitable in the field of aerial robotics.**

I. INTRODUCTION

Robotic manipulation is still a challenging research field nowadays. Recently, the interest of this task has increased in the field of aerial robots, with the idea of making these systems capable to perform manipulation in dangerous locations.

Aerial Robotic Manipulators (AROMAs) have the ability to access areas that are difficult to reach for humans or ground robots. For example, high voltage cables need to be repaired or even industrial facilities where the maintenance tasks have a high risk for workers.

However, the most used aerial vehicles, multirotors, have strict payload limitations and traditional actuators such as servomotors have a limited strength to weight ratio. For that reason, these must be extremely optimized so that they can be installed onboard UAVs without compromissing the payload.

The payload is always a critical variable to be optimized, that affects a lot of other properties of the robot, such as the maneuverability or the autonomy.

Recently, a new trend has appeared in the research of aerial robots. Ornithopters offer a balance between increased autonomy and the capability to perform low-speed flights. Moreover, these robots are safer for human interaction due to the fact that these systems do not use propellers. However, these UAVs have even more payload limitations. Thus being crucial to research in new low weight manipulators

For all these reasons above, there is a need to develop new manipulators that can be embedded in aerial systems regardless the payload capabilities. Thanks to modern manufacture process like additive manufacturing and the use of lightweight materials, it is possible to optimize the design of the limbs used to manipulate. Using plastic or low-density metals like aluminum these parts are taken to the limit, reaching an equilibrium between weight an mechanical resistance.

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Nevertheless, the most critical part is the actuators used for moving the limbs. Normally, servomotors are used, but these have an intrinsic trade-off between weight and strength. Smaller servos can not lift enough weight for most applications, while larger servos weight too much for small aerial robots. For these reasons, alternative actuation methods are being studied to replace servos.

This paper provides an overview of existing technologies that have huge potential to be used in aerial systems to perform manipulation or to actuate parts of the robots, including morphing capabilities. The following sections show the state of the technology and, additionally, presents new innovative technologies that have not been used yet in aerial robotic and could improve the performance of aerial robots.

The remainder of the article is organized as follow. Section II explains the mechanical based actuators that have been used for years and are still being used in aerial manipulators. Section III reviews actuators based on soft materials. Section IV introduces electroactive actuators, which provide useful attributes using different innovative materials. Section V exposes other actuators that are still in a development phase, but that have a strong potential in aerial robotics. Finally, Section VI exposes the conclusions about the potential and the future use in aerial robotics of the presented technologies. Analyzing which of them could be the best for some different design requirements.

II. MECHANICAL BASED ACTUATORS

This section covers the state of the technology in aerial manipulators based in traditional actuators. The research in this section is organized in ascending level of complexity and optimization, i.e., it starts with simpler actuators and manipulators, and ends with optimized designs which are close the limit of performance of this category of actuators. Weight and performance will be remarked.

A. Development of aerial manipulation actuators

The evolution of the aerial manipulation using mechanical actuators has been documented over the years. Articles [1] and [2] give a general overview of this evolution and of the methods used for developing AROMAs.

Authors in [3], [4] used helicopters to carry a 7DoF industrial manipulator to perform grasping tasks. Although this AROMA was able to lift relatively big objects thanks to their huge payload, it has big inconveniences. Their big size and weight made it difficult to maneuver in reduced spaces and also it has a high risk for people if they are near the place

Fig. 1. From left to right and up to down: 1) Commercial available traditional servo motor; 2) Pneumatic actuator out of "Ecoflex"; 3) SMA springs; 4) SMA linear actuator; 5) Commercial piezo motors; 6) MFC out of NASA; 7) PEA actuated sheet; 8) Commercial EAP plates; 9) Stacked PEA concept; 10) Commercial stacked PEA for low displacement, 11) Different configurations of TCP; 12) Peano-HASEL actuator.

where the system is operating. These systems have their use restricted to grasping in open fields.

Another similar approach is described in [5], where a helicopter is also used for aerial manipulation. In this case, a customized grasping mechanism much simpler and lighter than the robotic arm was presented. However, it has more limited performance.

