Self-Engineering – Technological Challenges

Rajkumar Roy[1], Sam Brooks[1]
[1]City, University of London, School of Mathematics, Computer Science and Engineering, Northampton Square, London, EC1V 0HB, UK
r.roy@city.ac.uk
sam.brooks@city.ac.uk

ABSTRACT:
Engineered products are becoming more complex and need longer lifetime availability; there is a need for new approaches is maintaining, repairing and overhaul (MRO). This paper presents the concept of self-engineering; the aim is to preserve the functions of a product or system and extend its lifetime and automate MRO processes. New developments in self-healing materials, self-reconfiguring electronics and robotics, which are already or could be self-engineering systems, are reviewed. Biological healing and repair mechanisms are discussed as a potential source of inspiration for new self-engineering systems. Examples of biological self-engineering are presented. Key technological challenges and research questions which need to be addressed in future self-engineering research are discussed throughout.

Keywords: *Self-engineering, through-life engineering services, repair, maintenance, self-healing*

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1. INTRODUCTION

Everything engineered will eventually break. Maintenance Repair and Overhaul (MRO) services can delay and extend product life and fix problems when they occur. However, in some systems, MRO is difficult to implement because it is too costly, or systems are inaccessible. This paper presents the concept of a self-engineering (SE) system that aims to deliver zero-maintenance products. This approach is ambitious but can draw on inspiration from existing man-made and biological mechanisms, such as self-healing, self-reconfiguration, self-adaptation and self-repair. SE can be implemented at a system, sub-system or component level, solutions from different levels have been discussed in this paper. However, the authors current work focuses mainly of a system level SE solution.

The objective of this paper is to present an overview of current SE methods and technologies relating to MRO. Research questions which need to be addressed in future work are presented throughout the paper and offer many potential areas of research.

1.1. Overview of Through-Life Engineering Services (TES)

Servitisation and Product-Service System (PSS) business models require sustained and optimum product availability to maximise income. Through-Life Engineering Services (TES) supports this requirement, enabling the development and application of PSS and *servitization* for complex engineering products or systems [1]. Monitoring, diagnostics, and prognostics technologies can be used to gather data and knowledge on performance, degradation and failures and inform services such as continuous maintenance [2]. When combined with new MRO practices, methodologies, and strategies a product (or systems) functional life can be extended and failures prevented. TES is especially important for complex interdisciplinary products and services and has a key focus on minimising total life-cycle cost [3]. One growing area for TES highlighted in a recent report is to support the development of Mobility as a Service (MaaS) [4].

TES is a growing area of research with increasing publications. SE is a strategy which can fall under TES because it can support *servitisation* and PSS businesses. However, it attempts to automate the processes and remove the need for human control from the services. PSS and *servitization* businesses are a key market which could benefit from SE systems.

2. WHAT IS SELF-ENGINEERING?

2.1. Definition

A working definition of a self-engineering system is: *a system is self-engineering when it registers and responds to a loss in function or operation capability, and automatically takes action to return the functionality.*

Some key characteristics of a SE system include:

1. There must be no human/user intervention, and system response/behaviour should be automatic.
2. It must have the ability to restore or partially restore its lost function(s).
3. It must be built into the system, not added later when required.
4. The aim should be to avoid/reduce maintenance, prolong life and/or increase the system robustness.

The concept of SE systems is not completely new; the concept of a self-maintaining system in software and computer science and zero-maintenance in electronics [5] have previously been presented. Many useful inspection and repair techniques have already been developed which could be utilised in SE systems [2]. However, SE aims to encompass a wider range of technologies and initiate collaboration between different engineering disciplines.

2.2. Processes involved

Some of the key stages involved in a SE system are:
Monitoring: the system has a sensor or procedure that enables it to register a loss of function.
Trigger: this initiates the SE response, it could be damage, degradation, or a reduction in function or performance.
Response: this is the action the system takes to restore function or repair itself.

Figure 1 outlines the stages in a biological and engineering SE process. For the engineering response the stages have all been demonstrated individually but not combined or inn an automated process [6]. Both examples use a similar method to repair material with a fatigue crack. Bioinspired SE is discussed further in Section 4.

