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An overview of self-engineering systems

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ABSTRACT

Failures in high value, safety-critical, inaccessible, and productivity-critical systems is an area of significant research interest. Despite advances in predictive and continuous maintenance services, there is still a need for a more ambitious approach to preserve a system's functions despite degradation and damage. This paper presents the concept of a self-engineering (SE) system which utilises techniques such as self-healing, self-repairing, self-adapting and self-reconfiguration to enable a system to respond autonomously to a loss or potential loss in its function. Two types of SE systems are outlined, systems with control and systems without control. A taxonomy of these key techniques and related concepts is presented. This review focuses primarily on physical SE systems, rather than the control and software systems where SE concepts are well advanced. Technology within mechanical, civil, electrical and electronics, mechatronics engineering disciplines and repair robotics is reviewed. Finally, key research gaps identified are discussed.

1. Introduction

1.1. Introduction

Systems and products will never last forever. A key mission for engineers is to prolong a product's or system's life and improve its resilience. Designers typically aim to produce robust or resilient systems; however, regular maintenance, repair, and overhaul (MRO) services are still required to prolong life. Current research in MRO focuses on condition monitoring, predictive maintenance and preventive maintenance which still require human intervention (de Jonge and Scarf 2020; Redding and Tjahjono 2018; Roy et al. 2016; Zonta et al. 2020; Kang, Sobral, and Guedes Soares 2019a). To maintain future systems, a more ambitious self-engineering system design is required which can maintain key functions of a system or product, despite lifetime degradation, wear, damage, or failures.

An initial definition for self-engineering (SE) system proposed by Roy and Brooks (2020) has been refined to the following definition. A self-engineering (SE) system is defined as: *An ability designed and built into a system to independently identify any loss or potential loss of function, and then automatically restore the functionality fully or partially to maintain its*

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availability and improve system resilience. There are four key characteristics of a SE system which have been identified. Firstly, it must have the ability to restore or partially restore lost function or capacity, which has occurred or will occur. Secondly, it must be built into the system, not added later when required. Thirdly, the aim should be to avoid/reduce maintenance, prolong life and/or increase the system resilience and robustness. Lastly, there must be no human/user intervention; any process, response and behaviour should be automatic. These characteristics are broad and encompass many different systems in use currently. SE can take place at a local material, component, sub-system or system level and all four have been considered in this review. This review focuses primarily on physical hardware systems and not software, control and operating systems where SE concepts are well advanced.

SE is a strategy which can be classified as a *Through-Life Engineering Services* (TES). TES support and enable the development and application of *Servitisation* and *Product-Service System* (PSS) businesses which require sustained and optimum product availability to maximise income. Monitoring, diagnostics, and prognostics technologies are used to gather data and knowledge on performance, degradation and failures and inform services (Redding and Tjahjono 2018; Redding and Roy 2015). However, SE attempts to automate processes and remove the need for human control from the services. PSS and *servitisation* businesses are a key market which could benefit from SE systems. For example, with the development of self-driving electric cars, there is likely to be a shift in the car industry towards Mobility as a Service (MaaS); a recent report in the UK highlighted SE systems as a key technology to support MaaS (Elsy, Jennings, and Roy 2018).

The aim of this paper is to provide an overview of the latest developments in SE systems. Existing SE systems were reviewed to identify what technology and methods are currently utilised in different sectors of engineering. The aim was to identify where developments have been made and where further research is still needed.

An initial overview of SE was outlined in the conference paper by Roy and Brooks (2020), though this was not comprehensive and focused primarily on biological SE solutions; several key future research questions on SE were proposed. Using this list, five key questions were identified at different stages of SE systems; these questions will be explored further in the paper to help identify further research gaps.

(1) *Monitoring* – Observing everything available helps reduce the chance of missing degradation or a failure, but systems quickly become expensive and complex. What sub-systems, parameters or components should be monitored?
(2) *Trigger* – At what point should SE be triggered, is there a set degradation limit or should it be when a function has been completely lost?
(3) *Response* – Do SE responses depend on factors such as available resources, time, damage severity and environmental conditions? How are these accounted for in the system?
(4) *Response* – Are SE responses repeated or designed to be a single-use response?
(5) *Verification* – How is the effectiveness (amount of function returned) of the SE response verified? Should the initial monitoring system be utilised or an independent system with different measured parameters?

1.2. Methodology

Key words were initially identified for the taxonomy and used to search academic online databases including Web of Science, Engineering Village, ScienceDirect, IEEE, Science and Nature. Key terms included: self-maintenance, self-repair, self-healing, self-adapting, self-reconfiguration, self-optimising, self-organising, self-optimising, redundancy, self-strengthening, self-folding, self-cleaning, self-sealing, self-managing, self-assembly, and self-x. The self- was also replaced with autonomous and automatic to make similar search terms such as automatic repair, which can encompass research not using self- terms.

Review papers were searched first to identify further sources. Patents were found by searching US, Japan and Europe databases for key terms. Identifying relevant SE systems was difficult for two main reasons. Firstly, many of the terms defined in the taxonomy are used in other areas of science and have different meanings. Secondly, the terms are often overused or used incorrectly as they have become buzzwords.

1.2.1. SE characteristics reviewed

The SE technologies and mechanisms found from the literature were evaluated against the key SE characteristics from the definition (See Sections 1.1):

(1) Returns or prevents the loss of function.
(2) Built into the system.
(3) Reduces/avoids maintenance or prolongs product life.
(4) It must be automated.

A traffic light system is used to grade how strongly the characteristic is met. Green: the characteristic is met. Yellow: the characteristic is partially met or close to being met. Red: the characteristic is not met. This colour coding is based on authors' interpretation and therefore, prone to bias. Numbers found next to the characteristics above correspond to the ones used in tables.

1.2.2. System levels

SE methods and technology can be applied at many different levels within a system. The key levels utilised here are system, sub-system, components and material.

1.2.3. Technology readiness level (TRL)

Technology Readiness Level (TRL) originally created by the National Aeronautics and Space Administration (NASA) is a method of ranking the maturity of a technology. One is the lowest ranking where basic concepts and principle are observed, to nine, which is an actual complete system proven and validated in its operational environment (Héder 2017). Information on the development of each system was compared to the TRL definitions as outlined in the Horizon 2020 programme definition (European Commission 2014) and TWI (2020). The authors identified and recorded the level which most closely describes the current stage of the SE system's development.

1.3. Paper structure

Previous authors have often focused reviews on one SE term, such as reviewing self-healing materials (Kanu et al. 2019; Kang, Tok, and Bao 2019b) or self-repairing systems (Frei et al. 2013). This paper represents a comprehensive, holistic review of SE systems and the different aspects and methods they include. Initially, in Section 2, a discussion of similar concepts presented by previous authors is shown. In Section 3, a taxonomy of key SE terms and mechanisms is outlined. In Section 4, current SE systems and technology developments are reviewed. Section 5 discusses research towards autonomous maintenance robotics. Finally, in Section 6, research gaps and future research questions are discussed at the end of the paper.

2. Self-engineering, what is it?

2.1. Evolution of the concepts

The concept of a SE system is not completely new; previously similar concepts have been presented. Umeda, Tomiyama, and Yoshikawa (1992), first presented the idea of a self-maintenance system. They developed a design methodology which was implemented with Mita industrial Co. Ltd in 1989 for a photocopier put to market in 1994 (Shimomura et al. 1995). A system was considered self-maintaining if its functions could be maintained despite failure or degradation. Their work focused on two key methods redundancy and reconfiguration within the system. The initial work on a photocopier, and follow-up work conducted by other authors, focused on control systems which could adapt and preserve the systems function, not on physical maintenance or repair of sub-systems or components (Labib 2006). The concept was never explored far beyond the control domain (Chakrabarti et al. 2016), possibly because sensors, actuators and data processing capacity were not as advanced as today. The term has been used by other authors more recently though without reference to the original work by Umeda, Tomiyama, and Yoshikawa (1992).

In 2001, IBM highlighted the problem that increasingly complex software systems were becoming impossible for a human to manage and introduced the idea of *autonomic computing* (Kephart and Chess 2003). Inspired by the human body's autonomic nervous system, the key aim was to enable the software to meet a higher aim or set policy despite possible changes. A key function of these systems was the ability to self-manage which required a system to have self-configuration, self-optimising, self-healing and self-protecting abilities.

Later work by Lee, Ghaffari, and Elmeligy (2010) developed the concepts of an Engineering Immune Systems (EIS) inspired by the human immune system; this work is closely related to SE. An EIS is designed to improve the robustness and resilience of the system, and it can use automatic control in response to disturbances to return the system to a stable state. The overall aim is similar to SE because it aims to achieve near zero-breakdowns. However, the focus is mainly on control systems and software for diagnosing faults, followed by automatic operating adjustments (self-tuning, self-optimising, etc.). There is less focus on other possible responses which do not require control, such as autonomic self-healing. Furthermore, a maintenance or service engineer would still be required for an EIS.

