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*Review*

# A Systematic Overview of Soft Actuators for Robotics

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**Abstract:** In this systematic survey, an overview of non-conventional and soft-actuators is presented. The review is performed by using well-defined performance criteria with a direction to identify the exemplary applications in robotics. In addition to this, initial guidelines to measure the performance and applicability of soft actuators are provided. The meta-analysis is restricted to four main types of soft actuators: shape memory alloys (SMA), fluidic elastomer actuators (FEA), dielectric electro-activated polymers (DEAP) and shape morphing polymers (SMP). In exploring and comparing the capabilities of these actuators, the focus was on seven different aspects: compliance, topology, scalability-complexity, energy efficiency, operation range, performance and technological readiness level. The overview presented here provides a state-of-the-art summary of the advancements and can help researchers to select the most convenient soft actuators using the comprehensive comparison of the performance criteria.

**Keywords:** soft-actuators, scalability, actuator performance, DEAP, SMP, SMA, FEA

## 1. Introduction

In this overview, it is intended to give a broad evaluation of the developments in soft- actuators. These alternative devices or structures either fundamentally differ from the traditional actuators which normally use electro-magneto-mechanical, fluidic and thermal combustion or they present the same operation principles under a complete new design, emphasizing new characteristics that are crucial in soft-robotics. One of the road-blocks in front of designing and realizing efficient and robust yet safer robotic structures is the inherent limitations in the traditional actuation. For example, in robots with serial kinematic chains, the joint closest to the base should be able to cope with all the weight and counter torque requirements of the preceding joints. This requires the base motor to be selected as large as possible, making the robot hefty in turn. In other words, the ratio between the energy supplied by the actuator and the weight of the actuator is a natural limitation. Even this basic fact was a set-back until harmonic drive and light-weight structures offered an intermediate and acceptable solution to robotics community. In addition to energy output/weight, the volumes occupied by the traditional actuators in the robot structure causes the packaging problem. Therefore 'energy output/volume' ratio is also an inherent limit in selecting the best actuator for a given application. Considering these two general criteria, the novel/soft actuators can give the researchers the opportunity to design compact, light-weight and compliant actuators to be used in autonomous soft-robots. In the soft robotics field, two recent reviews have been performed one concentrating on design, fabrication and control of soft robots [1] and the other on soft materials used in soft robotics [2]. However, there is no comprehensive review on the soft and novel actuators mapping their properties to possible applications and especially regarding them in a multi-criteria evaluation as presented here. Therefore, in this review, we provide a comprehensive evaluation of the current state-of-art in soft-actuators, focusing on four different type of actuators.

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## 2. Systematical Review Method

A systematical review of current developments in soft/novel actuators is needed including the performance comparison and application-specific selection criteria. Here, we provide seven selection criteria for four different actuator types namely shape-memory alloys (SMA), fluidic elastomer actuators (FEA), dielectric/electrically-actuated polymers (DEAP) and shape memory polymers (SMP). A special importance is given to seven selection criteria, including the aspect of compliance, topology-geometry, scalability, energy efficiency, technological readiness level, and operation range of the actuators.

To illustrate a systematical evaluation of a soft actuator with the perspective in this review, we can examine the Pneumatic-Nets which falls under the category of FEA-type actuators. Another name referring to this type of actuator is 'soft pneumatic actuators' (SPA) as used in [3]. Pneumatic-nets are devices essentially comprising a series of chambers formed by elastomeric substrates such as silicone, and supported by an inextensible layer. These devices can be pre-programmed by arranging their extensible and inextensible parts in a specific geometry to determine the bending and the orientation of movement in a specific way. Therefore, in terms of design criteria they are topologically programmable. From the mechanical compliance aspect (2.1), these devices are inherently compliant however, their structural stiffness can change greatly depending on the internal pressure [3]. The optimal topology and geometry (2.2) also plays important role in the efficiency of harnessing the full capacity of the generated power in the actuator. For the FEA-type actuators, especially the chamber geometry and the connection patterns are important since the pressure build-up regions and the orientation of the actuation is programmed by this structural parameter. The FEA/SPA type actuators are highly scalable and less complex to produce (2.3) while the energy efficiency (2.4) depends on the fluid used in the system. Since the pump, filter and valves already exist for more traditional pneumatic and hydraulic systems, FEA-type soft actuators can score high in technological readiness level (2.5). The pneumatic or hydraulic operation principles can be modified to come up with new FEA devices and the applications (2.6) can range from medical to industrial robotics where inherent compliance and adjustable stiffness is needed. For example, characteristics such as back-drivability and the off-axes deformation capability make FEA/SPAs safe for human-robot interaction [4]. Lastly, the operation range (2.7) of FEA-type soft actuators are determined by the internal pressure and the environmental settings such as temperature. Although the operational principle of the device is highly non-linear, control of such devices is relatively easy employing simple on/off control. A table summarizing the systematical evaluation in this paragraph is given in Table I to illustrate the review approach of this paper for a selected actuator type (i.e. FEA/SPA) to provide the readers an organized setting for overview and extracting relevant information.