The mechanical design of helicopters is complex and its maneuverability limited. Thus, they were rapidly substituted by multirotors in this field. These robots, offer new capabilities in terms of maneuverability, flexibility and are easy to control. However, their payload are lower. For this reason, smaller custom-designed actuators and arms were designed by researchers, such as [6]–[8], to be used in multirotors. These designs were a first step ahead in optimizing the weight of manipulators. However, they were still not able to be lifted by small-sized UAVs. Other examples of this kind are [9]–[11], these show specific applications of these aerial manipulators embedded in multirotor platforms.

This first steps showed a tendency to reduce the weight of the actuators. However, these were still limited due to the big motors used for the actuation and the use of relatively big UAVs.

B. Optimization of mechanical aerial actuators

The main problem of previous AROMAs is their size and maneuverability. In order to be able to operate in a larger variety of environments, a reduced size is needed. The subsequent research tries to optimize the designs to reduce size and weight while trying to keep the performance.

Authors in [12] centered their efforts in developing optimized actuators using lightweight materials and efficient designs. Additionally, in the same article, compliant joints were introduced so they minimize the interactions with the environment, making the platform safer to unexpected collisions. Another example is [13], which shows a 2DoF arm for a quadrotor small UAV for grasping tasks.

Other different approaches have been developed, researchers in [14] present a concept design of a UAV specifically made for support highly dexterous arms.

Authors in [15] use tensors to reduce the number of servo-motors and, consequently, the weight. This design also reduces the inertia of the manipulators changing the way of actuating the robotic arms.

In [16], authors designed a three DoF Delta manipulator to be placed on a UAV. This design was very optimized and lightweight (190 grams) offering the possibility of being loaded on a small-sized UAV. Nevertheless, the actuation range of a delta manipulator has different limitations compared to classical serial-link manipulators.

Optimizing the weight of actuators is a critical requirement for aerial robots. However, it seems that traditional actuation methods using servos are reaching their limit in weight optimization. More weight reduction implies a drastically reduction of the force exerted. That is the reason why alternative actuators must be searched to offer lower weights and a higher weight/force ratio. Next sections present alternative actuation methods, exposing their potential in aerial applications.

III. SOFTROBOT BASED ACTUATORS

This section summarizes the most important advances in the use of soft actuators that have promising applications in aerial manipulation. These are made out of elastic materials that have compliant capabilities. In this article, these have been categorized into two types: pneumatic based soft actuators and shape memory alloy actuators.

Several reviews centered in materials used for developing these soft robotics actuators have been done by researchers previously. Some examples are [17]–[20]. They show the potential of these technologies for performing a variety of tasks.

A. Pneumatic soft actuators

Elastomers have been widely used in research for developing soft actuators. This is so thanks to the property of these materials to have high deformations and to recover their initial state when the force disappears. Authors in [21] proposed some preliminary designs of pneumatic artificial muscles (PAMs) to be used in robotics applications. Researchers highlight the benefit of having a lower weight than traditional mechanical actuation method and their compliant behavior.

Thanks to their softness they are ideal for co-working manipulators, avoiding harming humans when interacting with them. Due to this fact, researchers have demonstrated a particular interest in their use for biomedical applications such as the work presented in [22], where authors showed effective designs and provided a guideline for designing these soft actuators.

In [23] an industrial application is shown with the design of a pneumatic actuator with sensing capabilities thanks to a set of the sensors embedded in it. This actuator is capable to measure its curvature and the force applied in the contact, allowing to control the grasping with higher accuracy.

A similar application is presented in [24], where the presented manipulator can also control its bending point. In this case, by embedding a low-melting-point-alloy, allowing easier control of the bending point and resulting in a more flexible actuator.

Authors in [25] centered their effort in optimizing the design of this kind of actuators. They developed a more complex design to increase the precision of the control, these actuators were called ”pneumatic networks”.

As mentioned above, one of the advantages of these soft actuators is that different sensors can be easily embedded on them, allowing to control them or perceive their environments without adding much weight to the system.

These materials have been used to develop complete robots, not only the actuators o manipulators. Authors in [26] worked in the design of aquatic robots such as fishes or octopuses. This material allows mimicking the movement of boneless animals. In [27] a ”Manta swimming robot” is presented mimicking the movements of this animal and producing a robot fully capable of swimming using these pneumatic actuators.

Another interesting approach is the PoseiDRONE [28] an octopus-shaped underwater robot composed of 80 percent of its volume of rubber-like materials. This robot is capable of swimming and also to perform manipulation tasks. This robot allows, as the previous one mentioned, to mimic natural behavior. Being bio-inspired and soft and adding the capability of performing manipulation and moving using these soft actuators.

