Abstract—Last 15 years, a wide range of self-healing (SH) materials has been developed and recently these materials are increasingly used in applications in multiple fields, like the automotive industry and aerospace. However, so far this material technology is not yet explored in robotics. The introduction of these materials in robotics will potentially reduce the over-dimensioning of current robotic systems, leading to lighter systems and eventually to more efficient designs. Compliant elements used in next generation soft robots, can be constructed from available SH-materials, making them able to autonomously heal cuts and perforations caused by sharp objects in unstructured environments. In addition, the use of SH-materials will have a beneficial impact on the life span of robotic components, reducing the required maintenance drastically. This paper presents the innovative concept of implementing a SH-mechanism in compliant actuators, using dynamic covalent polymer network systems based on the reversible Diels-Alder (DA) reaction. For two entirely different compliant actuators, a series elastic actuator (SEA) and a soft pneumatic actuator (SPA), an analysis is presented on the integration of the DA-polymer systems in the actuator designs. For both actuator types, a prototype was designed, developed and validated.

I. INTRODUCTION

Natural organisms have a remarkable, unique property, the ability to self-heal when certain damages and injuries occur. Their bodies are not over-dimensioned and fractures, ruptures and injuries will occur when a body part is overloaded in abnormal, extreme circumstances. When these extreme, damaging conditions are ended and the body is back in its normal state, the healing process will start up autonomously. This healing process will take some time but will, if the damage is limited, recover the body part to its original state. This powerful biological healing function has inspired chemists to impart similar properties to synthetic materials to create “self-healing materials”. Since White et. al. [1] first introduced this technology in 2001, a broad range of SH-materials has been developed [2]–[4]. Recent developments in SH-polymers have led to commercial applications, e.g., the SH-paints of Nissan and AkzoNobel, and are promising for future commercial applications, like the puncture SH-polymers in aerospace [5]. However, SH-materials have not yet been explored in robotics. So far, robots do not have healing abilities. To the best of the authors’ knowledge, only one paper by Hunt et al. [6] can be found in which a SH-principle is used to create a SH-dielectric elastomer actuator and in a publication of Wei et al. [7] it is suggested to use a SH-hydrogel in future soft robotics applications. The introduction of SH-materials in robotics has potential to tackle three problems, described in the following three paragraphs.

In order to be able to withstand unexpected loads, robotic systems are over-dimensioned. The different parts are designed to withstand extreme circumstances to avoid damage. Robots are dimensioned based on these extreme loads, taking into account a high safety factor, instead of on their performance tasks, resulting in heavy and over-sized robotic systems. This over-dimensioning is a first problem that can be addressed by integrating a SH-mechanism, in line with the general trend in robotics to design ever lighter and more compact systems to improve performance and efficiency. This trend encourages designers to create smaller, more elegant and compact robotic designs. Despite the over-dimensioning, some really compact, lightweight designs have been developed. However, in these complex structures, the components become less accessible for maintenance. If a component has failed, usually a large part of the robotic system has to be disassembled in order to replace it, a very costly and time consuming intervention done by specialists. Animals exploit soft structures to move effectively in complex, dynamic and unstructured environments. These capabilities have inspired robotic engineers to incorporate soft technologies into actuator designs. This has led to the development of a new robotic field: “soft robotics” [8]. In this soft robotics field, compliant actuators have been developed that insure safe contact with unstructured surroundings, by exploiting the embodied intelligence of an intrinsic soft mechanisms. An integrated compliant/elastic mechanism allows them to deviate from their equilibrium position, whenever an external force is applied on the actuator system. This intrinsic compliance ensures safe contact, protecting both surrounding and the robotic hardware. With this new concept safe, energy-efficient, and highly dynamic motions can be achieved for powering next generation robots, which have to collaborate with humans and interact with an unknown environment. However, in general, the compliant elements used in these actuator systems are susceptible to damage by sharp objects found in the unstructured environments, since they are constructed from soft materials (e.g. rubbers) instead of metal parts.

Despite available SH-concepts having the potential of being introduced in a lot of robotic components, this work is focused on self-healing of actuators. It is believed that the introduction of a SH-mechanism in actuators will have a
A major contribution to solving the three problems described above. However, the SH-technology can be used for other robotic parts as well, e.g., the robotic skin or cover could be protected against clamping and scraping with existing SH-coatings [3], [9], [10] or using a recently developed artificial stretchable SH-film for artificial skin applications [11]. Because robots are finding more and more applications in unstructured and dynamic environments, compliant actuators are increasingly used, rather than the traditional electric stiff actuators and servomotors [12]–[16]. Therefore, and because these actuators resemble more closely to biological muscle systems, the focus is on compliant actuators. However, the outcomes of this research can lead to the introduction of SH-materials in stiff actuators as well.