Morello, Karray, and Zerhouni (2010) built on the work of Lee, Ghaffari, and Elmeligy (2010) and outlined the concept of S-Maintenance. The concepts are very similar to EIS. A knowledge base of information on the systems is built, which can help evaluate

performance and determine maintenance actions or responses when needed. However, there is not much detail on the response or action taken by a system outside of the software domain. Other maintenance strategies such as Lean maintenance also aim to utilise automation with self-directed, self-monitoring or self-inspect capabilities to reduce human workers involvement (Gupta, Gupta, and Parida 2017), similar to SE, but it does not employ full automation required for SE.

Speck and Knippers (2015) used the term *self-x materials* to describe bio-inspired materials with intrinsic properties that enable them to react to external or internal stimuli. As with SE, self-organisation, self-adaptation and self-healing methods are included. However, their work only considers intrinsic properties and fails to take account of many potential biological sources of inspiration such as built-in redundancy, self-repair and self-optimisation.

Complexity engineering also encompasses systems with self-∗ properties and those with many interacting agents or components (Buchli and Santini 2005; Frei and Di Marzo Serugendo 2012). However, the term is much broader than SE, which focuses on systems to maintain or return functionality.

An early review of SE systems focused on *Zero-Maintenance* systems in electronics (McWilliam et al. 2017). The review drew on many similar concepts to this review, including self-healing and self-repair systems but was limited only to electronic systems. The authors noted electronic sensors form a vital part of most monitoring and diagnosing systems and therefore, need to be SE as well.

SE encompasses all these systems discussed above but attempts to go further and include a wider range of engineering and biological systems. SE adds additional holistic capability in preventive maintenance, more automation at a system level and design for self-repair/self-healing. One key way it differs from self-repair systems is that a repair occurs in response to failure, damage or loss of function, but a SE system can also take preventive action before the failure occurs (automatic preventive maintenance).

2.2. Self-engineering control

From reviewing different engineering SE systems, it was noted that they could be loosely divided into two categories: with control and without control. Both types of SE systems start with an initial *trigger* associated with a loss in function. The trigger leads to a *response* which is a process to return the functionality. When a control system or process is used, *verification* and *evaluation* steps are required to ensure the response is needed and implemented correctly, see Figure 1(a). Autonomic managers in autonomic computing use a similar control loop, MAPE (monitoring, analysis, planning and execution) (Kephart and Chess 2003). Other systems have no control (such as self-healing materials), and the response is automatically initiated by the trigger with no planning, evaluation or verification, see Figure 1(b). A more detailed version of Figure 1(a) and (b) is shown in Appendix A. Systems with control allows the system to respond to different conditions and have multiple responses but can be more complex to implement.

2.3. Chronology of concepts

SE technologies have been a growing area of interest over the last few years. Databases of granted patents in the US, Japan and Europe were searched for key SE terms highlighted in

a)

Automatic With Control

b)

Automatic No Control
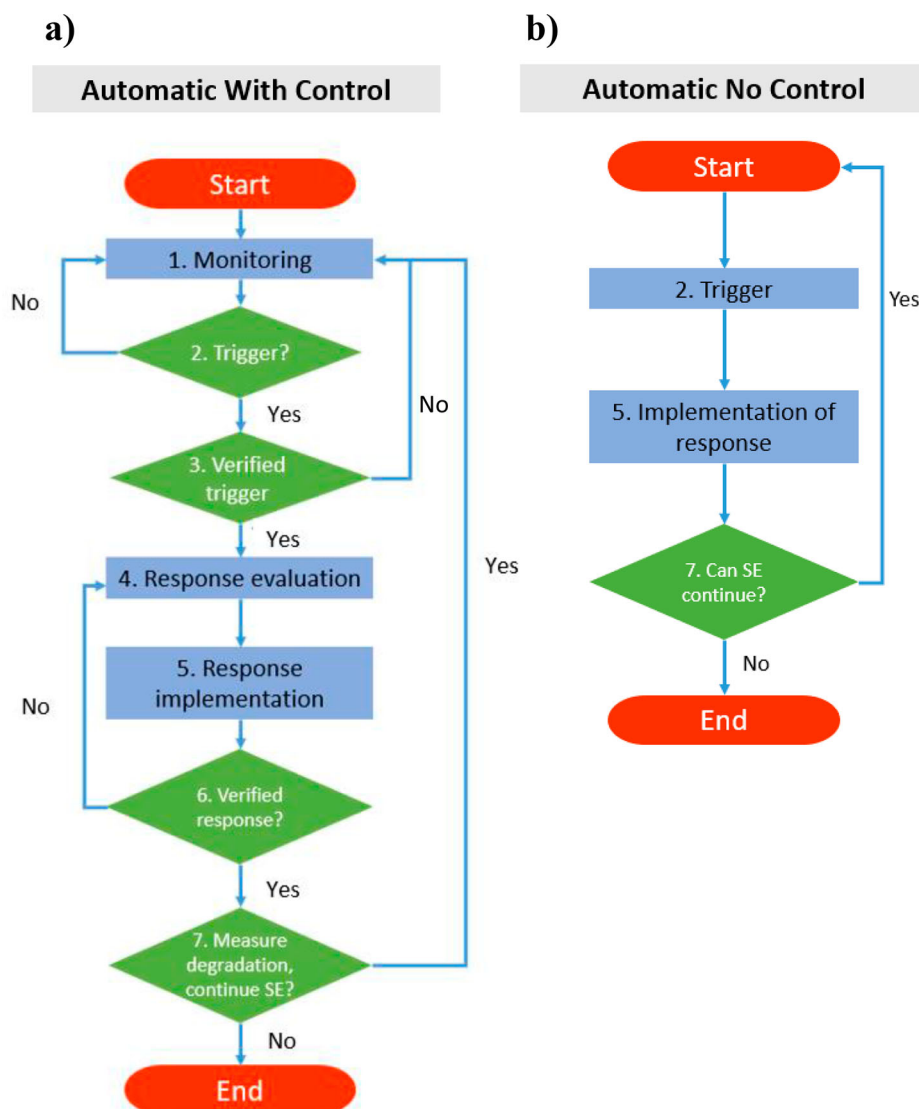
Figure 1. Flow diagrams of a basic SE system: (a) with control and (b) no control.

the taxonomy (Section 3). The number of patents for each term is displayed in Figure 2(a); terms such as self-cleaning, self-assembly and redundancy were not included as they are buzzwords often used to describe different non-SE systems. The total number of patents published each year since 1970 was also noted to increase; therefore, a new graph was plotted of the percentage of total patents published that year, Figure 2(b). Only the title, claims and abstract of the patents were searched for the terms and the US and UK spelling were both used (e.g. self-optimising and self-optimizing) as well as alternative terms such as self-heal, self-healed and self-healing. To improve the clarity of the graph in Figure 2, moving averages of the previous five years were plotted. Figure 2(a) demonstrates the number of patents containing the key terms all increased over the last 50 years, except

Figure 2. Graphs showing the (a) number, and (b) percentage, of patents granted each year with that key term used in the abstract, claims or title. The values plotted are a moving average of the five previous values.

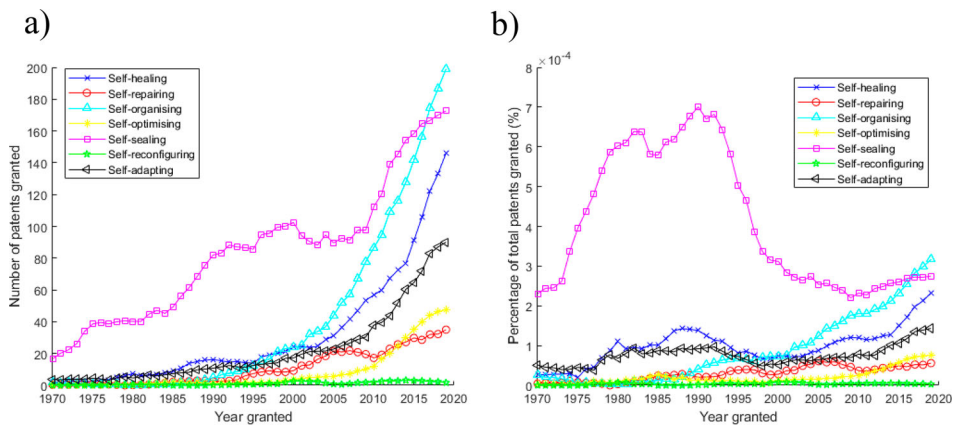self-reconfiguration which stayed consistently low. The latter may be as a result of the infrequent use of the term as authors tend to use self-adapting or self-repair instead. Figure 2(b) shows a notable increase in the rate of use of self-healing, self-adapting, self-organising and self-optimising terms in patents; these terms are all commonly used in software, computer and electronic system which is probably why the greatest increase is seen around the 2000s when autonomic computing was developed (Kephart and Chess 2003). A decrease in the rate is seen for self-sealing from the 1990s and no notable increase for self-repairing from 1995, this is likely because these systems are often mechanically based and were eclipsed by the increase in computer, electronics and software system patents in those areas.