This technology has also been extended in aerial robots. Authors in [29] applied them to fixed-wing UAVs to perform morphing of the wings. They proposed the use of an Ecoflex-made structure with pneumatic actuation. This design allows changing the angle of attack of the wing improving their maneuverability and performance.

These actuators have also been used to perform aerial manipulation as it can be seen in [30]. In this article, a pneumatic mechanism is presented to be used in a small quadrotor for opening doors.

As seen in this section, a lot of work has been done in this type of actuators. They offer some useful properties, such as softness, reliability or versatility. However, their use in aerial robotics is still limited. This is so due to their weight. Even though the removal of the servo motors allows a reduction of weight, the use of pneumatic actuators needs the existence of an air pump which adds weight to the system. Also, elastic elastomers, like the ”Ecoflex”, have a high density. Even so, they can be used in medium-sized UAVs for specific tasks where softness is more important that weight optimization.

To manufacture these pneumatic actuators the normal procedure is first to produce a mold with the shape of the desired actuator using a 3D printer. The most used material for filling the mold is ”Ecoflex”, a white translucent elastomer with a specified functional range of temperature from -53ºC to 232ºC. After a curing process of several hours (an entire day is recommended) the ”Ecoflex” becomes soft and stretchable with an elongation of up to 950 percent. After unmolding, the pneumatic tube is inserted in the actuator and sealed with an adhesive (a silicone-based is recommended). After that, the actuator is ready to use.

B. Shape memory alloys (SMA)

SMA, as explained in [31], are special materials that, once deformed, are capable of recovering their original structural shape. When heated they generate mechanical work to recover a predetermined shape. Due to their lightness, compactness and high mechanical performance, they have a high potential for developing optimized actuators.

In [32] the hysteresis and dynamic properties of the material are analyzed. They conclude that this actuators have great potential as actuators because these do not have size restrictions and can be geometrically customized to adapt to the requirements. Additionally, they can perform linear and torsional actuation in milliseconds without the need of any engine or pump. These alloys are typically bio-compatible and have excellent corrosion resistance. At last, one main advantage is that these actuators are free of parts, such as reduction gears, and they do not produce dust particles and are less prone to degenerate or break.

Compared with DC, AC, hydraulic and pneumatic motors the power/weight ratio is excellent in low weight applications. However, SMA are not very commercialized nowadays, thus it is difficult to access them for robotic applications.

Authors in [33] tested the actuation speed of a linear SMA-based actuator. During their test-bench, they reached up to a 35Hz actuation speed. They developed an actuator capable of performing huge deformations that could be used for grasping or perching purposes in aerial manipulation.

In regards to aerial applications, this intelligent material has also been used for morphing in fixed wings aerial vehicles. In [34], authors present a novel design of a bio-inspired SMA-based wing for UAVs. They came up with a prototype with a high degree of flight adaptability, enhanced maneuverability and improved performance. Furthermore, the overweight added to obtain this benefit is low compared with pneumatic or mechanical actuators. They used an antagonist configuration, solving the problem of continuous input of thermal energy. This is so because SMA requires thermal energy to deform but not to maintain its morphed shape. As a result, they achieved to develop a wing that can endow the UAV with the ability to reach a higher maximum speed using the same baseline thrust. This design can be of special interest in other aerial robots such as ornithopters.

Another approach in fixed wings is presented in [35] in which SMA-based actuators are used to morph winglets, mimicking the behavior of the wing-tip feather of gliding birds. This design reduces the drag forces generated by vortex in the wingtip, improving the efficiency of the wings and reducing energy consumption.

At last, in [36] authors use SMA to develop a landing gear. With a spring-antagonist configuration, this design is capable to deploy the landing gear on board on a fixed-wing UAV. This paper demonstrates the feasibility of using these actuators for actuating end-effectors in AROMAs.

The manufacture of this actuators is typically done by casting, using vacuum arc melting or induction melting. Normally, for engineering applications, the SMA are copper or NiTi-based. They exist specialized techniques to avoid to keep impurities to a minimum and ensure an homogeneous distribution.

The ingot is then hot rolled into longer sections and then converted into a wire. After that, the alloy must be ”trained” to get the properties wanted. This ”training” will allow this smart-material to remember their shape when heated. This occurs by heating the alloy so that the dislocations reorder into stable positions but do not recrystallize. Normally, they are heated between 400ºC and 500ºC for 30 minutes, shaped while hot and then cooled rapidly by quenching in water.