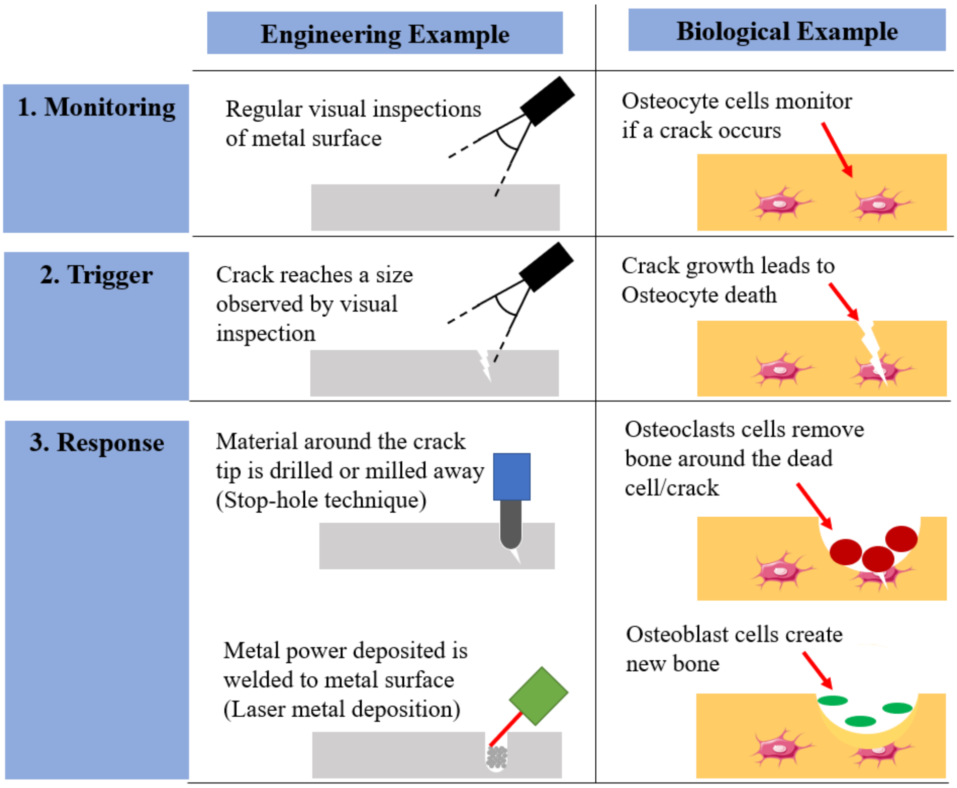

Figure 1. – Diagram showing key stages of SE process in biology and enineering. The biological example shows the process of bone repair. The engineering exmaple shows visual inspection, stop-hole crack repair and laser metal deposition [6].

2.3. Summary of key methods

There are several different methods of SE which are referred to in this paper; a definition of them is given here for clarity. These definitions change depending on the sector being looked at, for example, electronics systems referred to as self-healing in previous literature are actually self-reconfiguring and have been grouped as such in this paper.

- **Self-healing -** Self-healing refers to a system which, when a part or assembly is damaged, can return to close to its original state. No new parts or components are utilised the original one is 'healed'.

- **Self-repairing -** Healing requires rehabilitation of components, but a repair can include adding new materials or changing the ones already there. The repair does not leave the system in the original state; there may be damage patched using other parts.
- **Self-adapting -** A system is self-adapting if it can adjust in response to changing conditions or environments and maintain/improve its function. Self-folding and self-assembly mechanism can also fall under this definition, though they are more specialised self-adapting methods.
- **Self-reconfiguring -** A system is capable of changing its arrangement to meet new challenges, component damage or preserve its function. It is very similar to self-adapting, though the new system is a different configuration or arrangement than the original.
- **Built-in redundancy -** A system containing unused parts which the system utilises to replace parts with damage or reduced functionality. To utilise these parts, some reconfiguration of the system is often required.
- **Self-sealing -** A system can close leaks to prevent things (normally fluid) passing in or out of itself.
- **Self-organising -** A system can adapt itself without external direction to meet its needs, there is little or no centralised or hierarchical control, which may be observed in other systems.
- **Self-optimising -** The system ensures maximum utilisation of resources to meet the system requirements.
- **Self-assembly –** The system has the ability to configure from parts into an operating system autonomously.

3. CURRENT TECHNOLOGY

Many different SE systems exist already, examples of ones found in research papers and patents are shown in Table 1.