A similar review of published journal papers was conducted to assess the use of the terms and technology in academia. Web of Science database of papers was searched using the same key eight terms used previously, only journal papers (not conference or proceedings) with the key terms in the title or keywords were selected. Figure 3(a) is the number of identified papers published each year and (b) is the number as a percentage of the total journal papers published that year. It is clear from the data collected that self-organising has been widely used since 1970, however much of its use is related to the phenomenon discovered in physics, chemistry and biology; later usage in the 2000s also related to robotics and software systems, though the use of the term from 2005 appears to have fallen slightly. Another popular term appears to be self-healing with 10s then 100s of uses every year since 2001 when White et al. (2001) published their work on self-healing microcapsule composites (see Figure 4). Self-healing materials have become a large area of research which has led to an increase in the use of the term. The remaining six terms all increased at a slower rate over the last 50 years, as shown in Figure 3(c and d), which exclude self-healing and self-organising. Self-repairing and self-optimising show the largest increase in the remaining six. Self-sealing shows the smallest increase and is only used in relatively few papers, unlike in patents where it is one of the most frequent terms.

A timeline from 1990 to 2020 showing the evolution of these concepts leading up to the development of SE is shown in Figure 4.

a)

b)

c)

d)
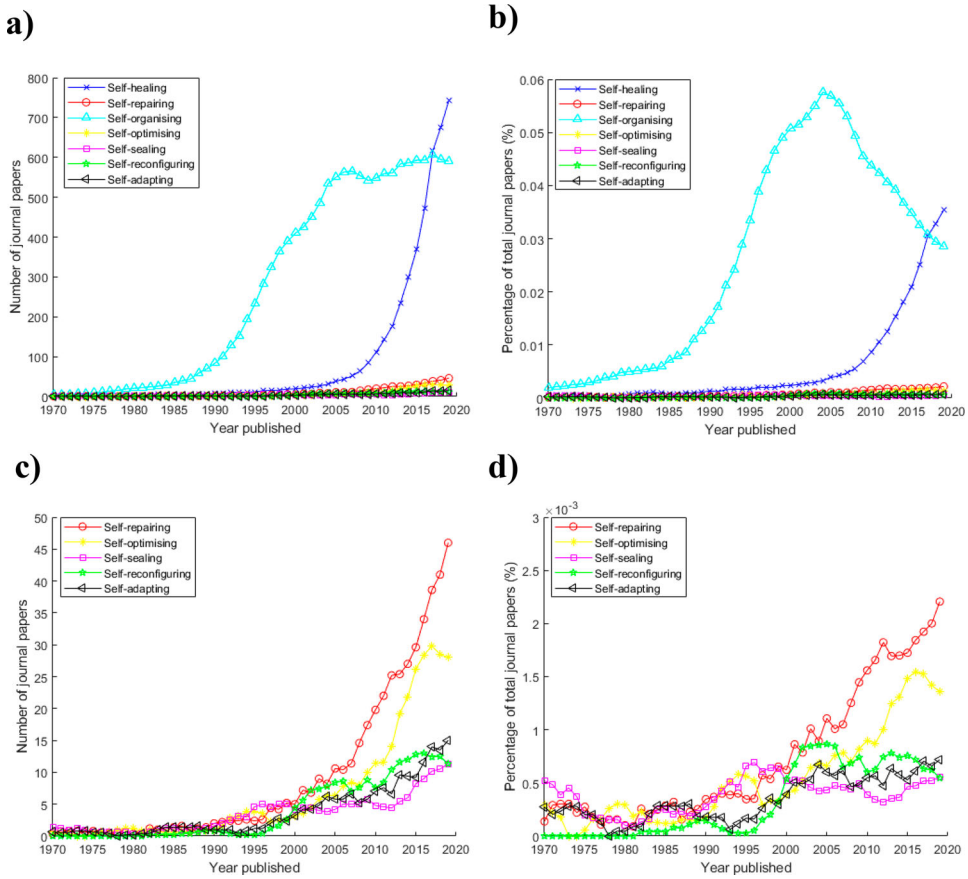
Figure 3. Graphs showing the (a) number, and (b) percentage, of peer reviewed journal papers published each year with the key term used in the title. Graphs (c) and (d) are the same graphs with the data for self-healing and self-optimising removed. The values plotted are a moving average of the five previous values.
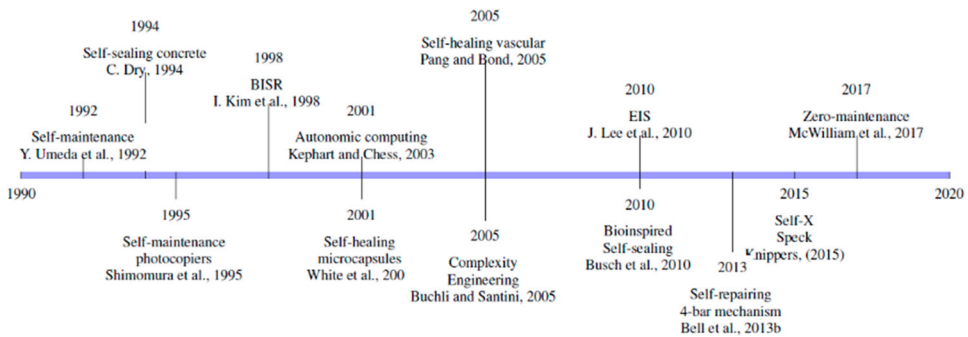

Figure 4. Timeline from 1990 to 2020 showing the development of key concepts and technologies over time leading to SE systems.

3. Taxonomy

There are many different subcategories (or methods) within SE; the most common ones are defined in this section. Figure 5 shows a summary map of the taxonomy terms and link between similar ones. Many of these concepts or strategies do not appear on their own; for example, a system could contain multiple self-∗ features such as self-healing and self-repairing. Alternatively, a SE system may also have self-testing, self-inspecting and self-monitoring aspects included to register a trigger and self-repair as a response.

3.1. Self-healing

Self-healing is one of the most common SE terms identified, though as Frei et al. (2013) noted the term is often used to mean very different processes even within the same industry. Previous authors have defined self-healing as a bottom-up approach which starts within a product (Frei et al. 2013). In this paper, 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-healing is often divided into autonomic and non-autonomic self-healing; 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 and implement the self-healing process (Kanu et al. 2019). Both have been considered in this review. Other classifications include extrinsic materials where the self-healing capability is due to an added component, e.g. microcapsules or vascular systems (more details in Section 4.1.1) or intrinsic, where it is a property of the material itself.

3.2. Self-repair

Self-repairing is similar to self-healing; however, while healing requires rehabilitation of components, a repair can include adding new materials or changing the ones already there. The term self-repair is used a lot in literature but often means different things (Frei et al.
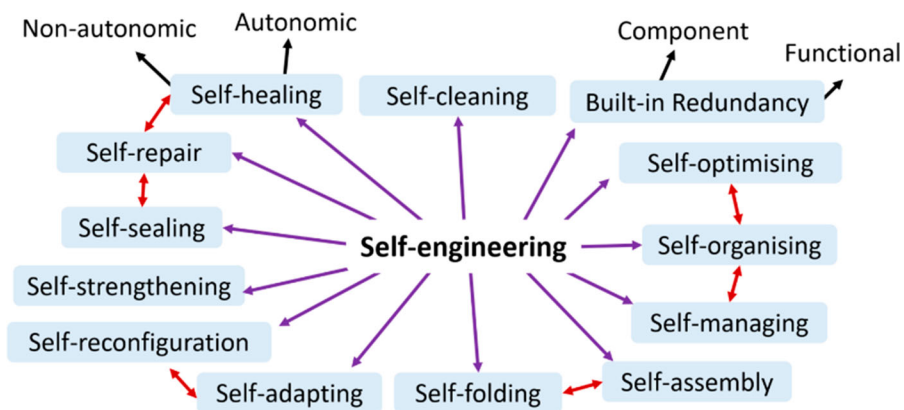

Figure 5. Diagram showing summary map of terms in the taxonomy and links between the terms or any subcategories.

2013). Self-repair is often used as a term to encompass many different SE responses. A key difference between self-repair and SE is that a repair requires a failure or loss of function (Fischer 2010) while SE systems can respond to a potential loss in failure as well.