IV. ElectroActive Polymer based actuators

This section presents a family of soft actuators based on electroactive polymers. These actuators use electric fields to modify the shape of elastomers. Thanks to that, they compress or dilate depending on the voltage applied and the distribution of the material in the actuator.

These actuators can be engineer shaped to bend in different directions. Moreover, they are capable to reach high weight/force ratios and also high-frequency movements. However, in order to generate quantitative forces with electric fields, high voltages are needed, with very low amperage. Thanks to that, the power consumption is virtually zero, so they are also very energy efficient.

A. Development of EAP actuators

The first research in this field focused on the use of piezo motors [37] which are still being used nowadays. However, most of them do not present a significant improvement in capabilities compared with traditional servos. Their main advantage is the extreme miniaturization and high accuracy compared to the mechanical based actuators. These have been widely used for medical applications or high precision research machines.

Authors in [38] used dielectric elastomer-based actuators to create a robot that mimics the behavior of earthworms. This work proves the capability of developing a lightweight, bio-inspired, soft robot. The use of these actuators also allows reducing mechanical and electronic components.

Due to the increasing interest in these actuators, authors in [39] studied the dynamics and behavior of them analytically. The conclusions of this work were the potential of the EAP in lightweight applications for controlling vibrations of structures. One specific example is the control of antennas deployed for space missions [40] controlling a membrane reflector. Other authors proposed the control of the flaps of fixed wings aircraft [41]. Also, the capability of performing control of these actuators by modulating the applied voltage and different theoretical models have been presented.

The use of EAP-based actuators is not only limited to flat membranes. There is an increasing interest in the use of these actuators as muscles. In [42], [43] researchers analyzed the potential of several smart actuation forms. These authors demonstrate that EAP-based actuators have a great force at a low weight. This result is of high interest in UAVs where the ratio force/weight is always a critical factor.

However, apart of all the previous work mentioned, two different technologies that have been successfully tried out in aerial applications will be now mentioned. These actuator types, being EAP, offers some specific attributes that are very interesting for some applications in aerial robotics and could be even adapted to performing other innovative ones. At the end, also an innovative actuator type, not fully developed, will be also mentioned.

B. Macro-Fiber Composite (MFC)

The MFC-based actuators were designed by the National Aeronautics and Space Administration (NASA). These actuators are a low-cost piezoelectric device, first designed for controlling vibration, noise, and deflection in composite structural beams and panels. These were planned to be used in helicopter's blades and airplane wings as well as for shaping of aerospace structures.

The MFC actuator is an encapsulated high-performance piezoelectric composite fiber, consisting of rectangular piezoelectric fibers sandwiched between layers of adhesive and electrode polyimide film. The advantages of the fibers are high strain energy, directional actuation, customization, and durability.

These works when attached to the surface to be actuated, which is usually a metal or composite thin plate. As the MFC stretches when a voltage is applied to it, it provides solid-state deflection of the surface.

In [44] MFCs were used to dynamically change the shape of wings in small air vehicles. These devices have a very low weight. Thus, compromise the payload of the small aerial robot.

Researchers in [45] also proved that these actuators could be used to perform morphing of the wings, being able to control the shape and the airflow in a high frequency bandwidth. The advantages are low weight and low energy consumption. Also, the authors highlighted the compliant characteristics of the actuators, taking advantage of aerodynamics loads and increasing control effectiveness.

At last, in [46] a general overview of materials that have potential for performing morphing of UAVs wings is shown, among the described materials MFC is also found.

MFCs offer the capability of being added to aerial structures like wings of different UAVs to perform morphing to them without adding much weight to the overall system and consuming low energy. Also, the addition of more electronics or mechanical parts is avoided using these actuators.

For manufacture these actuators NASA offers their own tutorial [47]. At first, materials needed for assembling the MFC are: one bottom interdigitated electrode film pattern, one top interdigitated electrode film pattern, one piezoceramic fiber sheet assembly and an epoxy adhesive.

