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POTENTIAL MERITS FOR SPACE ROBOTICS FROM NOVEL SOFT ROBOTICS ACTUATION CONCEPTS

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ABSTRACT

Autonomous robots in dynamic and unstructured environments require high performance, energy efficient and reliable actuators. In this paper we give an overview of the first results of two lines of research regarding the novel actuation principle we introduced: Series-Parallel Elastic Actuation (SPEA). Firstly, we introduce the SPEA concept and present first prototypes and results. Secondly, we discuss the potential of self-healing materials in robotics, and discuss the results on the first self-healing pneumatic cell and self-healing mechanical fuse. Both concepts have the potential to improve performance, energy efficiency and reliability.

1 INTRODUCTION

When novel robotic applications with increased performances are required, a surge in demand for more performant actuators is only logic. In order to open the frontier, novel concepts of actuation are needed. Automation/robotics use mostly actuators that are as stiff as possible. The actuator moves the link to the commanded position, whatever the external forces acting on the joint. These actuator systems usually consist of an electric motor with a high-gear transmission drive to reduce the rotation speed while increasing the torque. Such an actuator shows an excellent behavior for high bandwidth and high accuracy trajectory tracking. They are often deployed in industrial robots used in known and static environments. Because the actuator has its own dynamics (due to its mass, reflected inertia, stiffness, etc.), it heavily influences the global control and performance of the system. They are energy inefficient and the high-reflected inertia of the high-geared motor makes them unsafe in case of impacts and clamping. For this reason industrial robots powered by servomotors are often put in cages. The next generation of robots, however, will strongly collaborate with humans, implying new requirements such as safety and energy-efficiency. Compliant actuators try to cope with these new challenges [1]. The introduction of spring elements in the actuation of robots was inspired by biology that explains the important role of biological springs in animals and humans. The first compliant actuators were introduced by the so called series elastic actuator (SEA) of Pratt et al. [2] in 1995. The SEA includes an elastic element, typically a spring, in series with a traditional servomotor. Opposed to stiff actuation, the inertia from one link to the other is decoupled over the spring in a SEA, which is beneficial for safety and shock-absorbance [3]. Furthermore, the spring deflection can be used as a toque measurement, and energy can be stored and recoiled via the spring [4]. For about two decades, multiple research efforts proved the possibility of increasing the robustness, safety for human-robot interaction (HRI), energy efficiency and enabling inexpensive impedance control. More recently SEA technology found its way to the market, for example in the Baxter Robot from Rethink Robotics. Robonaut 2, the first humanoid in space from NASA and General Motors, is built out of SEAs as well. As described in [5], the series elastic arms do not sacrifice strength, or payload capacity, to achieve fine torque sensing at each of its joints. In [6] the potential use of a lower limb exoskeleton (driven by SEAs) in space is discussed.

In succession of SEAs, variable impedance actuators (VIA) have been introduced, which enable to change the damping and/or stiffness of the actuator. This resembles for example the human ability to alter the joint stiffness, by means of regulating the co-contraction of antagonistic muscles. As such, it is possible to increase the energy efficiency by tuning the natural frequency of the joint to the frequency of cyclic tasks. The review articles [4] provides full details on VIAs for the interested reader.

Recent efforts in the robotics community push the boundaries of current compliant actuators based on different technologies. Urata et al. [7] used active liquid cooling of the motor, Tsagarakis et al. [8] use a single rubber parallel to the knee joint which can be pretensioned and reduces the torque required from the motor, and Paine et al. [9] used an efficient ball-screw mechanism.

In this paper we give an overview of our work regarding Series-Parallel Elastic Actuators (SPEA) and self-healing materials (SH). In section 2 we introduce two SPEA schematics, and discuss early outcomes. The concept of integrating SH materials in compliant actuators, as well as first results on 2 prototypes, is discussed in Section 3.