**Table 1.** Systematical evaluation of FEA/SPA[1] for illustrative example of the review methodology

| Selection Criteria | Evaluation |
|---|---|
| Mechanical compliance | Compliant, light structures |
| Optimal geometry and topology | Depends on the inner chamber size and network |
| Scalability and complexity | Scalable, easy to manufacture |
| Amplification/ Energy efficiency | Amplification through structural parameters and snap-through property |
| Technology readiness level (TRL) | Utilizes existing infrastructure and devices, TRL 7-9 |
| Modality of operation | Pneumatics/hydraulics |
| Operation range | Force: up to 10 N, Stroke: up to 10 cm, Pressure: up to 0.5 MPa, Watt/Weight: 1W/g [5] |

[1]FEA: Fluid Elastomer Actuators, SPA: Soft Pneumatic Actuators

In the rest of the review, each selection criterion is expanded across all the soft-actuator types for the sake of brevity, producing a comparison across the actuator types for the criterion in focus. In the conclusion section, comparing the four types of actuators according to seven criteria to emphasize the strengths and weaknesses, a list of hybrid solutions is suggested. This table of hybrid solutions is

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expected to guide the robotic researchers in selection of the actuator type according to their applied field as well as clarifying which one of these actuator types could be used together for a hybrid-actuation solution.

### 2.1. Mechanical Compliance and Light-weight Structure

With the modern setting of industrial production lines and concepts of smart factory and Industry 4.0, the robots used in industry are required to be modular, adaptable, compliant and light-weight. In addition, the mobile robotics also moved towards more compliant and light-weight but robust structures. Another field of robotics where the compliance might be crucial is the medical/surgical applications.

#### 2.1.1. Compliance

The need for compliance is imposed by the human-robot co-operation and interaction scenarios. For example, in industrial robotics a human-robot co-operative team should be able to work together without the danger of robot partners harming humans due to collisions in the task trajectory. Therefore, the industrial robot arm should be inherently compliant, yielding the force control to the human partner in the task when necessary. A similar necessity is brought in minimally invasive robotic catheters where variable stiffness and compliance is desired while passing through torturous channels in human body to prevent tissue damage or rupture.

For some soft-actuators, the compliance can be inherent because of the material used. Although difficult, the compliant behavior can be also modeled and numerically represented. The compliance and the mechanical behavior for DEAP type materials was modeled using Timoshenko beam approach [6]. The general material used in lab-based DEAP is acrylic based VHB and the normalized Young modulus for this material is 210 kPa [7]. If the elastomeric dielectric polymers are used the Young modulus can be around 1 MPa while the material can sustain 380% strain in high electric fields [8]. In a non-traditional approach, a novel actuator for soft-robotics using discrete actuation units to form a muscle-like structure uses the compliance as the enabler for discretization of the muscle units [9]. Another polymer group that are used in SMP structures also have attractive properties in terms of high deformation capacity [10].

To make the compliance of the structure adjustable and more independent from the selected materials, a hybrid-actuator can be used following the approach in STIFF-FLOP [11], leading to controllable-stiffness. The compliance criterion is examined across all the actuator types and summarized in Table 2.

### 2.2. Optimal geometry and topology

In most of the actuator design, even in the traditional motor design, the geometry and topology of the actuator must be optimized to achieve the best energy efficiency, compactness, the most available stable force/torque from the structure. Even in traditional DC motor design the stator/rotor geometry and the air gap between windings are optimized for the best flow of the magnetic field curves. For the novel actuators, the topology and finding the optimal geometry for the specific task is indispensable since it directly effects either the force or the stroke capability or both.

In this section we will overview the effect of topology/geometry in SMA, FEA, SMP and DEAP based designs. However, to obtain a comparable base between different actuator modalities we will first describe the main topological features in these actuators which has a definitive effect on the force or stroke amounts.