3.1. Self-healing materials

Self-healing is a large and growing area of research. Autonomic self-healing occurs without the need for additional stimulus (e.g. no external heat, light or voltage is needed). Non-autonomic systems rely on outside stimuli such as heat or light to trigger the self-healing process [7]. Another key division within self-healing materials is intrinsic and extrinsic healing property. Intrinsic self-healing materials can heal due to non-covalent chemistry or dynamic covalent chemistry [8]. Diels-Alder reactions are frequently used to make intrinsic self-healing polymers. Key examples of materials with added extrinsic healing properties include the following:

1. Microcapsules – Capsules containing a liquid healing agent are embedded within or on the surface of a material, when capsules are damaged the healing agent is released and solidifies [9].
2. Vascular - Micro-tubes filled with healing liquid agent are embedded within or on the surface of the material. Cracks or damage break the tubes, releasing the healing agent [10].
3. Shape memory materials (SMM) – Used to make a composite material which contracts when heated, pulling cracks closed and making it easier for chemical bonds to reform and heal a crack [11]. However, it requires outside stimulus and intrinsic material healing properties to heal fully.
4. Embedded bacteria – Bacteria is added within concrete material to seal cracks and prevent water ingress by creating calcium carbonate [12]. This technology is well developed, with many trials taking place and patents filed.

Self-healing metals are much more difficult due to the stronger internal bonding; however, there has been some success with metal composites or preserving metal surfaces [13]. A growing area of self-healing materials is the textile industry where extending product life is a growing issue. Coating created from proteins found in squid can heal material samples using just water [14], this is currently being sold as a commercial product.

Material fatigue, damage, corrosion or deformation, are often the cause of mechanical failures in systems. A self-healing material can help mitigate against this and keep parts operating for longer, though more work is needed on integration into commercial products. Many self-healing materials also have a limited number of operations (often only one) which limits their possible applications.

3.2. Self-reconfiguring electronics

Electronic systems have regularly utilised self-reconfiguration and redundancy (normally together) to make fault-tolerant systems. One of the early solutions (from 1980s), was a field programmable gate array (FPGA), which contain programmable logic blocks and memory elements which can be re-configured when needed [15]. More recently, random-access memory (RAM) devices were repaired by reconfiguration. Data in faulty memory cells of a RAM can be stored at new spare addresses and the system self-reconfigures to the address change [16]. This is also referred to as built-in self-repair (BISR).

MEMS devices are relatively cheap components but form critical parts which are difficult to replace when damaged. Designs for a MEMS piezoelectric energy harvester [17], and an accelerometer MEMS device [18] have been presented with redundant modules which can reconfigure to account for the loss or damage of other modules.

3.3. Self-repairing systems

Self-sharpening plough-shears created during the industrial revolution are an early example of a self-repairing system [19]. One side of a blade is harder, and one is softer and more vulnerable to erosion, resulting in a sharpening mechanism. Bell et al. [20] investigated if a 4-bar linkage mechanisms could be self-repaired to maintain close to the original actuation path when one joint was damaged [20].

Table 1 – Table summarising current self-engineering solutions, the response, how it is initiated and what products it has been applied to.

SE method	Category details	Response initiated by	Response	Applied to	Ref.
Self-healing	Micro-capsules	Damage, cracks or wear	Release healing agent	Polymer and concreate	[9]
	Micro-tubes	Damage, cracks or wear	Release healing agent	Polymer composites	[10]
	SMM	Applied heat	Pulls cracks closed	Polymer composites	[14], [30]
	Embedded bacteria	Damage, cracks or wear	Fills voids in material	Concreate	[12], [23]
	Stimulus triggered	Applied stimulus	Heal chemical bonds	Polymer metals	[7], [8]*
Self-reconfiguration and Redundancy	Electrical parts	Failure of cell, module or component	Reconfigure to utilise spares modules	RAM, FPGA and MEMS	[15], [16]
Self-reconfiguration	Swarm robots	Robot removed or added	Reconfigure to keep shape	Swarm Robots	[24], [25]
Self-sharpening	Blade	Wear on blunt blade	Faster erosion on one side	Ploughshear, knifes, tools	[19], [26]
Self-repairing	4-bar linkage	damage to a linkage	Adjustment to other links	-	[27]
Self-sealing	Material	Small puncture to surface	Expansion or movement to reseal hole	Tires and pneumatic structures	[28]
Self-adapting (and self-modelling)	Robot	Loss or damage of limb	Model, evaluate and trial solutions	Starfish and 6 legged walker	[29]
Self-adapting	Robot gripper	No solid surface to grip	Flex around the object	Robotic hand gripper	[30], [31]
	Escape slide	Slide angle too shallow or steep	Inflate/deflate segment to adjust length	Aeroplane escape slide	[32]
	Flexible antenna	Antenna receiver flexes	Antenna re-tunes to receive signals	Flexible antenna	[33]
Self-adapting and Self-assembly	Photomorphog-enesis	Light source	Growth/adaptation towards light	Robot swarms	[34]
Self-folding and Self-assembly	Electronics	Heating of joints	Expansion and folding of joints	Resistor, strain sensor and robot	[35], [36]