2 SERIES-PARALLEL ELASTIC ACTUATION

As discussed in the problem analysis in [10], one of the essential remaining problems, resides in the fact that for either a stiff actuator, a SEA or a VSA, the full output load always stresses the motor since motor and load are in series, as indicated in Figure 1. Furthermore, a robotic joint typically operates at high torque and low speed, which is opposite to the nominal operation of an electric motor. Therefore, gear trains with high reduction ratios are required. The energy losses, however, increase with the number of stages and the weight increases with the maximum output torque. High torque electric motors are also heavy since the weight of electric motors is proportional to the maximum continuous output torque of the motor. Furthermore, the quadrant of low speed and high torque is the most inefficient quadrant in the energy efficiency contour of electric motors. Therefore, electric motors in robotics often work significantly below their maximum energy efficiency since the iron losses are in quadratic relation with the current, which is in linear relation with the motor torque. In general, one could state that the low torque-to-weight ratio and low energy efficiency are mainly limiting the performance of current actuator technology driven by electric motors [10].

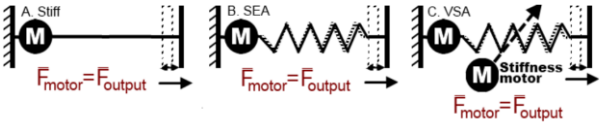

Figure 1 The linear schematics of a stiff actuator, SEA and VSA indicate that the motor is always in series with the load. As such, the motor torque is always proportional to the output torque.

In contrast to a SEA, a Parallel Elastic Actuator (PEA) has a spring in parallel to the motor and can provide load cancellation. In specific tasks, the stiffness of the PEA can be tuned, so that the parallel spring can deliver most of the required output torque while the motor should only deliver the difference [11]. One disadvantage of a PEA is that it limits movement dexterity since it is always engaged. Therefore, Haeufle et al. designed a clutchable PEA (cPEA) where the parallel spring can be connected or disconnected [12], and Au et al. implemented a uni-directional parallel spring in their ankle prosthesis [13]. These solutions are, however, only binary solutions and thus still limited to specific applications, while most robots need to preform very versatile tasks.

The concept we proposed in previous work [14] is to variably recruit and lock multiple springs and/or motors in parallel, in a single joint. The main idea is to allow for variable load cancellation through the locked parallel springs. We named this concept series-parallel elastic actuation (SPEA). In contrast to the schematics in Figure 1, the motor in a SPEA is not in series with the output. As such, the motor is only proportional to a part of the output torque, since the remaining part is provided by the parallel springs. As a result, the motor and gear train can be downscaled, and the energy efficiency can be increased. We identified two sub-concepts:

- iSPEA: SPEA based on intermittent mechanism and passive locking mechanism which allows a single motor to variable recruit multiple springs in parallel.
- +SPEA: consists of multiple layers, each composed of a SEA with non-backdrivable mechanism.

Both sub-concepts and experimental results will be discussed in the remainder of this Section 2.

2.1 iSPEA: intermittent locking mechanisms and parallel springs in the drive train

As shown in the schematic Figure 2, the SPEA consists of one motor (solid black circular motor symbol) which can shift position (shaded motor symbols) to variably tension and lock each successive parallel spring. This variable recruitment results from multiple dephased intermittent mechanisms in parallel, that position the motor from spring to spring, represented by the blue dotted rectangle. This allows to tension each parallel spring of the SPEA from unpretensioned to pretensioned phase (or vice versa) during the pretensioning phase. As a result, the motor of a SPEA with *n* springs is only loaded by the force of one spring of which the stiffness is *n* times lower than the stiffness of the spring in an equivalent SEA [10].

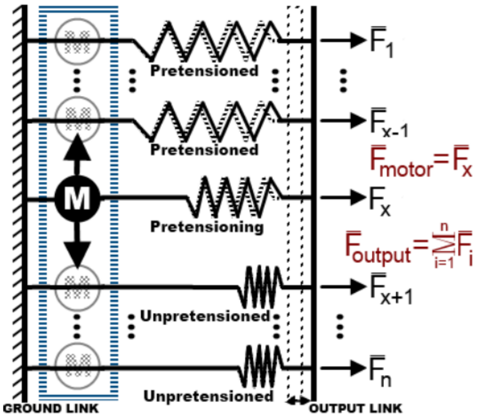

Figure 2 The dephased intermittent mechanisms in the blue box of this iSPEA schematic, allow the motor to switch between layers to tension the springs subsequently.