Compliant actuators can be classified in two major groups: “Variable Impedance Actuators (VIA)” [17] and “Soft-Bodied Actuators (SBA)” [18]. These two groups are dealing with specific problems for which the implementation of a SH-principle in the actuator designs can be the solution. The first part of this research focuses on VIAs, in which a mechanism is integrated that allows to physically modify the stiffness of the compliant element in the actuator. Currently, these actuators are over-dimensioned to withstand unexpected, potentially damaging loads, which occur in the unstructured, dynamical environments in which these actuators are used. By incorporating a SH-ability, these actuators can be dimensioned based on their performance tasks, instead of on extreme unexpected loads. If an overload takes place, a robotic part will fail. Using the SH-ability, the part can be healed back to its initial state, and this preferentially autonomously. In this way, “self-healing robotics” can lead to lighter systems and eventually to more efficient compliant actuator designs. The introduction of the SH-materials will have a beneficial impact on the life span of these systems, reducing the required maintenance drastically.

Secondly, this research concentrates on implementing the SH-ability in SBAs [15], [18], [19]. SBAs are constructed (almost) entirely out of soft materials and aim to achieve mechanical properties matching the requirements of the two actuators. By incorporating a SH-ability, these actuators can be dimensioned based on their performance tasks, instead of on extreme unexpected loads. If an overload takes place, a robotic part will fail. Using the SH-ability, the part can be healed back to its initial state, and this preferentially autonomously. In this way, “self-healing robotics” can lead to lighter systems and eventually to more efficient compliant actuator designs. The introduction of the SH-materials will have a beneficial impact on the life span of these systems, reducing the required maintenance drastically.

On both actuator types, the VIAs and the SBAs, a feasibility study was performed, which resulted in working prototypes for both actuator types, indicating the potential of SH-polymers to be implemented in other compliant actuator designs. The two prototypes and their experimental validation will be discussed briefly in Sections III and IV, after the used SH-polymers are introduced in Section II.

II. DIELS-ALDER SH-POLYMERS

A. Selection of the SH-material

Following the paper of Williams et. al. [2], the different SH-materials can be classified based on the underlying chemistry of their SH-mechanisms (Fig. 1), which are extensively discussed in review papers [2]–[4]. These mechanisms were analyzed, in order to see whether they were suitable to be used in a compliant actuator design. Diels-Alder (DA) polymers were chosen for a first implementation of self-healing in a compliant actuator. The SH-process of these non-autonomous SH-polymers requires a heat stimulus and is based on reversible covalent bonds. One of the reasons why the DA-polymers were chosen is because after healing the mechanical properties are almost completely recovered, which means that the number of SH-cycles for a polymer part is not limited. A second advantage is that these polymers have a relative high strength and high ultimate tensile strength, required for the compliant actuator applications, due to the strong reversible bonds in the polymer network. Furthermore, the maximum temperature of the SH-process is relatively low, between 70 °C and 130 °C.

B. Diels-Alder SH-polymers

The DA-polymers are a reversible polymer network, formed by a DA cross-linking reaction, between a synthesized furan functional compound and a bismaleimide. Furan rings, present on the four-functional furan compound, form DA-bonds with the maleimide rings, present on the bi-functional maleimide compound, resulting in a thermo-reversible network structure (Fig. 2). At the research group Physical Chemistry and Polymer Science (FYSC), of the Vrije Universiteit Brussel (VUB), the DA-polymers were developed. The complete description of the synthesis is described in [10], as well as the SH-mechanism. The SH-compliant actuator concepts, described in the following Sections III and IV, pose totally different requirements on the mechanical properties of the SH-materials used. However, the mechanical properties of the DA-polymers can be tuned by varying the furan spacer length (Fig. 3), the polymer chain length of the poly(propylene oxide) chain of the Jeffamine used in the synthesis. FYSC synthesized a series of three DA-polymers, noted DPBM-FGE-J400, -J2000 and -J4000, with specific mechanical properties matching the requirements of the two

1 A movie of the self-healing of a DPBM-FGE-J2000 sample can be found at: https://www.youtube.com/watch?v=jR6ddEfdPbs
actuator concepts. As a result, the self-healing of both concepts relies on the same SH-mechanism, a covalent polymer network based on the reversible Diels-Alder reaction.