**Table 2.** Evaluation of soft/novel actuators according to compliance criteria

| Actuator type | Evaluation according to criteria (2.1) |
|---|---|
| DC motor (benchmark) | Compliance is based on current control over armature, structural stiffness is high, and the weight increases greatly as the output power requirement gets higher. |
| SMA (shape memory alloy) | SMA has almost no inherent compliancy. It is not compliant in martensite phase and the austenitic phase lasts only when it is heated. However, when used in spring form or meandering profiles, it can obtain certain compliant features due to form. SMA enables light-weight construction when the circuits are left outside of robotic structure. |
| FEA (fluidic elastomeric actuator) | FEA platforms are inherently compliant due to the structural elements mostly comprising elastomeric polymers. The fluid also contributes to the compliance however it can be varied by changing the internal pressure of fluidic chambers. FEA is essentially a light-weight structure if compressors and the pneumatic circuit elements are left outside of the robot. |
| DEAP (dielectric polymer) | DEAP uses a hyper-elastic polymer membrane and compliant/stretchable electrodes, therefore it is inherently compliant. However, the pre-stretching rings or any rigid structure around it may cause the increased stiffness. DEAP supports light-weight structures however the high-voltage circuit should be placed away from the robotic platform. |
| SMP (shape memory polymers) | SMPs are also inherently compliant because of the polymers used in the structure. However, the thermal actuation can largely affect the state of the polymer and in some states the polymer is more rigid. |

### 2.2.1. Topology in SMA

There are very few studies focusing on the effect of topology/geometry of the actuator on the overall actuator performance. Among the possible geometries, the spring coil is examined [12] including four design parameters, namely wire diameter, the rod diameter, the pitch angle and the number of active coils. The peculiar contribution of this work was in its consideration for the de-twinning phenomenon in shape memory effect together with the geometrical variables. Therefore, the effect of the geometrical design was used efficiently to demonstrate that based on the spring index, a deformation up to 200%-1600% was possible. Using the carefully designed geometry, a two-way antagonistic actuation can also be achieved [13] using simple wire-form SMA elements. This type of design also requires kinematic considerations in addition to basic material properties.
Although overlooked in the previous studies, in addition to these obvious geometrical options (i.e. antagonistic couple and spring), meandering shapes on wires, inter-woven wire-meshes and parallel/series assemblies of SMA spring-coils can be examined to further explore the potential of geometrical/topological optimization on actuation performance (see Fig 1).

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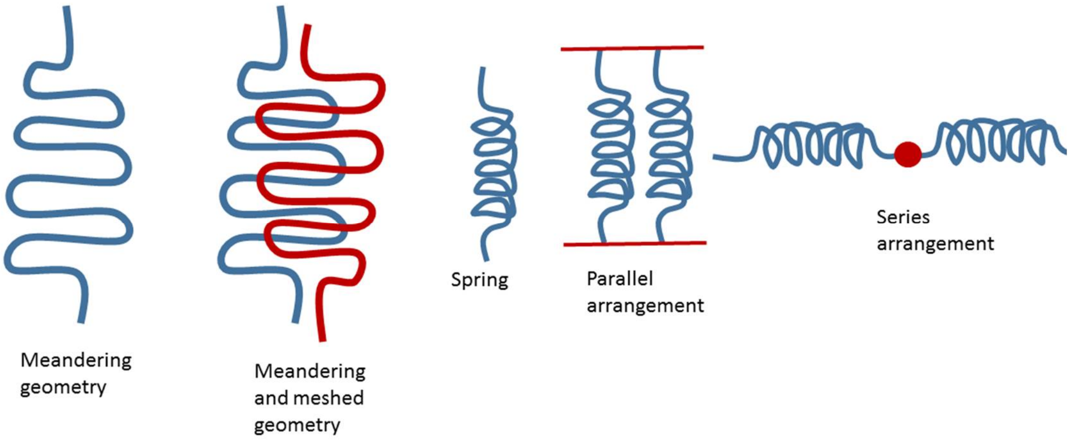


**Figure 1.** Different geometry/topological arrangements of SMA to increase the stroke or force, with subtle effects on cooling and reaction time

2.2.2. Optimal Geometry in FEA

Here the effective variables can be listed as the air/fluid chamber geometry and distribution, wall thickness, double polymer designs (to restrict the movement at particular direction), elastomeric fibers and their frequency/angle on the fluidic chambers. As in all other actuator types, the application determines the manipulator geometry and the suitable material, however here the specific emphasis is on the internal pressure and range of motion. In the work [14], finite element analysis is used to simulate the range of motion and hyper-elastic response of the two different type silicones. There, it clearly was indicated that different geometrical ratios and channel designs have affected the generated stress in the structure therefore causing a certain bending angles. The application is found to be appropriate in laparoscopic surgery due to internal tubing and volumetric allowance. Analytical models are also used in [15] to capture the explicit relationship between input pressure, bending angle and output force, by special emphasis on the actuator geometry.

Another significant example how the effective use of topology and geometry made it possible to build a macro-scale soft robot can be found in [16], (pp. 1). This soft robot is a 0.65m long, untethered structure able to support the miniature air compressors, battery, valves and controller on itself. The structure was able to operate because of the specific arrangement of the hollow glass spheres. Again, in order to increase the interaction area in the layer-by-layer process and prevent tear, a peg-hole geometry was used.