The prototype shown in Figure 3 is an iSPEA based on the VSA actuator developed at VUB, Brussels: the MACCEPA actuator [15]. The iSPEA consists of 8 parallel springs, which can each be moved/tensioned in self-closing guides, by motor arms connected to cylindrical cam-mechanisms. As shown in Figure 3 (a), continuous motor axis (brown) rotation results in intermittent axial and rotational movement of the cylindrical cams (yellow) to which a motor arm (red) is connected. As such, the complete mechanism is able to tension each spring in succession, after which each spring is mechanically locked inside its guide.

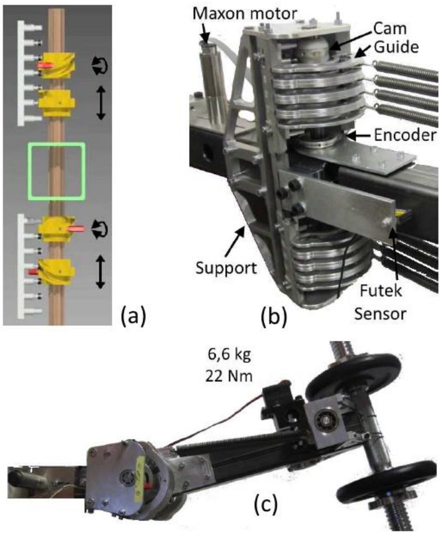

Figure 3 The cylindrical cam-mechanism shown in (a) ensures the (brown) motor axis is only loaded by maximum 2 springs at the same time. The practical realization of this mechanism is shown in (b) and the full actuator in (c).

The working principle described here above, can be linked to the experimental results in Figure 4. The motor torque is characterized by 8 repetitive profiles (8 positive and negative peaks). This is due to the unlocking of a spring on one side of the guide, then tensioning the spring towards the other side of the guide, and then locking the spring again to the guide. The output torque changes continuously and is approximately 8 times higher than the motor torque.

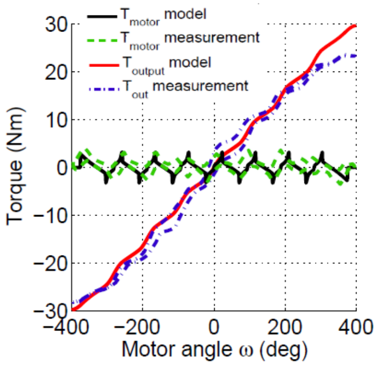

Figure 4 The measured output and motor torque match the modelled torque, in this experiment with fixed output position. The motor torque is also clearly lower than the output torque.

The interested reader can consult [16] [17] for more information and results on additional prototypes.

2.2 +SPEA: redundancy and modularity on the actuator level

A linear schematic of the +SPEA is shown in Figure 5. The main idea is to have multiple SEAs in parallel, of which each motor is in series with a non-backdrivable element (NBE). As indicated in Figure 5, this concept results in redundancy since, opposite to a standard SEA, the torque/force on the output can be delivered by multiple motors in infinite combinations. The theoretical functioning of the non-backdrivable element in each layer is as follows:

- Forward efficiency 100%: the motor can directly control the spring.
- Backward efficiency 0%: the spring cannot control the motor.

As such, the motor in a certain layer can deflect its spring, which will result in a torque/force generated on the output. Next, when the motor is standing still, the motor does not consume any energy in order to maintain this deflection. In other words, when the mechanical power is zero, the required electric power is zero as well.

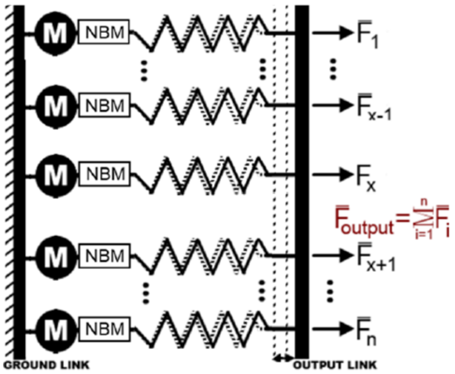

Figure 5 In a +SPEA each similar parallel layer consists of a SEA with a non-backdrivable mechanism in line with the motor in order to lock each layer to the ground.