3.3. Self-adapting

Self-adapting systems adjust in response to changing conditions to maintain or improve function. In computer science and software engineering, a system may also evaluate its behaviour and adjust to improve its function and performance (Macías-Escrivá et al. 2013); however, a better definition for this type of system is a self-optimising or self-tuning system. Self-adaptation is predominantly utilised in control systems, robotics and software (C.-H. Yu and Nagpal 2009; Macías-Escrivá et al. 2013; Tomforde and Goller 2020; Algabroun et al. 2017).

3.4. Self-reconfiguring

A system is capable of changing its arrangement to meet new challenges, component damage, or preserve its function. The system utilises only components within the system. It is a well-researched approach in robotics, electronics and software (Levi, Meister, and Schlachter 2014) but also utilised in many sectors where modules or redundant parts are used.

3.5. Self-organising

A self-organising system can rearrange or adapt itself without external direction to meet the needs of the system. There is little or no centralised or hierarchical control, which may be observed in other systems. Further details can be found in (Brueckner et al. 2005; Frei 2010).

3.6. Self-optimising

The system ensures maximum utilisation of resources to meet the system requirements, continuous monitoring of available resources and configurations is required. This includes three actions: (1) analyse the current situation, (2) determine objectives, and (3) adapt system behaviour (Gausemeier et al. 2006). Often also called a self-tuning system.

3.7. Self-sealing

A system can close leaks to prevent things (normally fluid) passing in or out of itself. Mechanisms used can be self-repair of self-healing based, and it is often classified as such. Is also referred to as self-closing in some literature (Mihashi and Nishiwaki 2012). The terms self-sealing and self-healing are often used interchangeable as some materials aim to prevent degradation by sealing cracks or damaged areas which water can get into and further degrade.

3.8. Other self-engineering terms

Some other commonly used SE terms include:

- *Self-cleaning* – Self-cleaning means that the removal of fouling material happens automatically. It should be noted that self-cleaning materials (such as Teflon) are hydrophobic, allowing water to slide off and carrying dirt with it. This is not a SE system as the response happens because of the material properties not as a response to a loss (or potential loss) in function.
- *Self-assembly* – The system can configure from parts into an operating system autonomously.
- *Self-strengthening* – The system can add stability in response to observed weakness to prevent failure.
- *Self-folding* – The system can be bent or flatten into a more compact shape to preserve components or functionality; this is often done as part of a self-strengthening, self-assembly or self-adapting process.
- *Self-managing* – The system has control of itself often utilising other self-∗ properties to do this; it is used in autonomic computing.

3.9. Associated terminology

The terms discussed so far in this section are SE responses. However, a SE system could also have other observational stages which do not take action to change the system, including:

- *Self-diagnosing* – A system which can identify the cause of a fault in the system. The findings of the system can inform further responses, but a self-diagnosing system does not have a response action built-in.
- *Self-modelling* – A system which can simulate system performance or behaviour and normally forms a base for a system to decide on a solution or action. Commonly used in robotics.
- *Self-evaluating* – The system can perform assessments and make judgements about itself using the resources or information available.
- *Self-inspection* – The system can perform checks or investigation on its internal states; this can involve comparison to an ideal or target state.
- *Self-awareness* – The system knows current and previous states.
- *Self-testing* – A system can monitor or observe its state and recognise when a fault has occurred.

3.9.1. Robustness

A system is robust if it does not easily get disturbed from its normal function; it can cope with failures or changing conditions and remain usable (Žiha 2000). It is important to note that SE is not the same as robustness though this definition sounds similar. A SE response takes action in response to a loss (or potential loss) of function, while a robust system aims to prevent the loss of function in the first place. A system should first be robust, then SE methods included to deal with failures which a robust design cannot deal with. For example, a material may have self-cleaning properties (hydrophobic) but could also have a built-in

self-cleaning mechanism to deal with high levels of fouling which are not prevented by the hydrophobic material.

3.9.2. Built-in redundancy

There are many different types of redundancy, Murata et al. (2001) categorised redundancy as component or functional.

- *Component Redundancy* – identical components are available to manage the system if one fails. An example is a system with spare memory cells which it can use to replace broken ones. Component redundancy is often the more expensive redundancy method.
- *Functional redundancy* – the same function is performed by other components in the case of failure. For example, a car engine could fail, but the starter motor could be used to keep it moving (if it was adequately designed).

Other categories of redundancy relate to how the components are used before they are required for a repair or reconfiguration (Chen and Crilly 2014).

- *Active redundancy* – Different material or components share a set function; if one (or more) is lost, the others maintain the function.
- *Partial active redundancy* – Various system functions are maintained by all components or materials and can be maintained even after some components are damaged.
- *Passive redundancy* – Spare components and material are inactive and activated to replace broken ones.

Utilising built-in redundancy only does not make a system SE. However, redundancy is regularly utilised in SE systems. What makes the system SE is the combination with another SE strategy. For example, in Section 4.3.2., the electrical systems outlined with built-in redundancy also have a self-reconfiguration mechanism which enables the system to automatically change and utilise the inbuilt redundancy in response to lost function. However, if an operator had to initiate the reconfiguration or it occurs at a set time not in response to lost function, then the system no longer classifies as SE. Similarly, if a shelf has three supports and can remain up with reduced loading if one breaks this is a robust design but not SE because there is no action or response to the break or loss of capacity.

3.9.3. Autonomous systems

A system is considered autonomous if it can operate in the real world without any external control for an extended period of time (Bekey 2005; Bradshaw et al. 2013). Often autonomous systems respond to environmental changes similar to self-adapting systems. An automated response is a key characteristic of SE systems as outlined in the definition; however, this can take different forms. SE systems which use control will display some level of autonomy to control response, decision making, planning, and verification steps. SE systems without control may often be autonomous; for example, many self-healing materials heal autonomously in response to damage. Even if all SE systems can be considered autonomous systems, not all autonomous systems will be SE systems. SE systems could even be combined with, or part of, an autonomous system.

4. Current self-engineering systems

Current SE technologies identified from reviewing literature have been grouped under different engineering disciplines: (1) mechanical, (2) civil, (3) electrical and electronics, and (4) mechatronics. A summary of each sector is shown in Tables 1–4 at the end of each sub-section, with technologies identified reviewed as outlined previously in the methodology.

4.1. Mechanical

4.1.1. Self-healing

Most research on self-healing materials has focused on polymers or polymer-based composites and has been covered in many earlier reviews (Kanu et al. 2019). The key extrinsic self-healing delivery methods utilised are discussed below.

- Micro-capsules – Capsules are embedded either within or on the surface of a material. Capsules can contain a liquid healing agent which solidifies when released or mixed with other agents (often an epoxy). See the diagram in Figure 6 for an example of the process. White et al. (2001) were the first to demonstrate this concept with polymer composites, though it has been developed further since. The process is effective but has limited uses within a bulk material because the capsules cannot be replenished for multiple uses to repair multiple cracks.
- Vascular – Similar to veins and arteries in our body, micro-tubes filled with a liquid healing agent are embedded within or on the surface of the material. Cracks or damage break the tubes and release the healing agent (Pang and Bond 2005; Norris et al. 2011). This technology is well developed, with some patents for these types of system (Patrick et al. 2013), though not utilised in any commercial products yet. The vein structure allows a larger supply of healing agent to damage sites. However, the process is still limited; once a vein is broken, the healing agent can harden and block further healing agent delivery.
- Shape memory materials (SMM) – SMM are added to make a composite material, when heated cracks are pulled closed, making it easier for chemical bonds to reform and heal a crack (Kirkby et al. 2008; Wang et al. 2013). However, it requires outside stimulus and intrinsic material healing properties to heal fully. The effect of direction and position of SMM on healing efficiency needs further consideration.

Intrinsic self-healing materials can heal due to non-covalent chemistry or dynamic covalent chemistry (Wei et al. 2014). Healing is triggered by a stimulus, including pH change, light, temperature, pressure, or oxygen. Dielse-Alder reactions are frequently used to create self-healing polymers. Intrinsic healing methods are often non-autonomic and need an initial trigger. For example, Dielse-Alder reactions require warm temperatures (up to 80°C) often an operator needs to remove the material and place it in a warm environment. Making the healing process difficult to automate.