In an interesting work [17], (pp. 2164) using topology/geometry to enhance the response of the device fast-pneu-nets (fPN) was proposed. In contrast to previous and slower motion, the extensible layer of fPN contains gaps between the inside walls of each chamber. The dimensions of chambers here are designed in such a way to have inner wall thinner and greater surface area compared to the outer walls.

2.2.3. Topology in SMP

Here the coiling parameter, the self-coiling vs. mandrel coiling, chirality, the number of strands, any patterns of braid in the structure are important. A particular type soft actuator derived from fishing-line or sewing-thread uses thermo-mechanical actuation principle and can be considered in SMP category. In these actuators, the over-twisting and coiling is used before the heat treatment is applied. The geometry is extremely important because inserting the twist can introduce instability. To counter-balance this a counter-balancing braiding structure should be designed [18]. Perhaps one of the most interesting application ideas employing the topological/geometrical optimization is to consider vascularized structures made out of SMP materials using additive manufacturing [19].

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2.2.4. Geometry in DEAP

The ratio of elastic band/electrode area, the pre-stretching of the polymer (elastic strain), piling/stacking of the material. One of the very early works reporting on electro-active polymers has suggested a two-way working and tubular geometry [20]. A recurring idea to produce useful actuators from DEAP is to use stacking, folding [21, 22] or rolling the elastomer/polymer to increase either the force or the stroke as the main output of the actuator. A rolled elastomer design reported in [23, 24] was able to bend in many directions, therefore presenting a good candidate for surgical or mobile robotics use. Another common approach to manipulate the surface deformation in DEAPs to harvest the stroke/force in the desired orientation is to use fiber strands in various geometrical lay-outs [25]. This fiber surfaces can be arranged in micro-scale and the diamond shape areas can be customized to obtain the better result in actuation output using the angle between intersecting fibers [7].

*2.3. Scalability and Complexity*

A challenging problem in robotic design is the increasing complexity of the actuator as it is produced in larger or smaller scales. In order to better understand this problem and probe into certain limitations, herein the scalability and complexity of each selected actuator type are examined. The scalability can be limited by current manufacturing and assembly methods as well as physical limitations of the modality of the actuator (i.e. saturation, non-linear operation, uncertainty, deterioration of the physical phenomena at a particular scale).

2.3.1. Scalability of SMA

Although the studies on SMAs as actuators do not particularly focus on scalability and complexity issues, some applications may be singled out to provide a leading idea on the scalability. In one of those cases, [26] have studied the feasibility of the production of micro-scale structures using the micro-pulling growth technique to obtain thin wires of SMA involving single crystals. This ability of producing single-crystals in micro-scale allowed them to overcome the brittleness of SMA structures when they are produced in small-scales using poly-crystal inner structure. In their work involving the design of a torsional actuator based on SMAs, [27] have used a meso-scale antagonistic structure for bilateral functionality. Despite the disadvantage of difficult heat-transfer in macro-scale, SMA structures as passive super-elastic units in seismic applications is possible as seen in [28].

2.3.2. Scalability of FEA

We can see from the work in [16] that the soft lithography is a scalable molding process. In that work, they used this method to produce a robot with length of 15 and 65 cm. Although the manufacturing is scalable without much effort, the operation of the robot does not follow the same trend. The macro-size robot actuated by FEA should use a reduced density material or the actuation pressure should be increased to counter-balance its own weight. In addition to layer-by-layer soft-lithography method, better continuous soft actuators can be molded by a spin production process which is highly scalable [29] to produce monolithic soft-machines. In this scalable casting process, they could control more parameters compared to basic layering such as: (i) viscosity evolution during casting, (ii) rotational speed of the primary axis, (iii) axial speed ratio of the machine and (iv) the internal surface geometry of the two-part molds. This scalable monolithic casting process can be seen in Figure 2.
The soft robots actuated by FEA can be assumed to be much simpler than the mechanical ones, since they may be operated without an internal or external skeleton. Although the structural complexity might be low, complex locomotion patterns are possible such as ones including the change in gait [3], (p. 4). A limiting factor for such actuators could be related to the power supply for FEAs. Most fluidic actuators include compressors and bulky supply lines, increasing their complexity level [30], (p. 484).