The +SPEA concept opens to door towards modularity on the actuator level. In the robotics community, several groups have investigated the potential of creating a limited amount of modules which can be the basis to create many different robots. One example is the University of Pisa where the VSA-cube is developed [18]. Besides being a variable stiffness actuator, these cubes are modular which enables the design of several different robotic platforms such as parallel robots, robotic arms, robotic torso with arms, etc. In [19] a modular actuation architecture is described, which is scalable.

A modular design is built up of *n* modules, which are few in type but many in number. The main advantages of a modular system are threefold [20]:

- Versatility: the different modules can be connected in many different ways.
- Robustness: due to the redundancy, the failing of certain modules does not cause abrupt malfunctioning of the system, but gracefully degrading of the overall performance.
- Low cost: due to economies of scale module prices can be reduced. Furthermore, development costs for a new system can be reduced drastically.

The difference in this work is to introduce modularity on the actuator level, i.e. the creation of modular actuation layers which can be combined to create actuators with different specifications. In order to design an elegant modular system, one needs to overcome the following challenges:

- Limit the size of one dimension of the minimum actuator bounding box. This is needed since different layers will be stacked.
- Limit the weight of one layer.
- Integrate electronics in each layer with daisy chain communication towards the master controller.
- Provide a convenient way to stack and mechanically connect two layers.

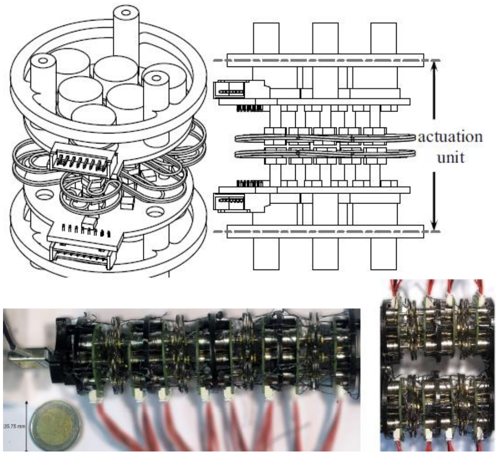

Figure 6 A CAD drawing of one actuation unit consisting of 12 solenoids, each in line with a spring. Two pictures of a string of 4 units in series, and a bundle of two strings with 2 units in series. Figures taken from [21].

A first prototype consists of a linear uni-directional muscle-like actuator. The SEA layers in this actuator consist of relatively small solenoids in series with a leaf spring. These SEA layers are then combined in series and parallel as shown in Figure 6. One actuation unit consists of two times 6 SEA layers in parallel. Each solenoid can only be activated discretely; however, due to the high number of solenoids a nearly continuous output force profile of the entire actuator can still be obtained. Future work consists of implementing a suitable NBM in series with each solenoid in order to avoid energy consumption

3 SELF-HEALING PNEUMATIC ACTUATOR

The second research track is about self-healing (SH) materials. SH materials are inspired by the remarkable ability of nature to recover systems, e.g. the human body, after being overloaded in abnormal conditions. Chemists have developed these materials since 15 years after the introduction by White et al. [22]. Recently these findings resulted in first commercial applications, like the puncture SH-polymer in aerospace [23], and SH-paints of Nissan and AksoNovel in the automotive industry. Inspired by this SH feature, an extensive literature study [24] was conducted on the use of self-healing (SH) materials in robotics. Diels-Alder (DA) polymers were chosen as an appropriate SH-material. The SH-process of DA-polymers, which relies on a thermoreversible network formed by Diels-Alder covalent bonds, is non-autonomous and requires a heat stimulus (between 70°C and 130°C). After this SH-process the material is back in its original state, resulting in unlimited SH-cycles in applications. Furthermore, DA-polymers have favorable mechanical properties, like a relatively high strength and Young’s Modulus [24].