C. Characteristics of the DPBM-FGE-Jx series

In this section, it is illustrated that by varying the spacer length in the synthesis of the DPBM-FGE-Jx materials, large variations in mechanical properties can be obtained. The three materials, J400, J2000 and J4000, can be classified in: the "reversible glassy thermosets" and the "reversible elastomers", based on their viscoelastic behavior at ambient temperature (T_{ambient}). J400 contains furan compounds with short polymer chain length. Due to these short chains, the network has a high cross-link density, which raises the glass transition temperature (T_g) of the polymer above T_{ambient}, leading to (brittle) glassy thermosets. J2000 and J4000 on the other hand are built up out of furan compounds with longer polymer chain length, limiting the cross link density. These materials are elastomers, with ductile characteristics, having a T_g lower than T_{ambient}. In Table I the T_g, measured by Scheltjens et al. [10], and the densities of the three DA-polymers are presented.

In order to determine the viscoelastic behavior of the DA-polymer series at ambient temperature, a Dynamic Mechanical Analysis (DMA) was carried out. As the viscoelastic properties of the materials are frequency dependent, DMA is typically carried out at a frequency of 1 Hz. For J400 and J2000 a fixed strain amplitude of 0.1 % was used, the test with J4000 was done with an amplitude of 1.0 %. In Table II the Storage modulus, Loss modulus and the ratio between these two, tan(δ), are presented for ambient temperature (25 °C). At 25°C J400 is in the glassy region (Table II), where the storage modulus (2280 MPa) is high compared to the loss modulus (111 MPa), which results in a low tan(δ) (0.049), indicating that there is almost no viscous contribution. J400 behaves like an elastic solid, almost all the energy required to deform the sample is elastically recoverable. Therefore, in following applications, J400 is considered an elastic material (instead of viscoelastic) at ambient temperature, with a Young’s modulus equal to the storage modulus. This however is not the case for J2000 and J4000: their viscoelastic behavior makes it impossible to neglect the viscous contribution at 25 °C and attention should be given to this in their applications.

To derive the fracture stress and strain, a static tensile test until fracture was carried out. The test was done with a minimum of four samples for each material, for which a mean value of the fracture strain and fracture tension was calculated, as well as the maximum deviation (Table III). It can be noticed that the variations of the fracture tension and fracture strain, are quite substantial. This is due to small defects, cracks or remaining solvent-induced bubbles (synthesis [10]), which have a large impact since the samples used in the DMA are relatively small.

As the studied reversible polymer networks differ only in spacer length, it is possible to mix different furan compounds during the synthesis, to obtain DA-polymers with intermediate desirable material properties. All these DA-polymers will contain the SH-property, however, since their T_g varies, the duration and the maximum temperature of the required SH-procedure will differ. This mixing ability is a great advantage as it provides a certain degree of freedom in the design of

### Table I

<table>
<thead>
<tr>
<th>Transition temperatures of DPBM-FGE-Jx</th>
<th>Classification</th>
<th>T_g (°C)</th>
<th>Density (g/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J400</td>
<td>Glassy Thermoset</td>
<td>55.5</td>
<td>1.19 ± 0.01</td>
</tr>
<tr>
<td>J2000</td>
<td>Glassy Thermoset</td>
<td>55.3</td>
<td>1.13 ± 0.02</td>
</tr>
<tr>
<td>J4000</td>
<td>Elastomers</td>
<td>64.6</td>
<td>1.05 ± 0.00</td>
</tr>
</tbody>
</table>

### Table II

<table>
<thead>
<tr>
<th>Visco-elastic properties DPBM-FGE-Jx series at 25 °C</th>
<th>Series</th>
<th>Storage Modulus (MPa)</th>
<th>Loss Modulus (MPa)</th>
<th>Tan(δ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>J400</td>
<td>2280</td>
<td>111</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>J2000</td>
<td>28.0</td>
<td>8.85</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>J4000</td>
<td>7.85</td>
<td>1.72</td>
<td>0.22</td>
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</table>

### Table III

<table>
<thead>
<tr>
<th>Fracture parameters of the DPBM-FGE-Jx series at 25 °C</th>
<th>Jx-Serie</th>
<th>Fracture Strain (δ)</th>
<th>Fracture Strain Variation</th>
<th>Fracture tension (MPa)</th>
<th>Fracture tension Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>J400</td>
<td>1,24</td>
<td>± 0,60</td>
<td>17,7</td>
<td>± 0,7</td>
<td></td>
</tr>
<tr>
<td>J2000</td>
<td>131</td>
<td>± 15</td>
<td>3,10</td>
<td>± 0,41</td>
<td></td>
</tr>
<tr>
<td>J4000</td>
<td>450</td>
<td>± 110</td>
<td>2,43</td>
<td>± 0,79</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Classification of the DPBM-FGE-Jx series into 2 groups: Reversible Glassy Thermosets and Reversible Elastomers.
future SH-actuator applications.