Self-healing in metals is much more difficult. There has been some success with metal composites or preserving metal surfaces. van Dijk and van der Zwaag (2018) reviewed much of the work on self-healing metals and noted two obstacles: (i) that metal atoms are an
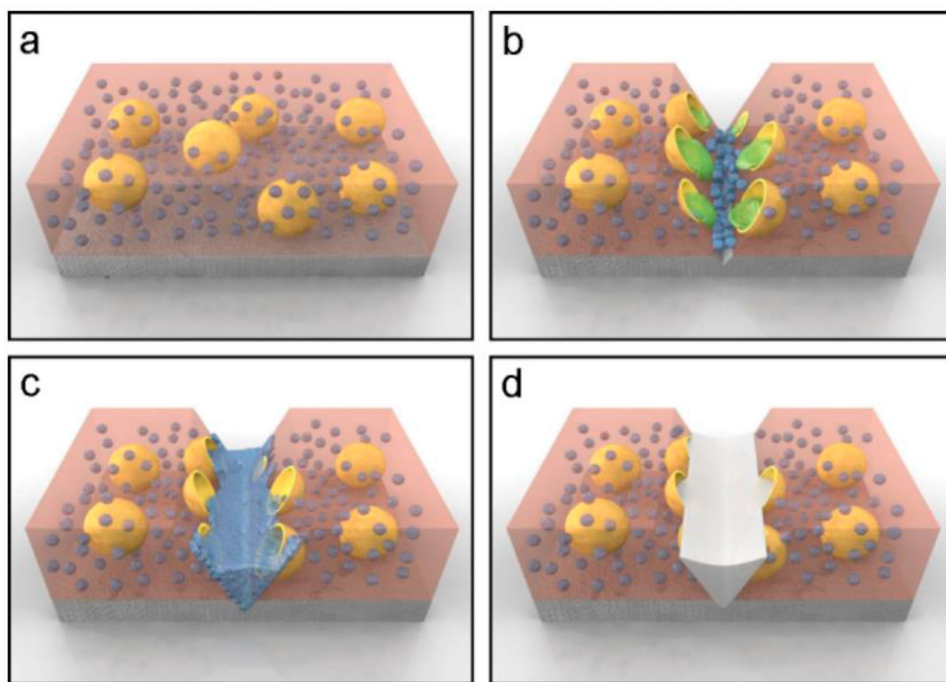
Figure 6. Schematic of the self-healing process using microcapsules. Catalyst is released due to damage and mixes with healing agent healing the damaged region. Reprinted with permission from Cho, White, and Braun (2005) Copyright 2009, Wiley-VCH.

intrinsically small size and (ii) the metallic atom motion is generally in the opposite direction of a vacancy. Lumley and Polmear (2007) noted a small amount of self-healing ability in certain aluminium alloys (Al-Cu-Mg-Ag); strength in creep tests was improved by heat treatment of the alloy to allow solute atoms to move along dislocations. Added solute atoms (gold in iron) can also propagate into the cavity formed during creep tests with high temperatures and stress, once the cavity is filled, its growth is stalled. High temperatures below the melting point and electrical fields can also help heal bonds in some metals, see van Dijk and van der Zwaag (2018) for more details. A problem with all the techniques used in metals is the dependence on precise loading and temperature conditions. One alternative is room temp liquid metals alloys (such as gallium-based alloys) which have been utilised in polymers as a self-healing and self-strengthening agent (Thuo and Boyce 2018; Adam Bilodeau and Kramer 2017). The metal hardens in air but two surfaces held together can re-join, allowing it to be cut and healed as long as surfaces are held together. However, the metal offers little structural support.

One growing area of self-healing materials is clothing where extending product life is a growing issue. Gaddes et al. (2016) developed a textile coating which can be used to heal material samples back together using water or high humidity, examples of healed fabrics can be seen in Figure 7. The main protein used is extracted from squid, and Tandem Repeat own and sells the self-healing coating commercially (patent found in Raab and Bachelet (2019)).
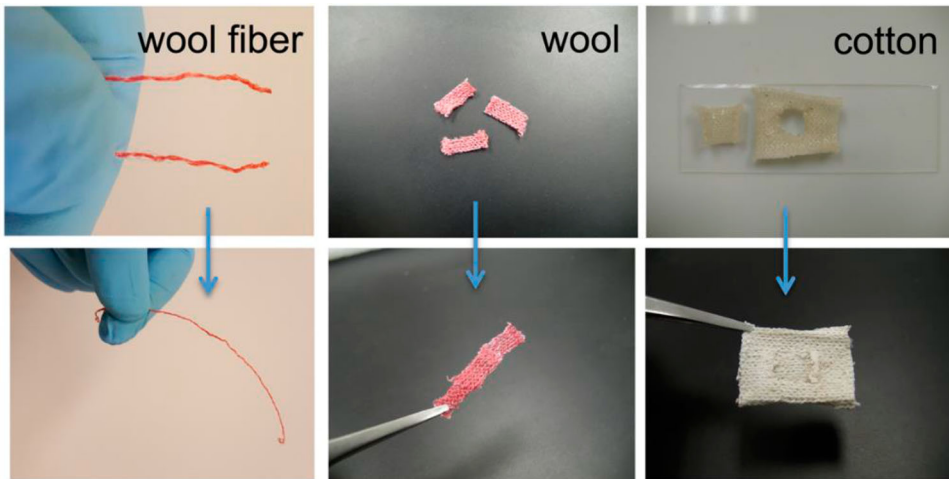
Figure 7. Fabrics are coated in a polyelectrolyte LbL film containing squid ring teeth proteins, water is then coated on the materials and used to self-heal the fabrics back together. Reprinted (and adapted) with permission from Gaddes et al. (2016). Copyright 2016 American Chemical Society.

Self-healing ceramic composites were created by using high temperatures above 1000 °C (but below the melting point) for over an hour (Kim et al. 2008; Liu et al. 2009). However, the high temperatures make it difficult to implement in any commercial product or system.

Self-healing coatings is a well-researched area with many earlier reviews (Zhang et al. 2018). Polymers healing agents and oils are often added into micro-capsules (or within micro-tubes) damage to the surface breaks the capsules (Cho, White, and Braun 2005); Figure 6 shows a diagram of microcapsule self-healing polymer coating. The release is initiated by physical damage, a Ph change or chemical change as in oxidisation or rusting of the surface. Non-autonomic triggers include UV radiation or heat applied to the surface. Coatings can be hard to heal because they are thin and not always uniform. A patent exists for a lubrication coating with adding micro-capsules which break when wear starts to occur, releasing anti-degradation fluid to help preserve the lubrication oil (Ventura et al. 2019).

A SE system utilising non-autonomous self-healing materials would have to utilise automated monitoring, verification, and application of a stimulus such as heat, radiation or chemicals. Non-autonomic self-healing processes are often only demonstrated in lab experiments, not in operational environments, and none have been found utilised in a fully autonomous SE process. Autonomous self-healing materials do not require monitoring of verification stages; healing response is determined by the type and severity of damage which initiates it. The response is simplified and easy to implement but difficult to manage and control.

Significant research has been conducted on self-healing materials, but some fundamental issues remain, which have prevented the wider adoption of technologies highlighted. Firstly, the healing response often requires very precise conditions to heal; these conditions may easily occur in a lab but not in reality (such as no strain on a material or a set temperature range). Secondly, the cost of the materials is higher often due to their complex composition. Lastly, the process is often restricted to one occurrence; after being triggered, it cannot happen again without further inputs. Even with high healing efficiency materials,

the properties of the material (yield strength, conductivity or flexibility) can be reduced. The design of the material also limits the number of healing cycles.

4.1.2. Self-sealing

Self-sealing tires which can withstand punctures were developed for the military in the 1930s (Crossan 1934). Many other companies including The Goodyear Tire & Rubber Company (Mruk, Kaes, and Roskamp 2015) have published patents for self-sealing tire designs (Dien 2019; Dry 2017; Gobinath et al. 2008), some of which are now sold commercially. Rampf et al. made self-sealing components created from a foam coating inspired by the way plants self-seal when cut (Rampf et al. 2011, 2013); internal pressure and an expanding material block holes in the surface. The successful method did not completely seal the hole (up to 99.9% air loss reduction was seen). Basu et al. (2016) experimented with fluid insulation for cables. A solidifying agent added to the insulating oil self-sealed leaks when they occurred, though the method is not extensively tested. Also, insulating 100s of miles of cables in the oil would be expensive. A similar method is presented in a patent for self-healing armour for the US army (Daniels and Petrovich 2011); a viscous liquid inner layer moves to fill damaged sections. Other self-sealing seals for pipes which expand when in contact with water are also presented in patents (Barnhouse, Clark, and Williams 2019).

A self-sealing pressure vessel panel created by Huston and Hurley (2010) can detect damage and the location by monitoring the capacitance, resistance and inductance of the material; a healing response is then assigned when a set deviation in capacitance, resistance or inductance is reached. It was only demonstrated in a laboratory setting successfully, and it is unclear from the research if the material created would be strong enough to use in any pressure vessel.

4.1.3. Self-repairing

The first example of a self-repairing system was created during the first industrial revolution when self-sharpening ploughshares were created by making one side of a blade harder and one which is softer and more vulnerable to erosion (Brunt 2003). A more recently patented coating (Hardide) has been applied to knives and tool blades to make them self-sharpening using a similar method (Zhuk 2007; Castronovo 2012). When tested on a rotary paper-knife, it remained sharp for ten weeks of operation instead of 12 hours without the coating.