The research group Physical Chemistry and Polymer Science (FYSC), of the Vrije Universiteit Brussel (VUB) developed three DA-polymers: DPBM-FGE-J400, -J2000 and -J4000. Although the mechanical properties of these materials differ over a broad range, the SH-property relies on the same Diels-Alder cross-linking in the polymer network. The network of the -J400 material is built out of relatively short polymer chains. This results in a high cross-linking density, which is translated in a brittle, glassy thermoset behavior. The –J2000 and –J4000 series, on the contrary, are made of longer polymer chains, and present a ductile, flexible elastomeric behavior. Since the synthesized DA-polymers differ only in the polymer chain length, it is perfectly possible to mix them during synthesis in order to derive materials with mechanical properties lying in between the standard three.

Our research focusses on integrating SH-materials, more specific the DA-polymers, in robotic actuators, as such creating self-healing actuators. Two specific and novel concepts [24] were recently elaborated, which are discussed in the subsections underneath:

- A SH-mechanical fuse, which can be integrated in a VIA in order to limit over dimensioning and allow the actuator to withstand unexpected loads without sacrificing reliability.

- A SH soft pneumatic actuator (SPA), which can overcome damages, caused by sharp objects, using an autonomous SH-procedure and as such increases its reliability.

3.1 SH mechanical fuse in VIA

Based on the DA-polymers, a self-healing mechanical fuse is designed. The fuse can be implemented in the design of a VIA, like for example, it can be positioned in series with the spring of a SEA as shown in Figure 7. The fuse is designed to be the weakest link and whenever a damaging overload, which could potentially damage one of the actuator components, occurs on the system, the fuse fractures sacrificially. However, after fracture of the fuse, the actuator will be put in an offline mode, in which the fuse can be self-healed using a fully autonomous system. The main advantage is that using this principle all components, of high-value or ones which are difficult to replace, are protected, while there is no need for large over-dimensioning.

After failure, the actuator will be put in offline mode after which the self-healing process can start. In order to have minor mechanical contribution in normal operation, the fuse is constructed out of –J400 material, the most brittle available DA-polymer. By varying the diameter of the fuse (Figure 7), the fracture force can be imposed. In first proof of concept study, three fuses were produced. These were sequentially self-healed, using a SH-procedure, and fractured for three times, while the fracture forces were measured. The SH-procedure took 170 minutes and reached a maximum temperature of 119.5°C [1]. The experimental results (Figure 8), clearly indicate that the initial fracture force (after 1 SH-cycle) differs for the three fuses, due to manual processing of the –J400 material. However, what is important though is that for the fuses individually, the mechanical properties after three SH-cycles remained near the initial properties. There was no decreasing trend in the fracture force recorded, which indicates that the mechanical properties of the fuse remain stable for at least three SH-cycles.

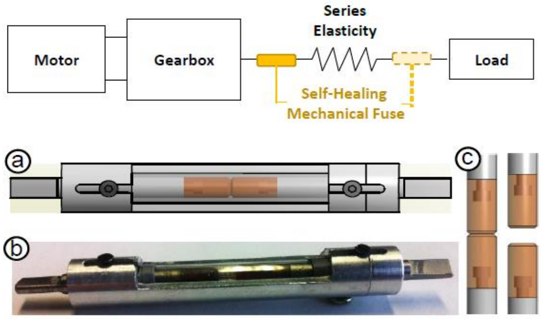

Figure 7 Schematic of the SH-MF in a SEA, and a CAD and picture of the fuse and cover. The orange part is SH material.

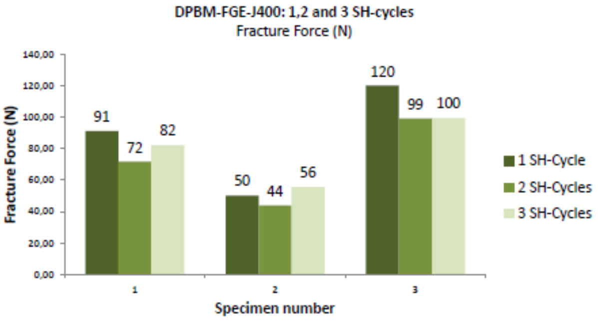

Figure 8 Measured fraction force after different self-healing cycles.