III. CONCEPTUAL DESIGN AND PROTOTYPE: SH-VIA

To make a first implementation of the SH-principle in a VIA, a series elastic actuator (SEA) [21] was selected. This basic VIA consists of a motor, a gear, and a compliant element (Fig. 5). The compliant element, often a spring, is placed in series, between the gear train and driven load, to intentionally reduce the stiffness of the actuator. In this SEA a self-healing mechanical fuse (SH-MF), containing a DA-polymer part, will be imported in series with the compliant element, as shown in Fig. 5.

The mechanical fuse (Fig. 6a) is designed as the weakest element in the construction, such that when the actuator is overloaded this elements will fail first, protecting the expensive components and the ones that are difficult to replace: the motor, the gearbox, and the compliant element. It will break sacrificially before a potentially damaging overload occurs on one of the three previously mentioned components. When the fuse is broken, the actuator will be put into an offline mode, in which the SH-procedure can be started. When the healing of the fuse is completed the actuator can be put online again. Using this principle all components are protected and there is no need for large over-dimensioning. The cylindrical core of the SH-MF, the SH-fuse core (Fig. 6b), is build out of -J400, the most brittle SH-material of the DPBM-FGE-Jx series. At 25 °C this elastic polymer possesses a quite high storage modulus (2840 MPa) and exhibits small (almost negligible) strains before fracture. Due to the stiffness of the material, the SH-MF, placed in series with the original compliant element, will have no (or minimum) mechanical contribution during normal operation. The brittle -J400 core has a negligible viscous component at ambient temperature and will break forming clean fracture surfaces, without the occurrence of necking. Clean fracture surfaces benefit the SH-process of the SH-MF.

For three prototypes (Fig. 6b) the fracture force was measured in a tensile test until fracture. To measure the influence of the SH-cycles, the three fuses were repeatedly self-healed and fractured in the tensile tests for three times (Fig. 7). The SH-procedure used, took 170 minutes, had a maximum temperature of 119.5 °C and was performed in an external furnace. The mean fracture force of the different fuses varies over a broad range, between 106 N and 49 N, probably because the prototypes were built manually. However, what is more important is the reproducibility of the mechanical properties of the fuses after a SH-cycle. For the fuses individually, the mechanical properties after three SH-cycles remained near the initial properties (fracture force after consecutive SH-cycles varies not more than 21%). There was no decreasing trend in the fracture force recorded, which indicates that the mechanical properties of the SH-MF remain stable for at least three SH-cycles. With some fine-tuning of the SH-MF design as well as the SH-procedure, the variations in fracture forces can be drastically reduced.

IV. CONCEPTUAL DESIGN AND PROTOTYPE: SH-SBA

A large part of the soft-bodied robotics, consists of a subcategory, Soft Pneumatic Actuators (SPA), which are actuated by compressed air and made almost entirely out of very soft elastic material (unlike other pneumatic actuators [22]). A variety of different SPAs [23], [24] has been constructed, all working according to the same principle. Most SPAs consist out of multiple cells, containing air chambers that 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 chambers. 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. Because of its relatively simple design, the Bending SPA (BSPA) [24] (Fig. 8a) was chosen for a first implementation of the DA-polymers in the soft-bodied robotics.

To evaluate the potential of creating a SH-SPA from the DPBM-FGE-Jx series, a single Soft Pneumatic Cell (SPC) was built entirely out of the DA-polymers (Fig. 8b). The cubic cell was developed out of the most flexible, -J4000
material (Storage modulus: 7.85 MPa). -J4000 is less soft in comparison with Ecoflex 00-30 (Tensile Modulus: 69 kPa) usually used in literature [23], [24]. However, due to the high fracture strain (Section II, Table III) of 450 %, the SPC can be used to create relative large deformations before a failure occurs. If multiple SH-SPCs would be put in series, a BSPA could be constructed, similar to the one produced by Yi Sun et al. [24], but stiffer. Based on the BSPA, the bottom sheet was produced out of a less flexible material, -J2000 (Storage modulus: 28,0 MPa), in order to create an anisotropic movement response. Combining the different mechanical properties of both -J2000 and -J4000, an entire self-healing SPC is developed, in which the air chamber as well as the less-stretchable sheet have the SH-property.