*Review paper of methods

Many companies have published patents for self-healing (self-sealing) tires [28]. Other research on making self-sealing components created a foam coating inspired by the way plants self-seal when cut [37], [38]. Internal pressure and a flexible material block holes in the surface.

3.4. Self-adapting robots

Self-adapting robots aim to adapt to damage or changes in their environment. Self-adapting modular robots have been a particular area of interest, with cube and tetrahedral modules used in previous work. A starfish like robot (with 4 arms) was taught to move using built-in self-modelling and trial and error; it evaluated different actions and distance travelled in each trail to find the best way of moving. Once it learnt how to move the system was able to adapt and continue moving when a limb was removed [39]. A similar approach with a six-legged robot was tested more recently with optimised algorithms, reducing the time needed to adapt to minutes [29]. Robots which could self-adapt have many uses and could operate in harsh environments without the need for human intervention, even when damaged.

3.5. Robotic maintenance and inspection

Robotic inspection, MRO or servicing tasks are research subjects of interest for industry and academics, recent work in some industries is outlined below.

- Ships form a vital role in global trade and require regular inspection of hulls. Currently, ships are removed from the water for cleaning, visual inspection and repairs, taking it out of operation for weeks. The HISMAR and AURORA projects built fully automated underwater robots, but they were only able to perform inspection and basic cleaning duties unaided [40] [41].
- Airlines and manufacturers are increasingly looking to automate required inspection, servicing and maintenance. A snake-like robot developed by Nottingham University and Rolls Royce was used inspect and repair inaccessible areas of engines [42]. Another project, CompInnova, aims to create a robot to move around an aircraft's outer body, inspecting and repairing composite parts [43].
- Electricity is carried along 1000s of miles of cables, wet cold weather increases the chance of cable degradation. LineScout is an automated power line inspection and repair robot which has to be attached to a cable but is then able to inspect and re-join lose cables autonomously [44].
- Wind turbines are growing bigger to facilitate greater efficiency and are moving to more remote locations. Drones have previously been utilised for visual inspection of wind turbines [45]. Alternative robots have been developed, which can climb the towers or blades to inspect parts closely [46]. The recently funded MIMRee and WindTTRo projects in the EU aim to go further and include repair processes in these systems.

Most of these robotic systems employ only visual inspection techniques, repair is often left to a human operator. Combining both processes is needed to make SE systems. Repairing a system is much harder and can require specialist training, though this could change in the next few years with the growth of artificial intelligence. Another key issue is equipment size, making a suitable robot to carry inspection equipment is hard enough, adding the weight of tools and repair parts will increase the weight and complexity of the design even further.

4. SELF-ENGINEERING IN BIOLOGY

Biology is full of excellent examples of SE, only a few examples have been outlined in this section. Table 2 summarises the SE method used in many biological processes and indicates where this has inspired and been utilised in an engineering system.

4.1. Bioinspired and biomimicry design process

There are two key approaches to create biomimicry and bioispired solutions.
Top-down (or problem-driven) - This approach begins with an engineering problem. Biological systems are searched for a suitable role-model; the search could focus on looking for a particular function, feature or process. Once an appropriate role model has been identified, this can then be investigated further and applied to solve the problem. *Bottom-up* (or solution-driven) - This approach starts with a biological solution and looks closely at behaviour, response, functions and mechanism involved. A particular solution is identified, investigated further and extrapolated. Finally, there is a search for an engineering problem to apply the solution to.

Both approaches are useful and can be utilised for different aspects of a product's design, Flectofin is an example of this [47]. It can often be difficult to replicate all biological mechanism as some will only work on a smaller scale and not the scale required by engineers [48].

Table 2 – Summary table of some biological self-engineering systems and methods used. Where the system has been utilised in a product (bioinspired) it has been indicated. Green boxes indicated methods used.