3.2 SH soft pneumatic actuator (SPA)

Inspired by the intrinsic softness and the corresponding embodied intelligence principles, soft pneumatic actuators (SPA) have been developed, which ensure safe interaction in unstructured, unknown environments [24]. Most SPAs consist out of more cells, containing air chambers, which can be inflated by putting them under an over-pressure. The actuators are designed to have an anisotropic response to a stress, generated by the over-pressure in the air chamber. To introduce this anisotropy, non (or less) stretchable but flexible materials are used in the designs, which restrict the elongation of parts of the soft actuator. The use of SPAs in unstructured, unknown environments will introduce a new problem: the actuator parts can be easily ripped, perforated or scratched by sharp objects. This can be solved by designing SPAs entirely in SH-material. The general design is presented in Figure 9 (b) and in (c) the cell is shown under test while the produced force is measured. In future work, multiple cells will be combined to a bending soft pneumatic actuator as shown in Figure 9 (c).

To evaluate the SH-property of the SPC, an incision of 4 mm (Figure 10) was made in one of the cube's planes and self-healed, using a SH-procedure with duration of 30 hours and a maximum temperature of 70 °C. Both before and after the incision was made and the SH-procedure took place, for an increasing over-pressure, the cell failed at exactly the same spot, different from the location of the incision. This indicates that the incision was completely healed and the cell did not get weakened. The combination of adequate mechanical properties and the excellent SH-property of the SPC indicates that the DA-polymers have high potential for being used in soft-bodied robotics.

[1] A movie of the self-healing of a DPBM-FGE-J2000 sample at: https://www.youtube.com/watch?v=jR6ddEfdPbs

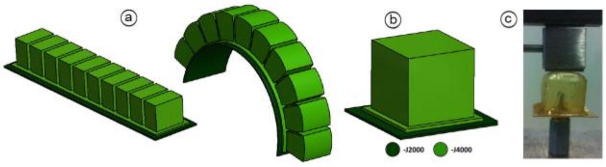

Figure 9 In future work multiple cells will be combined to form a bending soft pneumatic actuator as shown in (a). A soft pneumatic cell in (b), and under test while the resulting force is measured (c).

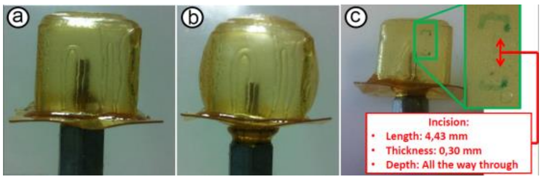

Figure 10 SH cell in rest state (a) and in pressurized state (b) The incision made in the cell for SH in (c).

3.3 Shaping through folding and self-healing:

In our research on SH-SPAs, we developed a completely new shaping method to develop 3D polygon structures starting from synthesized self-healing polymers sheets, which utilizes the SH-properties of these polymers; "shaping through folding and self-healing" (Figure 11). In this process, a 3D polygon structure is constructed by folding a 2D SH-polymer sheet, similar to making an origami structure. The sides of 3D polygon structure are made air tight using a SH-procedure at relative low temperatures, not higher than 100 °C. This shaping through folding and self-healing principle was used to develop the SPC prototype (figure 8). Not only the cube sides were sealed using this shaping process; because the SH-property of both the –J4000 and –J2000, relies on the same Diels-Alder cross-link bonds, sheets with completely different mechanical properties can be joined together. Therefore, also the bottom –J2000 sheet could be joined with the cube, using a self-healing procedure. The resulting prototype showed that the SH-property of the DA-polymer introduces an advantage in shaping processes; it can indeed be used to join SH-polymer sheets to form 3D structures.

Figure 11 Shaping through folding and self-healing.

4 DISCUSSION AND FUTURE WORK

The work on SPEA actuators is fundamental in nature. Nonetheless, implementing the SPEA actuators in specific applications are identified as future work. For example, exoskeletons, hand-arm systems and co-workers are possible candidates. Mainly since the actuator performance is crucial and challenging, and since the energy efficiency is important. Besides further hardware development, we are working on controls strategies, which is challenging due to the increased redundancy. The self-healing soft cells will be combined to form bending actuators, which can for example be used for hand rehabilitation exoskeletons.

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