For assembly, epoxy must be applied to the copper side of one electrode film and also to the piezoceramic fiber sheet. After discarding excess and achieve an homogeneous distribution the electrode film must be places on the piezoceramic sheet. Then, this partial assembly must be vacuum pressed and cured. The same procedure must be performed with the top electrode pattern and the exposed piezoceramic fiber. The remaining electrode film is afterwards placed onto the partial MFC assembly. To end, the vacuum and cure process is applied again and the fabrication process is completed. For more detailed descriptions, refer to [47].

C. Piezo electric actuators (PEA)

These actuators offer similar features to the previous MFC but they do not need to be attached to a surface to perform actuation. These are designed to bend straight when a voltage is applied to them. PEA can work at high-frequency cycles and work at lower voltages than MFCs.

Researchers have applied this EAP for morphing, similar to previous ones as it can be seen in [46]. One of the most significant applications of PEAs is the high-frequency flapping of micro aerial robots described in [48], [49]. The authors used PEAs to mimic the flight of insects and hummingbirds. This technology can be reused to develop other flapping aerial robots such as ornithopters.

Lightweight and low energy consumption es well as lack of add-ones for their use are coincidence points with the MFC. But, higher resistance and adaptability to design changes, as the before mentioned higher frequency actuation are attributes that chow the potential of these actuators.

The manufacture of the PEA is similar to the MFC. In this case a piezoelectric layer is sandwiched with two passive insulating layers, mostly out of carbon fiber. These layers restrict the movement of the piezoelectric, allowing the system to bend without being glued to any surface. Also, they add durable protection to the piezo layer.

D. Stacked piezo-electric actuators

These stacked piezo actuators or EAP use the same principle as the previous exposed EAPs. However, they consist in several stacked layers of the electro-active material that creates a linear muscle that can compress when a voltage is applied generating high linear force instead of rotary or bending actuation.

Nevertheless, this technology is still immature. Most applications limits they range to prove of concepts [50], [51]. Commercially available products offer too low actuation length, limiting them to vibration control of precise actuation of medical devices.

Despite that, the development of this stacked actuators could lead to a low weight and high performance, in terms of weight/force ratio and energy consumption, linear actuator.

For manufacturing of this actuators, several piezo layers are attached on top of each other. After attaching hundreds of this layers an actuator is obtained, capable of directly transform electrical energy in linear actuation.

V. New trends of actuators

There a new types of actuators that cannot be clearly classified in previous types. This section introduces these novel actuators that have been developed in recent years. These actuators have also promising attributes to be applied to aerial systems.

A. Twisted and coiled polymers (TCP)

TCPs, also know es nylon muscles, were first introduced in 2014 [52]. Authors studied the effect of twisting and coiling traditional fishing line threads. After several twists, and applying a longitudinal force to maintain the tension on it, the thread collapses producing a spring. Thanks to nylon's memory properties, the spring contracts when heated, being capable of lifting weight hundreds of time its own weight.

In the first articles, these muscles were handcrafted one by one by the researchers. Author in [53] proposed simple but effective machine to automate the creation of muscles.

TCP actuates when heated. Initial test-benches used hot water or air. However, heating method is quite inefficient and barely applicable in real robotic applications. So, the research on TCP was limited in the first years to proof of concepts.

Trying new ways of heating them, researchers in [54] proposed the use of copper wires, coiled over the TCPs, acting as electric heaters. Later, researchers started using nylon threads mixed with silver particles, used typically in the textile industry for developing "smart" clothes. These thread are electrically conductive so that they can be heated with an electrical energy source taking advantage of the Joule effect. This silver coated nylons demonstrated a more efficient heat transmission. Several works appeared using this new material, as for example, small humanoids robots [55] and robotic hands [56].

Up to this point, the next limitation of TCPs is nylon's melting point. If the temperature is not controlled, the muscle may break. On the other side, if the muscle is not rightly heated, it will not actuate.

In [57] authors embedded the TCPs in silicone elastomers ("Ecoflex") for using them in soft robotic applications. With them, they tried to mimic animals natural behaviour while isolating the TCPs from the outside to get a more uniform heat transmission. Also, authors in [58] developed more complex systems for embedding the TCPs and being capable of perform different movements and actuation.

Thanks to their low weight and high force/weight ratio these actuators makes then perfectly suitable for aerial robotics applications. TCPs act as linear actuator, mimicking animal muscles and reaching a contraction of 10-20 percent. Nevertheless, control of overheat that ends up with the TCPs break and control of the actuation level are still unsolved challenges in this type of actuators.