A first prototype (Fig. 9a) was build and tested for different over-pressures of the air chamber. The relatively high forces that can be applied by the top plane, in the range of Newtons (Fig. 9, and the high deformations (Fig. 10b) that can be achieved, are adequate for SPAs [24]. To evaluate the SH-property of the SPC, an incision was made in one of the planes of the cubic part (Fig. 10c), which was subsequently self-healed in an external furnace. The SH-procedure used, had a maximum temperature of 70 °C and a duration of 30 hours. Both, before and after the incision was made and cured, the SH-SPC was pushed to its limits: the over-pressure was increased until a small perforation occurred in the cell. In both cases, the perforation occurred at the location, shown on Fig. 10b. This indicates that the incision was completely cured after the SH-procedure: no weak spots were created and the initial properties were retrieved.

The steady state force, applied by the top plane, was measured as a function of the overpressure before and after the incision was made and self-healed (Fig. 11a and 11b). Taking into account the fact that there was a little difference in testing conditions (manually positioning of the setup), the steady state force, has similar values for the two experiments, which illustrates that the SH-SPC has the same performance before and after the SH-procedure.

The combination of adequate mechanical properties and excellent SH-properties of the SPC, indicates that the DA-polymers have high potential for being used in soft-bodied robotics. Starting from this single-cell SPC, it is straightforward to build a multi-cell prototype, a Bending SPA, the first SPA ever built completely out of self-healing polymers.

V. CONCLUSION

This paper introduces a brand new field, “Self-Healing Robotics”, by integrating self-healing materials in robotics, more specifically in compliant actuators. Adding a SH-mechanism to compliant actuators will potentially lead to a significant reduction of the overall dimensioning of robots. In addition, the compliant elements in these actuators are in general susceptible to damage caused by sharp objects found in unstructured environments. This problem can be solved by developing these elements entirely out of SH-material.

A broad range of SH-materials, available in literature, was analyzed, focusing on their implementation in robotics. This showed that, Diels-Alder (DA) polymers, dynamic covalent polymer network systems based on a reversible Diels-Alder reaction, pose great potential to be used in robotic applications. The synthesis allows tuning these SH-polymers towards specific desirable mechanical properties. Three DA-materials, noted DPBM-FGE-J400, -J2000 and
-J4000, were synthesized, containing completely different mechanical properties. Using the series of three DA-polymers, two SH-compliant actuator concepts were designed. The brittle, glassy thermoset -J4000 material was used to develop the center piece of a self-healing mechanical fuse (SH-MF). This sacrificial component will be integrated in a series elastic actuator (SEA). Whenever the SEA is subjected to an over-load, the fuse will fail first, protecting the other components of the actuator. Once fractured the fuse can be healed in a SH-procedure. Using this principle all components are protected and there is no need for large over-dimensioning. A SH-MF prototype was developed and validated. The SH-MF could be repeatedly fractured and SH-healed, while its mechanical properties remained near the initial properties. To illustrate the feasibility of developing a SH-soft pneumatic actuator (SPA), a soft pneumatic cell (SPC), containing a single air chamber, was developed entirely out of two SH-elastomers, -J2000 and -J4000. If SPAs are constructed out of SH-polymers, they can autonomously heal damages, like perforations and cuts, caused by sharp edges. A SPC-prototype was developed and validated. The forces that could be applied by the SPC and the substantial deformations, measured for different over-pressures of the air chamber, are adequate for SPAs. To evaluate the SH-property, an incision was made in the SPC. Using a SH-procedure, the incision was completely cured: no weak spots were created and the initial properties were retrieved. This paper showed that by tuning the mechanical properties, DA-polymers can be developed, which introduce self-healing in two distinctive actuator types. The DA-polymers used in these two actuator concepts, the SH-MF and the SH-SPC, have completely different mechanical properties, however, their self-healing relies on the same reversible DA-reaction. In addition, both prototypes were completely recovered after the healing of macroscopic damages, proving the potential for further investigation on the use of DA-polymers and other SH-polymers in robotic actuator applications. This research will potentially be pioneering for the introduction of these SH-materials in stiff actuators as well.

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