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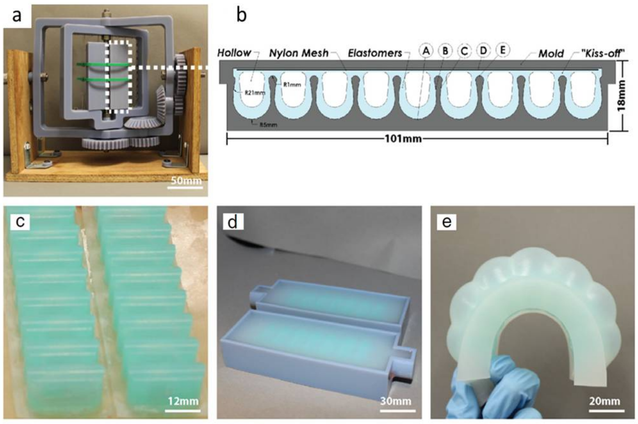


**Figure 2.** Rotational casting method (a) machine, (b) interior structure, (c) monoliths, (d) encapsulation, (e) inflation of cuboid actuator [29]

2.3.3. Scalability of SMP

SMP In the vascularized SMP blocks, the scalability was determined to be one of the limiting factors [19]. Since SMP structures can usually be actuated only in one direction, to eliminate this a composite containing SMP and SMA is manufactured in [31]. Here the structure is more functional and scalable since the two-way actuation is achieved by the SMA embedded in SMP and the actuation load is not on SMP. Another scalable format for SMPs is to use fiber or yarn based structures [32].

2.3.4. Scalability of DEAP

In order to examine the scalability and complexity in DEAP based actuators, a pre-strained circular actuator was modeled in detail [33]. To reduce the complexity and render the DEAP actuator scalable, an automated folding and production procedure was proposed in [22].

### *2.4. Amplification and Energy Efficiency*

The possibility of optimization of the stroke or force obtained from the actuator versus its energetic efficiency is highly linked together in SMA based actuators. In [34], hollow helical springs based on SMAs were proposed to reduce the weight of the actuator and increase the efficiency of the heating-cooling cycle. This work keeps the geometrical advantage of the helical design in amplification of the stroke but also reduces the loss of energetic efficiency by reducing the effective mass with the hollow-structure. In addition, the dimensionless units are employed for a better comparison between the hollow SMA springs and their solid counterparts, demonstrating a significant improvement. In terms of energy efficiency, the smaller the SMA structure, the better the energy conversion dynamics would be handled. An example of this behavior can be seen in SMA ultra-thin films [35]. The energy efficiency and work production is not frequently studied, however, for thermal cycles and work production of special SMAs can be found on a case by case basis as in [36].

In order to operate non-conventional actuators based on smart-materials, we often need to use amplification. In many cases, the energy transformation during actuation is from electrical energy to mechanical energy. For the case of SMP this transformation is thermo-mechanical and for FEAs hydro-mechanical/fluidic to mechanical domain. The need for the amplification and the nature of the energy domain change may bring problems related with efficiency. For this particular problem, we will compare our four selected actuators based on their need for amplification and energy conversion efficiency. It should be although noted that the actuator types with lower efficiencies cannot be considered completely insignificant based on this criterion because low-efficiency type actuators tend to provide compact actuation spaces which might serve as critical solutions especially for medical robotics.

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The DEAP based actuators is the most disadvantageous option among the soft actuators because of its need for high amplification of the voltage to obtain high electric fields [23]. The high-voltage requirement brings about extra problems such as electrical breakdown. In order to overcome this problem, the dielectric constant of the polymer can be improved by adding silica nanoparticles [37]. Although the amplification requirement and high voltage is a drawback, DEAP actuators can convert energy up to 0.4 J/g [38] which is larger than piezoelectric ceramics or electro-magnetic actuators. It is reported that the electro-mechanical coupling is around 60-80% in acrylic and can go up to 90% for silicon based polymers [8].

For the SMPs the amplification is not needed however the energy conversion efficiency during contraction is around 1.08-1.32% for Nylon and Polyethylene [18]. Another factor affecting the energy efficiency of SMP based actuators is to change the environment of the heat conduction, such as using water instead of air [32].

FEA based actuators can be using the topological optimization for the amplification and their energy efficiency is comparably low because they operate below 0.5MPa. The specific energy is particularly low in that pressure range, however reaching as high as 200 J/g when the pressure is around 5 MPa [39].

### *2.5. Technology Readiness Level (TRL)*

This is particularly relevant if these four actuator types are considered to be future solutions for robotics design. Unfortunately, most of the soft-robotics literature reports actuator designs which are not in the adequate TRL, therefore cannot be widely used outside of the laboratory conditions when they are placed in harsher environments with minimum control on the environmental conditions. We will assess the TRL of the selected four actuators based on the manufacturing methods, complexity and available materials.

Although being employed in many advanced engineering structures as deformation compensators, shape morphing or surface actuation applications especially in aerospace, the SMA-based actuators cannot be considered in the highest category in terms of technological readiness level (TRL). For example, in order to predict the relations between the variable thermo-mechanical conditions and the behavior of SMA a nonlinear model was formed in [40]. Understanding the underlying mechanism in thermos-mechanical behavior and presenting them in a mathematical model with predictive power is a very important step in terms of increasing the technological readiness level of SMA based actuators. In this way the disadvantages can be leveraged based on the thermos-mechanical conditions for a particular technological application. It is very effortful to reach to high TRL and asses it. In [41], it was demonstrated that for the full assessment of the TRL of SMA mechanical, magnetic, corrosion resistance and biocompatibility were considered.