Peairs, Park, and Inman (2004) presented the design for a self-repairing bolted joint. Piezoelectric sensor washers register when the force holding a bolt is falling due to vibrations, heat can then be applied to a shape memory alloy (SMA) washer to add torque to prevent any movement in the bolted plates and increase force. The process is not fully automated, and heating the SMA effectively can be difficult. Other authors have used a SMA bolt instead of a washer to perform the same task (Travassos, Rodrigues, and de Araújo 2017).

A 4-bar linkage mechanism is used to drive a set path from rotational motion. Bell et al. (2017) investigated if the mechanisms could be self-repaired to maintain the original actuation path when one joint is damaged. Damage can be registered by monitoring a deviation in the actuation path. A self-repair approach presented by the authors involves four steps: Cause and detection of fault, diagnosis, confirm diagnosis, and corrective action (Bell et al. 2013). This approach is applied to design new bar lengths to create a similar pathway to an original one before the damage. Only a simulation of the concept was created and presented.

4.1.4. Self-reconfiguring

Reconfigurable manufacturing systems (RMS) combine modular machines which can change their functionality as required to meet different production requirements (Koren et al. 1999). Li, Nassehi, and Epureanu (2019b) designed a process for an RMS which self-reconfigured itself not only to meet manufacturing demands but also to utilise data on machine degradation to avoid potential failures. Monitoring of the machine condition and outputs would be required to enable and verify the effect of reconfiguration.

4.1.5. Self-adapting

Adapting mechanisms are used regularly in engineering; one common use is for grasping objects. Mechanisms created can allow multiple degrees of movement with fewer actuators (under-actuated) (Sun and Zhang 2012), which is useful for adapting to pick up objects from different orientations and positions without assistance. These mechanisms are used for robot hands (Gao et al. 2014) and a gripper for picking up bins (Bayne 2001) but could also be utilised in many other SE systems.

Other notable self-adapting systems found in patents include:

- an escape slide which adjusts to the position and height of the aircraft using sensor data on slide angle and a control systems, developed by Boeing Company (Alberts 2003),
- a self-adapting screw cap which can adjust to different thread sizes using passive mechanism (Courtenay 2018),
- an adaptive wing with collapsible sections allowing the aerofoil shape to change as needed (Hemmelgarn and Pelley 2015).

Only the first of these three patent designs appears to have been used in a commercial product.

4.1.6. Self-cleaning

As mentioned earlier, most literature on self-cleaning refers to self-cleaning materials or coatings, which have hydrophobic properties (Sethi and Manik 2018). These materials are not SE because cleaning occurs when water (normally rain) carries dirt or fouling material off the surface. The materials are designed to prevent fouling from building up and causing a loss in performance. To be classified as SE, a self-cleaning system should respond to a loss in performance or function, rather than preventing it.

There are mechanical self-cleaning systems which clean fouling build-up; self-cleaning filter systems have been in use as early as 1976 (Neaman and Anderson 1980), with different techniques developed and used for cleaning since then (Ricco 2018). The initial cost of a self-cleaning filter system can be ten times higher than a regular filter system (Ricco 2018) but significantly reduces the servicing and maintenance compared to a regular filter without self-cleaning abilities, making it useful for critical services such as water treatment and cooling. Pressure loss through the filter is often used as feedback to initiate a self-cleaning cycle managed by a control system (Bennett 2004). Some designs have even utilised no electrical components or control to reduce costs (Silva Vieira, Weeber, and Ghisi 2013).

Many different designs exist, but all use similar techniques:

- Backwash – the most common cleaning method which uses a reversed flow of clean water back through the filter dislodging fouling and flushing it out of the filter.
- Mechanical scrapers – scrapers or paddles to remove fouling.
- Water jet – often used with a backwash, jets are used to increase the cleaning force on the filters.
- Ultrasonic and pulse – spark discharges are used to reduce the adhesion of fouling material to the filter (Yang et al. 2010a, 2010b; Sofi Filtration 2016). Scrapers or a backwash are required to remove the fouling completely.

Some of these techniques are also used for cleaning fouling in heat exchangers. Fluidised-bed heat exchangers are also a very common method used; small particles are added to the flow inside the heat exchanger to reduce fouling throughout operation (Klaren 2000; Klaren and De Boer 2011). This method could be changed into a SE method if the particles were released only when fouling was detected and not all the time.

4.1.7. Summary

The largest area of scientific investigation is self-healing materials, though other areas have also been presented in this section. An overview of the systems discussed in this section is shown in Table 1. Table 1 highlights that most mechanical SE systems are applied at the material or component level; there is also a need for more automation in the processes as many still rely on human assistance. For example, lots of non-autonomous self-healing processes do not have automated mechanisms for monitoring damage, triggering SE and verifying when it is complete. Self-sharpening and self-cleaning are the most developed technologies identified with both being used regularly in industry.

Table 1. Table of current SE technology outlined in the mechanical section, TRL, system level it is applied to, key SE characteristics and section of the paper.

SE Mechanism	Utilised in or for	Article section	System	Sub-system	Component	Material	TRL	1	2	3	4	References
Self-healing autonomic	Plastic, vascular or capsules	4.1.1				✓	4					White et al. 2001; Pang and Bond 2005; Norris et al. 2011; Patrick et al. 2013
	Metals (galinstan)	4.1.1				✓	3					Thuo and Boyce 2018; Adam Bilodeau and Kramer 2017
	Coatings	4.1.1				✓	7					Zhang et al. 2018; Ch et al. 2005; Ventura et al. 2019
Self-healing non-autonomic	Dielse-Alder or SMM polymer	4.1.1				✓	6					Wei et al. 2014; Kirkby et al. 2008; Wang et al. 2013
	Metal	4.1.1				✓	2					van Dijk and van der Zwaag 2018; Lumley and Polmear 2007;
	Ceramics	4.1.1				✓	1					Kim et al. 2008; Liu et al. 2009
	Clothing coating	4.1.1				✓	8					Raab and Bachelet 2019
Self-sealing	Tires, insulation, panel	4.1.2			✓	✓	8					Mruk, Kaes, and Roskamp 2015; Dien 2019; Dry 2017; Gobinath et al. 2008; Rampf et al. 2013; Basu et al. 2016; Daniels and Petrovich 2011; Barnhouse, Clark, and Williams 2019; Huston and Hurley 2010
Self-repair	Self-tightening bolt	4.1.3			✓		3					Peairs, Park, and Inman 2004; Travassos, Rodrigues, and de Araújo 2017
	4-bar joint	4.1.3			✓		1					Bell et al. 2017; Bell et al. 2013
Self-sharpening	Blades/tool coating	4.1.3				✓	9					Zhuk 2007; Castronovo 2012
Self-reconfiguration	Manufacturing system	4.1.4	✓				1					Li, Nassehi, and Epureanu 2019
Self-adapting	Robotic hand	4.1.5		✓			8					Gao et al. 2014; Bayne 2001
	Screw cap	4.1.5			✓		4					Courtenay 2018
	Plane slide	4.1.5		✓			8					Alberts 2003
Self-cleaning	Scrapers and water jet	4.1.7		✓			9					Ricco 2018; Bennett 2004; Vieira, Weeber, and Ghisi 2013; Yang et al. 2010; Sofi Filtration 2016; Klaren 2000; Klaren and De Boer 2011

Key
Characteristic met
Characteristic partly met
Characteristic not met

4.2. Civil engineering

4.2.1. Self-healing and self-sealing

Concrete is one of the most commonly used materials in civil engineering. It is, therefore, unsurprising that there has been a significant amount of research focusing on making self-healing and self-sealing concrete (Snoeck and De Belie 2015). A key failure mode of concrete structures is water ingress into cracks which can accelerate degradation. Many researchers have therefore focused on healing concrete by sealing cracks; this makes it difficult to separate the research, which is why key methods for both have been reviewed together. Many of the methods used are similar to those used for composite materials.

One of the earliest examples of a human-made self-healing material is a mortar designed by the Romans. Crystallisation occurs in the material due to the volcanic ash added (Jackson et al. 2014), crystals formed over 100s of years grow towards micro-cracks, helping to prevent cracks growing and preserving the material. However, the hardening takes 100s of years and is a natural ageing process; it is not a response to a loss of function as required for a SE system.