For manufacture this actuators several steps must be followed that are described, for example, in [52]. First, a nylon thread must be cut and coiled. For the coiling, the rotation must be restricted and a weight must be putted on one and to ensure tension. The choice of this weight is critical, two less will make the coiling fail due to collapse of the wire on itself. To much of them will trigger a break of the thread.

After this process, the next step is the annealing of the coiled spring with several heating and cooling cycles. In this part, the weight must also be taking into consideration, as it will affect the elongation of the muscle and so also the total length of the linear actuation. When several cycles are completed the actuator will start to compress when heated, sign that the fabrication process has finish.

B. Peano-Hasel actuators

The soft electrohydraulic transducer named Peano-HASEL [59] (hydraulically amplified self-healing electrostatic) actuator combines the strength of fluid and electrostatic actuators. These actuators use electrostatic and hydraulic principles to perform linear contraction when a voltage is applied to them, similar to the PEA.

These actuators do not need of any rigid frame, pre-stretch or stacked configuration and are manufactured with inexpensive commercially available materials. They can perform a controlled actuation of up to 10 percent of its length with actuation at 50HZ and lift more than 200 times their weight.

Also, characteristics like optical transparency and self-sense of their deformation sense are interesting and demonstrate promising features industrial automation or robotic devices. However, design should be optimized to reduce weight and size for adapting to UAVs.

The design of this type of actuators consists of a series of rectangular pouches made from a flexible and in-extensible shell that is filled with a liquid dielectric. Electrodes cover a portion of each pouch on either side of the actuator. When a voltage is applied, electrostatic forces displace the liquid dielectric, causing the electrodes to progressively close.

To fabricate them, they consist of three principal components. The shell material is a bi-axially oriented polypropylene film. The liquid dielectric is "Envirotemp" FR3, a high breakdown transformer oil. Last, the electrodes are ionically conductive hydro-gel electrodes. The film is filled with the liquid dielectric and sealed. After that, the electrodes are placed on the pouches to create a complete actuator with a weight of 5 grams. For more detailed description refer to [59].

VI. Conclusions

Several different types of actuators have been showed and their potential in aerial robotics has been analyzed. This may help researchers in the future to decide which technology feats better with their requirements.

Also, Figure 2 shows a visual state of art of the applications finds until now in UAVS using these technologies.

It can be observed that most of the current applications center their efforts in performing morphing of the UAVs. These applications have been proved to being viable, and open the door to improvements and optimization also in flapping wings UAVs where these technologies have not been applied.

However, some advances have been done also in actuation of end-effectors or other deployable subsystems of UAVs. These works demonstrate the potential applications in this field, where there is still a long way to go and a lot of progress can be achieved.

Figures 3 and 4 shows a qualitative comparison of the actuators. These compares the strength, weight and power consumption visually. This is a relative comparison to help

Fig. 2. From left to right and up to down: 1) Pneumatic actuation of a wing profile using actuators out of "Ecoflex"; 2) UAV performing vertical perching on a door and opening it using pneumatic actuators; 3) Wing profile with MFC used for morphing; 4) Wing profile with SMA springs for morphing; 5) Fixed wing UAV with SMA linear actuators for the winglets; 6) Conceptual design of a deployable landing gear on an UAV using SMA; 7) RoboBee micro UAV actuated by PEA; 8) Grasping end-effector of an ornithopter, actuated by TCP.

choosing among the different options during the design phase of a new research.

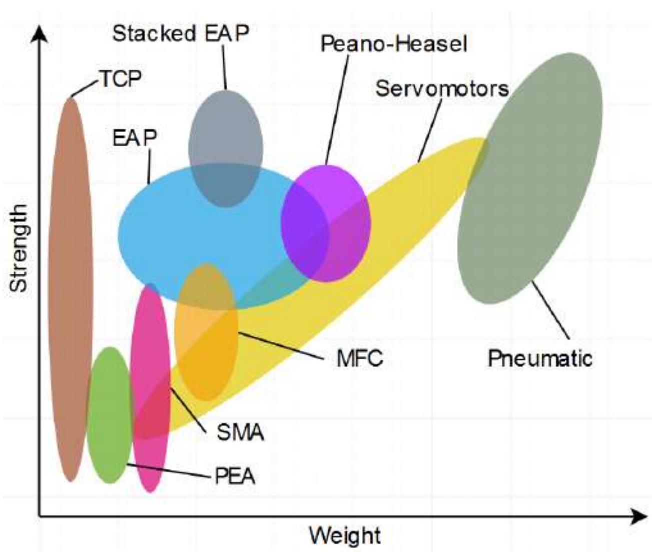

Fig. 3. Qualitative comparison between the strength and weight of the different actuators.