DEAPs are technologically not ready to be used fully in medical and industrial robotics. Some of the challenges are actuation force levels, lifetime and activation voltage levels [23]. An important step to make them more durable and easily manufacturable through an automation process was performed in [22]. There, a fast and automated dry-deposition manufacturing process is demonstrated by producing several multi-layer stack actuators based in roll-to-sheet process. The problem with the DEAP production lies in the fact that, although well-adapted to laboratory experiments, carbon-based compliant electrodes have limitations with patternability, scalability and has no practical aspects for the large volume production [42].

For the SMPs, although these materials have been more studied and used in specific applications, their one-way actuation and limited strain endurance limited their potential. In order to alleviate these disadvantages, in [43] a two-way reversible shape memory effect using two types of polymers as the main core and matrix and a double extrusion process. There have been also other works reporting two-way operating SMPs using lamination process [44]. Although the two-way actuation is demonstrated in custom polymer matrix in laboratory conditions, it is not in the level to be used in large quantities or industrial settings. A comparison table for all four actuator types is given in Table 3.

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**Table 3.** Application oriented TRL comparison of soft and novel

| Actuator | TRL | Explanation |
|---|---|---|
| SMA | 6-8 | Adequate research background, some applications in robotics, still needs to be developed into full products. The problems with hysteresis and limited work-range needs attention. |
| FEA/SPA | 7-9 | Built on already existing technology and components from pneumatics and hydraulics, closer to be produced for large amounts in an automated manner. Limited range of work. |
| DEAP | 5-8 | Very few examples outside of laboratory, still needs improvement on materials, control and electro-mechanical design improvements. Limited due to high voltage requirements. |
| SMP | 5-8 | Very few examples outside of laboratory, one-way actuation, limited mechanical recovery. |

*2.6. Modality of operation*

The modality herein describes the energy domain the actuator mainly works in. For example SMPs are essentially thermo-mechanical actuators because they use the heat energy to relax the bonds between oligomers or re-contract when the heat is taken (cooling). Another case is DEAP which works based on electro-actuation depending on the Maxwell and Coulomb Laws defining electro-restrictive and electro-static forces on a flexible capacitor structure. SMA mainly works electro-mechanically however exploits the heat to transform the micro-structural change. FEA types depend on the fluidic power to obtain mechanical movement. Comparing these four actuation methods, the SMA and SMP are not highly efficient in terms of energy conversion because both of them involves heat-processes. DEAP is relatively efficient however requires amplification of feed-voltage and FEA requires additional complex equipment (compressor, filter and a valve) for the pressured air. Herein leaving aside the efficiency issue, we consider the four actuators in terms of application suitability based on their modality (thermal, fluidic, and electro-mechanical). By this way we clearly can identify which modalities are more appropriate for certain applications, therefore matching the actuators with the best applications to accentuate their significant side/ leverage their usage.

When the application convenience is considered for SMAs, any case where super-elasticity or shape memory is relevant can be thought. It is not uncommon to have SMAs as actuators in aerospace applications for shape-morphing of aero-foils [45] or for the simplification and compactness of UAV actuation [46]. The super-elasticity and shape memory property of SMAs also make them an excellent actuator choice for biomedical applications [47]. Although being not a conventional mechanical application, SMAs can also be used in small-scale thermal engines and pumps [48]. Mainly utilizing their super-elasticity, civil engineering also benefits from SMA materials [49], however, these applications usually benefit from the extra damping feature of SMA and can be considered as passive uses.

SMPs can be used in very specific applications, such as orthopedics, endoscopic surgery, orthodontics, kidney dialysis, neuro-prosthesis and bio-MEM [50]. As a sub-group of SMPs, using the super-coiled Nylon-based yarns, smart-textiles [18] can be produced using nylon as muscles, conductive silver-plated fibers for electro-thermal heating and polyester/cotton mixture for textile functionality.

For the FEA type actuators, it does not always have to be with pressurized air or fluid, a non-conventional prototype uses a system of interconnected chambers and vacuum [51] to achieve gripping force with compliant action. In this type of vacuum-operated actuators, the internal air chamber topology is extremely important since it determines the buckling pattern, please see Figure 3.