In 1994, Dry conducted early lab experiments with glass capsules and tubes of liquid adhesive embedded in concrete (Dry 1994, 1997). The capsules were burst by cracking the concrete or by human control when required. Similar plastic composites with vascular (Pang and Bond 2005) and microcapsule (White et al. 2001) self-healing presented later used healing agent similar to the bulk material, while Dry used a polymer adhesive to seal the concrete cracks. This approach could be considered self-healing or self-sealing and is not repeatable as the polymer hardens and blocks channels. Areas with cracks are still weaker than the bulk concrete and are likely to be where future cracks form when loaded. The concrete also needs to be unloaded to seal cracks, which is not possible in many structures. Other authors have explored using vascular or microcapsules in concrete to release other healing agents (Snoeck and De Belie 2015). An alternative vascular method utilised heat to trigger the release of adhesive from a thin film; the heat was provided by a composite self-diagnosing device running parallel to the film (Nishiwaki et al. 2006). Current runs through the self-diagnosing device (monitoring for damage), cracks increase the resistance in the device and lead to local heating releasing the adhesive locally. The problem is a continuous current supply is required, and the crack has to penetrate the self-diagnosing device, otherwise it is not registered. Only lab experiments to prove these methods have been demonstrated so far.

A concrete structure that replicated bone, with a porous concrete centre was used to deliver epoxy to crack sites in the solid outer structure (Sangadji and Schlangen 2013). This is harder to make than a solid concrete structure and only effective for one healing cycle after which the epoxy blocks the porous structure, see pictures in Figure 8 The porous structure is weaker than a solid concrete structure, and a proven strength increase after healing comes from the epoxy filling the internal gaps rather than the repair of the crack. The addition of the healing agent is also triggered by the researcher, not automatically using a monitoring and trigger system.

Bacteria is added within concrete material to seal cracks and prevent water ingress by creating calcium carbonate. This technology is well developed, with field trials taking place and patents filed (Lee et al. 2019; Al-Tabbaa et al. 2019). Keeping bacterial alive within the concrete is a key problem; different methods of micro-encapsulation have been tested as
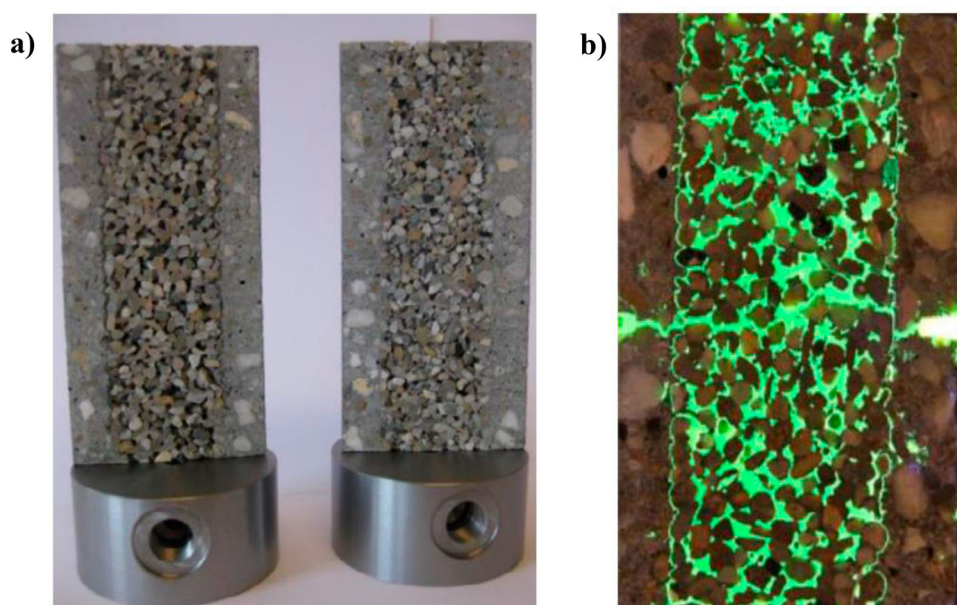
Figure 8. (a) Cross-section of the original concrete structure tested designed to replicate bone. (b) Longitudinal cross section showing the crack which has been filled by epoxy. Reproduced with permission from Sangadji and Schlangen (2013), CC By 4.0. (Creative Commons Attribution 4.0 International 2020).

a solution (Pungrasmi et al. 2019). Water triggers the bacteria meaning this method is only useful for a few applications of uncovered concrete structures which are outside. Concrete is sealed but does not completely recover properties.

Leaks from landfill can be toxic to wildlife; they are often sealed with a lining material before and after being filled to prevent any contamination. Shi and Booth created a lining which could self-seal (Shi and Booth 2005). It was formed of two parent material layers separated by a thin barrier material; when the seal is broken, the barrier breaks, allowing parent materials to react together and reseal the lining. This method was successfully tested on a landfill site and patented. It is unclear if the self-sealing layer can withstand all surface punctures, and how long it remains effective for.

4.2.2. Self-repair

Tensegrity structures are lightweight, flexible structures made up of tensioned cables and struts in a continuous self-stresses state with cables in tension and struts in compression. Adam and Smith (2007) modelled and built a self-diagnosing and self-repairing tensegrity structure. The critical struts can extend or contract, creating different forces and enabling the structure to diagnose where a load change or damage has occurred. The structure contains more cables and supports than required for stability. The repair process uses this redundancy and changes cable tension to reduce the peak load on the cables until an optimum point is reached. However, the repair is designed to maintain the structural stability and safety but not the full functionality; for example, the top nodes may no longer form a flat surface. This forms a complete SE system though it is reliant of humans to manage stages of the process, the repair is also dependent on having redundant cables and struts to cope with damaged ones. A similar approach was modelled for a tensegrity bridge design; when

Table 2. Table of current SE technology outlined in the civil engineering section, TRL, system level it is applied to, key SE characteristics and section of the paper.

SE Mechanism	Utilised in or for	Article section	System level				TRL	Characteristic met				References
			System	Sub-system	Component	Material		1	2	3	4	
Self-healing/ Self-sealing	Vascular or micro-capsules	4.2.1			✓		4					Dry 1994; Dry 1997; Snoeck and De Belie 2015; Nishiwaki et al. 2006
	Porous bone structure	4.2.1			✓		1					Sangadji and Schlangen 2013
	Landfill sealing	4.2.1			✓		4					Shi and Booth 2005
	Embedded bacteria	4.2.1			✓		7					Lee et al. 2019; Al-Tabbaa et al. 2019; Pungrasmi et al. 2019
Self-repair	Tensegrity structures	4.2.2.	✓				2					Adam and Smith 2007; Korkmaz, Bel Hadj Ali, and Smith 2010

Key
Characteristic met
Characteristic partly met
Characteristic not met

a strut was broken, the cable length and tension were adjusted to cope and not deflect excessively (Korkmaz, Bel Hadj Ali, and Smith 2010). Unfortunately, the process was only modelled and not verified in a prototype or experiment.

4.2.3. Summary

Table 2 summarises the civil SE research identified; excluding using bacteria in concrete most techniques are only in the lab-based research stage. Most research has focused at a material level, healing and sealing of concrete structure; only tensegrity structure repair focused at a higher system level.

4.3. Electrical and electronics

4.3.1. Self-repairing and self-healing

Many electronic systems are said to have built-in self-repair (BISR) which was first developed in 1998 (Kim et al. 1998); in reality, this self-repair is usually a reconfiguration and built-in redundancy. A sub-system uses a spare cell in the system instead of the faulty cell, discussed further in Section 4.3.2. As with self-repair, many self-healing electronics possess this property by re-configuring their system to utilise redundant components to repair the damage. However, these methods can be combined with a self-healing solution where one exists for the damaged component. Previous authors followed this approach to heal solid-state drives (SSD) (Wu, Dong, and Zhang 2011) and flash memory cells (Lue et al. 2012); built-in heaters provided localised heat and accelerate degradation healing of component cells. Heaters are initiated in response to a loss in memory capacity and on for a set period of time. Heaters would have to be placed next to each cell to allow targeted repair control of every cell, which would increase the size of the hardware.

Self-healing actuators made for soft or flexible electronics are often created using Dielectric Elastomers (DE) (Li et al. 2016a), this work is discussed further in Section 4.5.

A photopolymerisation-based additive manufacturing technique is used to create complex self-healing elastomers from specially designed photoelastomer ink (Yu et al. 2019). By doping the material with carbon-black, a contracting actuator capable of lifting 10 g
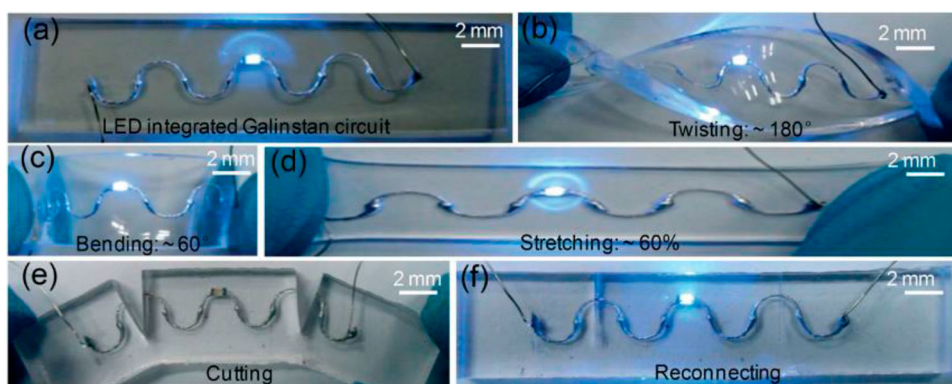
Figure 9. LED-integrated galinstan circuit in S shape. (a–d) physical deformation, (e) the LED-integrated galinstan circuit is cut with a blade and (f) the circuit is healed. Reproduced from Li, Wu, and Lee (2016b) © 2016 The Royal Society of Chemistry.

is made. However, temperatures of 60°C are required for healing, while DE can heal at 20°C (room temperature). A further system would need to be created to monitor when heat should be applied and removed to provide appropriate elastomer healing, creating a complete SE system.