Organism	Description	Self-engineering method used										Utilised in bioinspired product	Ref.
		Self-healing	**Self-repairing**	**Self-sealing**	**Self-organising**	**Redundancy**	**Self-reconfiguring**	**Self-adapting**	**Self-optimising**	**Self-sharpening**	**Self-assembly**		
Human	Skin healing process	■	■	■								Yes	[49]
	Blood vessels constriction							■	■			No	[50]
	Kidney redundancy					■		■				No	[51]
	Bone repair process	■	■									No	[52]
	Neurons (synaptic plasticity)								■			No	[53]
Sea creatures	Sea urchin teeth		■							■		No	[54]
	Molluscs shell layers structure	■	■									Yes	[55]
	Moon jellyfish re-organise limbs				■		■					No	[56]
Plants	Seed capsules expand/open in water										■	Yes	[57]
	Photomorphogenesis										■	Yes	[34]
	Stem wound sealing with latex	■	■	■								Yes	[58], [59]
	Internal cell sealing mechanism		■	■								Yes	[37], [60]
	Pre-tensioned structure for wound sealing			■								Yes	[61]
	Regeneration from cutting				■	■		■				No	[62]

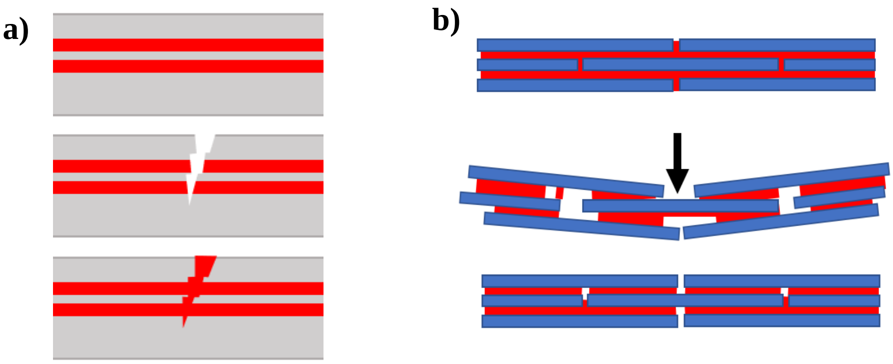

Figure 2. – Diagram of bioinspired methods of self-helaing; a) shows vascuar micro-tubes used to self-heal a crack, with healing agent in red (see [10] for more information); b) shows a block and mortar stucture inspired by mollusc shell with breakable bonds which can be repaired when force is removed, see [55] for more informaiton.

4.2. Examples of biology inspired SE work

Biology has inspired many SE mechanisms, some of these are listed below.

- Photomorphogenesis, the growth and movement of plants towards light, was mimicked with a robotic swarm creating a light-responsive, self-assembly and self-adapting mechanism [34].
- Vascular structures used in our bodies inspired a self-healing polymer composite with hollow glass fibres which released a healing agent when damaged [10], see Figure 2 a) for a diagram.
- Mollusc shells, inspired a self-healing polymer and glass brick composite. Sacrificial healable bonds between layer allowed the structure to deform and return to its original shape [55], see Figure 2 b) for a diagram.
- Delosperma cooperi plants (see Figure 3. a)) have pre-tensioned structures which self-seal wounds in the plant, to prevent water being lost. Shape memory materials were used to replicate the effect in a composite material [61].
- Hardide coating has been applied to knives and tool blades to make them self-sharpening, it was inspired by sharks and sea urchin teeth (see Figure 3. b)) which have a softer and harder side [54]. However, a similar mechanism was invented earlier with self-sharpening plough shears, without bio inspiration.

Biology can inspire many innovative new products and solutions, but designers should be careful as biology is not always the optimum solution. Nature does not contain wheels or gears, but they have been a vital engineering component for hundreds of years.

a) **b)**

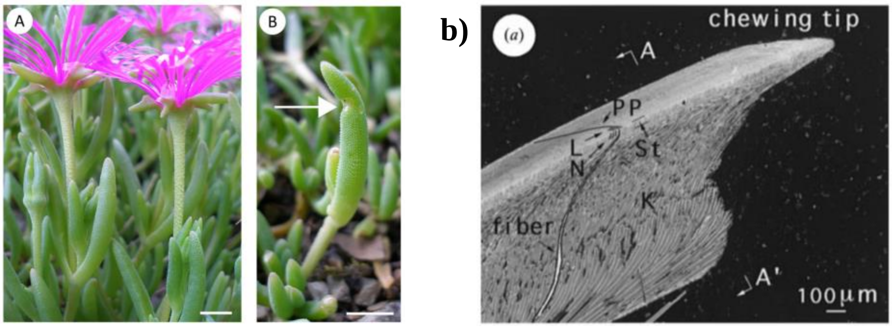

Figure 3. – Two sources of biological inspiration for SE systems. A) Delosperma cooperi plants leaves which bend to self-seal when cut due to pre-tension, © 2018 Speck et al.; licensee Beilstein-Institut [61];. B) Close up picture of self-sharpening sea urchin teeth, reproduced with permision from [64].