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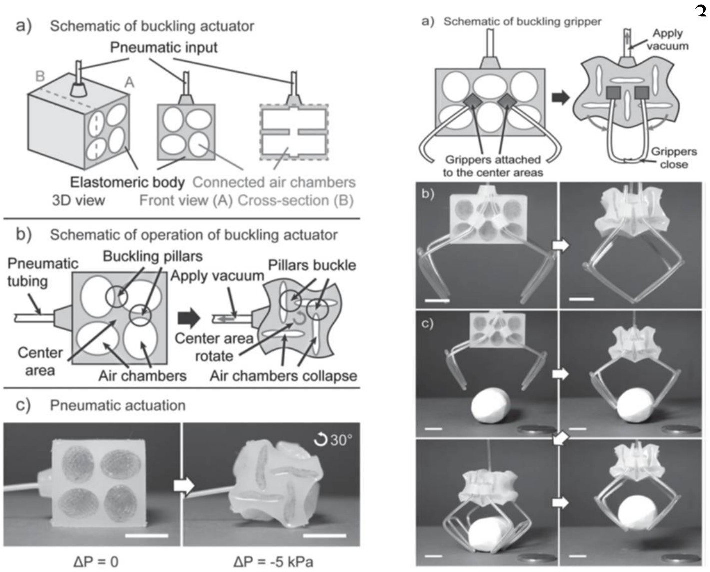


**Figure 3.** Vacuum-operated buckling FEA actuators, courtesy of [51]

Sometimes the pneumatic FEAs have to be integrated with a hybrid actuation as seen in [11]. To achieve elongation and bending in controlled directions, FEA and tendon drives can be used together. Regarding the modality or the physical characteristics of the actuators, a particular good example with the match of the robot function with its environment can be seen in soft jellyfish robot [52] using DEAP based actuators. This is an application where an underwater robot is designed which can also handle its own load. It also uses pneumatic principles together with DEAP based actuation to obtain a specific solution for underwater explorations. In order to widen the application of DEAP based actuators the flexible and stretchable electrodes are extremely important [42].

*2.7. Operation range*

2.7.1 Operation range of SMA

The maximum stroke of linear SMA wire actuators lies between 5% and 8% [53, 54]. Higher strains can be achieved with coil springs made from SMA wire, which represents a trade-off between smaller forces and larger strokes. The operation range of the SMAs can be increased with material science engineering studies. Perhaps the most relevant operation range property of SMAs is multi-cycle performance. Certain types of SMAs are studied to identify their functional performance under multi-cyclic conditions such as the work in [55].

2.7.2. Operation range of FEA

The FEA based soft robots are manufactured using siloxanes and elastomers and they are vulnerable when they meet sharp objects [3]. This property may limit their operation range in high pressure applications. In a recent work [16], it was demonstrated that robots can be propelled by pneumatically powered soft actuators with untethered operation underwater, in-land performing rolling and serpentine movements. Some of these robots had rigid structural components and did not move in locomotion patterns requiring to work against the gravity. Another performance limitation also mentioned by [16] is related to reaction time (100 ms) although the actuation itself is rapid because of the high pressure employed in this work (138 kPa).

In 'pneu-net' structures, recently they reduced the amount of the gas needed for actuation thus accelerating the actuation response [17]. In such structures, a simple actuator can bend from a linear to a quasi-circular shape in 50 ms when a pressure of 345 kPa is applied. In a normal operation scenario, pneu-nets ca be inflated with pressures as low as 50 kPa and they require a volumetric change of 20-folds of their initial volume to achieve their full range of bending. Unfortunately, this volumetric change may also be a disadvantage because of the need of certain workspace and the transfer of large volumes of gas is a thermodynamically inefficient process. In addition to this, because of the large strains on the material, the operating life-span of pneu-nets are rather short [17].

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The other important performance criteria may include the controllability, durability in adverse ambient conditions, and exposure to extreme heat, humidity and light. Some of these criteria is meaningful in the context of medical use since a sterilization might be necessary. While the others, such as controllability could be more important in an industrial setting. The robots with a silicone body are inherently resilient to adverse conditions such as cold weather, water exposure, direct exposure to the flames and high impacts [16]. In the same category with FEA, the pouch-motors proposed by [56] the measured maximum stroke was up to 28% obtaining 100N. In that work, the researchers also demonstrated an easy way to manufacture printable soft-actuators.