Pneumatic actuators are the stronger option but at the cost of a high weight due to the requirement of pumps or compressed gas tanks. On the other side, TCP muscles present the best ratio between strength and weight. However, as can be observed in Figure 4, TCPs have a large power consumption. As aforementioned, servomotors have a balanced ratio between all the specifications, this makes them fairly good for a range of operation. Nevertheless, as stated, in order to operate in limited situations, the other actuators offer better ratios of strength/weight.

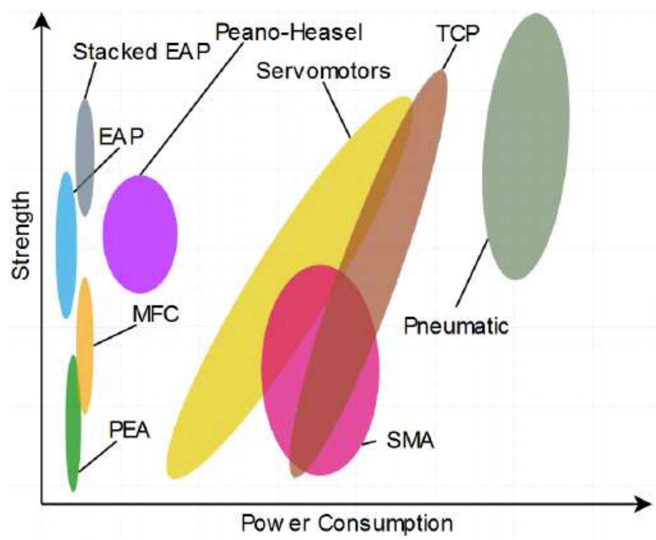

Fig. 4. Qualitative comparison between the strength and the power consumption of the different actuators.

Shape Memory Alloys are not remarkable in this ranking. However, one of the good properties of these actuators is that can be adapted to almost any shape. For this reason, these are suitable to build morphing bodies, self-healing shells, and similar applications.

The characteristics of EAP-based actuators vary depend on the specific design. Stacked EAP are the strongest solution but have more weight. PEAs and MFCs are weaker solutions but at a better force/weight ratio. In any of the cases, EAP are the most efficient solutions in terms of power consumption.

TABLE I

SUMMARY OF ALL THE BIOINSPIRED ACTUATORS AND MANIPULATORS

Type	Subtype	Advantages	Disadvantages	References
Mechanical actuators	Servo-joint based	Commercialized wide range operation	Limited force/weight Only rotatory	[6]–[8], [12], [14], [16]
	Servo-tensile based	Commercialized Compact	Complex design Limited actuation	[15]
Soft technologies	Pneumatic based	Strong Accurate	Need pump or tank Pipes and pressure	[21]–[30]
	Shape memory alloys	Accurate Versatile	Hard to manufacture Need heating	[31]–[36]
EAP actuators	”basic”	Flat Low-weight Low-consumption	Only torsion High-voltage Hard to manufacture	[37]–[43]
	MFC	Flat Low-weight Low-consumption	Only torsion High-voltage Hard to manufacture	[44]–[46]
	PEA	Flat Low-weight Low-consumption	Only torsion High-voltage Hard to manufacture	[46], [48], [49]
	Stacked EAP	Linear actuator High-strength Low-consumption Fast actuation	High-voltage Hard to manufacture	[50], [51]
New actuators	TCP	Linear actuator Ultra light weight Best force/weight ratio	Power consumption Hard to manufacture Slow actuation	[52]–[58]
	Peano-Hasel	Fluid+electrostatic Strong Fast actuation	Cost Hard to manufacture weight	[59]

As they operate using the electric field, the consumption is virtually zero.

Table I shows a summary of all the presented actuators. Advantages and disadvantages are summarized as well that references of each are actuator type are put together.

Future work should follow the line of increasing the use of these technologies in a greater number of applications, also paying attention to the continuous innovation in the field of soft actuators. The goal should be trying to remove mechanical based actuator and reach the point of an fully bio-inspired and soft aerial robot.

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