5. TECHNOLOGICAL CHALLENGES AND RESEARCH QUESTIONS

There are many challenges and research opportunities with SE systems. Some of the key research questions which need addressing in future work are outlined in this section. Subheadings are the key stages in a SE system outlined in Section 2.2.

5.1. Monitoring

- Where should the monitoring be built-in to a component or added to the system? For a new product it could be built-in but existing system need monitoring which can be added on.
- What should be monitored, and why? Only critical functions or all functions and operations?
- Should monitoring be continuous, intermittent or based on the age of a product?
- How can monitoring take place without interfering with the products function?

5.2. Trigger

- Products will continuously degrade and lose function throughout their life at what point should SE be triggered?
- Can the trigger be reset or repeated, does it occur only once?
- Should there be different levels of a trigger? For example, should it be a binary yes-no response or should it be a scale 1 to 10 based on severity?
- How do you verify if the trigger is correct?
- What other back up sensors can you use to verify the initial trigger?
- Does the trigger determine the SE method used, how is it chosen? Is the chosen SE response the best one?
- If a trigger is not verified, should the system return to the monitoring stage? Should monitoring be increased, is there a risk of a genuine trigger being missed?

5.3. Response

- How is the best response chosen? Can previous SE actions, updates and upgrades be taken into account?
- The response needs to account for factors such as available resources, time, damage severity. How are these best monitored or recorded in the system?
- When should the response be implemented, can all operations be paused if needed? Is the system vulnerable during the implementation of the response?
- What is the best was to utilised and transported resourced where needed?
- Is the system stable and functionality fully or partially restored by the SE response?
- Was the SE response appropriate, is a further response or adjustment required?

6. EVOLUTION OF SELF-ENGINEERING

6.1. Evolving automatic control (Industry 4.0)

Many systems utilise automated monitoring to help predict when maintenance is required as part of Industry 4.0 [63]. To create successful SE systems further work is needed to automate all the stages. Automating many repair processes which are dependent on human experience and training is a significant challenge and one that needs to be addressed for SE systems to be realised.

6.2. Evolving beyond automatic control

In some systems, the trigger for the SE mechanism starts the repair response without any processing; a good example is microcapsules and vascular materials discussed in Section 3.1. These systems have the advantage of requiring no decision making or processing and can occur reactively. Currently, most human-made SE systems require some form of control to help determine when it should be implemented. Reducing the need for control in the system could have many benefits, such as reducing the complexity and cost of running a SE system. However, it could mean that SE responses have to be limited to one method and a system would not develop or change to meet new challenges.

7. SUMMARY

In summary, there is a need for significant and long-term research to create complete SE systems with zero-maintenance. They could greatly benefit s safety-critical, inaccessible and productivity-critical systems. Many different techniques are being developed to identify material degradation and enable predictions of failure automatically. Alongside this, there has been significant developments in some SE response methods, such as self-healing materials and self-reconfigurable electronics. Considerable research is still needed outside these areas especially combining automated monitoring and automated MRO tasks. The sectors with the most well-developed SE solutions are electrical and computer systems.

Biological systems can provide a source of inspiration for SE mechanisms or methods and have already inspired developments in robotics and self-healing materials. Even some human made solutions designed without biological inspiration share similar characteristics, as shown in Figure 1. It should also be noted that biological systems are often not limited to one SE method, while human made ones are and could potentially benefit from utilising multiple methods.

SE systems are likely to be most useful in high value industries where a *servitisation* or PSS business model is utilised. Identifying what parts or sub-systems should be made SE is another challenge which could be helped by utilising techniques used in continuous maintenance services, such as degradation mechanics, monitoring diagnostics and prognostics, and repair mechanics.

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CORRESPONDANCE:

Dr Sam Brooks
Mechanical Engineering,
School of Mathematics, Computer Science and Engineering,
City, University of London,
London, UK
E-mail: Sam.Brooks@city.ac.uk