#### 2.7.3. Operation range of DEAP

A general operation requirement for elastomer based DEAPs is an electric field of 100V/µm, however in some of the chemically tailored polymers this performance can be greatly improved. For example in [57] a new class of all-organic-field-type EAP composite was derived exhibiting high elastic energy densities that are induced by an electric field as low as 13V/ µm. In a study exploring the nonlinearity and time-varying properties of DEAP based actuators [58], it was observed that DEAPs display linear dynamic response from approximately 1.5 to 3 kV, after this value a nonlinear actuation mode starts. In the application of DEAP for underwater robots [48] has reported a maximum trust force of 0.15N, which is relatively low for industrial robots however meaningful for the under-water self-sufficient exploration robots. In [33] using acrylic and gold particle-solution for stretchable electrodes, they were able to obtain 200MV/ m for a film thickness of 25µm corresponding to 200V/ µm, applying 5kV source of voltage. In the work by [24], rolled spring actuators based on DEAP were actuated using 5.9 kV for one side and a bending angle of 600 was achieved. The maximum lateral force obtained by this actuator was 1.68N at 7.7 kV. For the repeated and safe operation, the actuator was operated at 6kV obtaining 1.15 N. In order to obtain better performances, using electro-thermal and electro-strictive effects together with the enhanced electro-mechanical coupling, new composite research such as [59] is needed. In that study, titanium oxide nanotubes and carbon nanotubes are used to enhance the properties of candidate membrane materials. Enhancement of polarization and reduction of the stiffness are two parameters in such polymer research to obtain better electromechanical properties. Another work has the focus of eliminating the need for rigid frames in membrane type actuators [60]. In that work, after curing a certain additive, force equilibrium between the polymeric networks was able to preserve part of the pre-stretch, therefore eliminating the need for external rigid frames. Another attempt to reduce the necessary high voltages is to produce thinner elastomeric members as seen in the work by [61]. In the fabrication method described by that paper, the thickness variation was 4% and they were able to fabricate a layer of 5 µm thickness which in turn making it possible to drive such systems only at 150V. Further performance enhancements can be observed if the snap-through instability of such membranes can be harnessed by controlling the air chamber pressure [62], removing the need of constant voltage application. Sometimes the performance range can be enhanced by utilizing a different geometry and a suitable application. For example, in [63], the tubular form was employed for fluidic control. The system was able to create a rise in pressure by 3.0 kPa when the valve was passive and 0 kPa when it was activated at 2.4kV level.

#### 2.7.4. Operation range of SMP

Comparing SMP with SMAs, the SMPs have large recovery strains (above 300%) while having low recovery stress (around 1-10 MPa) while SMAs have lower recovery strains (less than 8%) and higher recovery stress (around 1GPa). The other performance related advantages of SMPs come from their biocompatibility, implantable structure and tunable actuation using the glass transition temperature [47]. The super-coiled nylon based SMP actuators have a very encouraging performance when they are used in filament state. For example extreme twisting and spinning of filaments can form artificial muscles that are able to contract by 49% and can generate around 5.3KW of mechanical power per kg of the material [18]. In order to further increase the performance and enhance the energy efficiency of such artificial muscles, passive cooling offers and economical solution to increase the cycle rate. According to the same study, when immersed in water, a two-ply, coiled, silver-plated 180 µm diameter Nylon fiber can be electro-thermally actuated at 5 Hz while producing 10% stroke and lifting 22MPa load. In the work of [64], the focus was to program the SMPs for a sustainable and repeatable operation of bidirectional actuation. They have achieved at least 250 cyclic thermally controlled actuations with almost constant performance.

## 3. Conclusion and Discussions

In this comprehensive overview of the soft and novel actuators in robotics, we have considered seven categories of selection criteria over four different type actuators. The overview provides a state-of-the-art evaluation of the field as well as providing a selection guide for the researchers in applied robotics field, especially involving soft robotics. It is very difficult to judge if a particular actuation device is appropriate for the given application without a clear comparison ground. Lastly, as an open discussion for the research community especially in soft robotics, combinations of these four type of actuators should be studied to identify the areas we can leverage their short-falls. Early examples of limited combinations are studied, for example SMA+SMP combination for more effective solutions have been proposed in [31]. However, a wider exploration space is necessary for the combinations of the actuator types. A combination table (see Table 4) is prepared here with possible application domains and improved capabilities.

**Table 4.** Soft and novel actuator combination table for hybrid solutions

| Combination | Improvement/ Leverage | Application domain |
|---|---|---|
| SMA + SMP | Wider bandwidth, removal of the need for external force for SMP, wider cooling window for SMA | Active construction solutions, adaptive and self-healing structures, soft robotics solutions in construction |
| FEA + SMA | Antagonistic principle can be used, wider time window for SMA to cool down, fast responses with FEA action, increase in compliancy, light-weight, shape morphing and stiffness variation is possible | Spine-like or worm-like structures in surgical robotics |
| FEA+DEAP | Snap-through property can be used to increase overall stroke or force capability, increased electro-mechanical durability of DEAP, removal of constant need to pressurize a particular system | Active touch-boards and human-machine interfaces |
| FEA+ SMP | Superb-shape morphing property via thermal or pneumatic actuation, low-weight | Soft surgical robots and exe-skeletons for augmenting human posture and physio-therapy, soft and adaptable prosthesis structures |

As it can be seen in this combination (Table 4), many novel hybrid actuators can be envisioned and produced to strengthen a particular side of a certain actuator type while allowing the other type to fill in the gap. The application domains of soft and novel actuators can be widened using multiple actuator types in a suitable topological and geometrical arrangement or using additive manufacturing possibilities to obtain a seamless hybrid actuator.

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