Galinstan alloys (Ga–In–Sn) are useful as a conductive metal which remains liquid at room temperature. Li, Wu, and Lee (2016b) created a method for printing with galinstan alloys by preventing oxidisation, allowing it to be added to self-healing elastomers (poly-dimethylsiloxane (PDMS)) to create a flexible and stretchable self-healing electronic circuit, demonstrated in Figure 9. When connecting wires are cut with scissors, they heal, though only when the surfaces are held together.

Self-healing batteries is an area of growing interest; however, as such, there has been no solution found which will enable lithium-based batteries we use in products every day to heal. Much of the current work focuses on making self-healing electrodes (Wang et al. 2019) or supercapacitors components (Wang et al. 2014; Huang et al. 2015; Peng et al. 2019). Many successful self-healing batteries found require conditions with high temperature or chemical reactions, which cannot be achieved outside of a lab (Cheng et al. 2020).

4.3.2. Self-reconfiguring and built-in redundancy

Electronics component designers have, for a long time, exploited the ability of reconfiguration and redundancy to make fault-tolerant systems. One of the early solutions (from the 1980s) is a field-programmable gate array (FPGA), which contains programmable logic blocks and memory elements which can be reconfigured when needed. FPGAs offer a cheaper solution than having a complete redundant system which can quickly lead to spiralling costs (Frei et al. 2013). FPGAs and other evolvable hardware have been extensively researched by previous authors (Zhang et al. 2016). Other authors repaired random access memory (RAM) devices with reconfiguration; faulty memory cells are identified using a memory test (monitoring storage and change of data in cells), data in a faulty memory cell is stored at new spare addresses and the system self-reconfigures to adapt to the change (Nair and Bonifus 2018; Shvydun and Adham 2014). The repair ability of these systems is limited by the availability of redundant parts. Diagnosing faulty cells can be difficult in a

complex system, a Built-in Self-testing (BIST) system is often used in electronics to identify faulty cells or parts (Bell et al. 2013).

Micro-electromechanical system (MEMS) devices, though relatively cheap components, can form critical parts which are difficult to replace when damaged. A MEMS piezoelectric energy harvester design with redundant parts is presented by Farnsworth and Tiwari (2015); when the piezoelectric harvester is damaged, the circuitry is designed to re-configure to cope with the change. Another accelerometer MEMS device designed utilises modules made up of parallel rods (Xiong, Wu, and Jone 2005). The modular design means the accelerometer has redundant parts to compare performance and take over if one is damaged. However, by having smaller modules all performing the same function rather than working together, the accuracy of the sensor is reduced. A designer would have to balance between having high accuracy or resilience from a self-reconfiguration ability.

One approach tested by many authors utilised a bio-inspired hierarchy with organism, organ and cellular level components (Bremner et al. 2013). Embedded memory in the system cells can carry information about themselves and their closest neighbours, rather than the whole system, similar to DNA fragments (Samie, Dragffy, and Pipe 2009, 2010). A repair uses the information from neighbouring cells to create a replacement from redundant cells, thereby maintaining the function of the whole organ.

An earlier bio-inspired project (the BioWall project) attempted to replicate three biological characteristics: phylogeny (systems which can evolve), ontogeny (systems which can grow through replication and regeneration) and epigenesis (systems which can learn) (Teuscher, Mange, and Tempesti 2003). This is an ambitious aim and not completely realised in the project. An interactive BioWatch was created, touching a cell in the clock display kills the cell and causes the system to adapt and heal using the neighbouring cells, which contain a map of the whole system. The system is designed to respond to expected types of damage, making it easier to design a response than it would be for unknown failures.

4.3.3. Self-adapting

Self-adapting electronic systems, though similar to self-reconfiguring systems, are slightly different; for example, they can adapt to changing environments, conditions or damage. One demonstration of self-adaptation is a self-adapting antenna for flexible electronics (such as on clothing); it uses changes in the incoming signal to register a change in its orientation or receiving surface and compensates accordingly (Braaten et al. 2013). The adaptation trigger and response stages require prior knowledge of the incoming signal, which might not always be available. Similarly, Apple Inc. recently filed a patent for a self-adapting phone vibrator and haptic device; the device registers if vibrations are dampened by the surroundings (such as a handbag or pocket) and adjust vibration frequency for a more noticeable vibration (Hill 2017). Few details are given on how a suitable vibration frequency is identified and verified.

4.3.4. Self-optimising (self-tuning)

Many electronic devices have built-in self-tuning or self-optimisation achieved using sensors and a feedback control circuits. Examples found in patents include:

- a medical lancing device (Alden and Freeman 2008) which prevents skin puncture from being too deep,

Table 3. Table of current SE technology outlined in the electrical and electronics engineering section, TRL, system level it is applied to, key SE characteristics and section of the paper.

SE Mechanism	Utilised in or for	Article section	System level				TRL	Characteristic met				References
			System	Sub-system	Component	Material		1	2	3	4	
Self-healing	SSD + memory cells	4.3.1.	✓				3					Wu, Dong, and Zhang 2011; Lue et al. 2012
	Elastomer actuators	4.3.1.			✓		2					Li et al. 2016; Yu et al. 2019
	Connecting wires (galistan)	4.3.1.			✓		2					Li, Wu, and Lee 2016
	Batteries or supercapacitors											Wang et al. 2019; Wang et al. 2014; Huang et al. 2015; Peng et al. 2019; Cheng et al. 2020
Self-reconfigure /redundancy	FPGA	4.3.2.	✓				9					Frei et al. 2013; Zhang et al. 2016
	RAM											Nair and Bonifus 2018; Shvydun and Adham 2014; Bell et al. 2013
	MEMS											Farnsworth and Tiwari 2015; Xiong, Wu, and Jone 2005
	BioWatch/Wall	4.3.2.	✓				3					Bremner et al. 2013; Samie, Dragffy, and Pipe 2009; Samie, Dragffy, and Pipe 2010; Teuscher, Mange, and Tempesti 2003
Self-adapting	Antenna, haptic device	4.3.3.		✓			2					Braaten et al. 2013; Hill 2017
Self-optimising	Amplifier, antenna	4.3.5.		✓			3					Bayar and Quintall 2019; Sengupta et al. 2012; Asrani, Katragadda, and Ananthanarayanan 2016
	Medical lancing device	4.3.5.	✓				2					Alden and Freeman 2008

Key
Characteristic met
Characteristic partly met
Characteristic not met

- an amplifier which adapts based on the signal strength and quality (Bayar and Quintall 2019; Sengupta et al. 2012),
- a phone which registers it has been dropped and tests the antenna, re-tuning it if needed (Asrani, Katragadda, and Ananthanarayanan 2016).

4.3.5. Summary

Electrical and electronic SE systems identified have been reviewed in this section; a summary is detailed in Table 3. SE methods have been applied at all system levels, though most frequently at the system level. Self-reconfiguration and redundancy is the most developed technique and has been widely used in commercial products (such as RAM and FPGAs). Self-healing methods have been extensively investigated, but they still rely on some form of human control.

4.4. Mechatronics

This section reviews robotic and mechatronic SE systems identified and is summarised in Table 4.

4.4.1. Self-healing

Most of the advances in self-healing robotics have been in soft robotics; a summary is given here see Adam Bilodeau and Kramer (2017) for a more detailed review. Dielectric Elastomers (DE) contain a flexible elastomer between two electrode layers (similar to a capacitor), the charge on the electrode compresses the elastomer layer. They have gained interest in soft robotics as flexible actuators and sensors. However, they break regularly as

Table 4. Table of current SE technology outlined in the mechatronics section, TRL, system level it is applied to, key SE characteristics and section of the paper.

SE Mechanism	Utilised in or for	Article section	System level				TRL	Characteristic met				References
			System	Sub-system	Component	Material		1	2	3	4	
Self-healing	Soft robotics	4.4.1.			✓	✓	2					Adam, Bilodeau and Kramer 2017; Yuan et al. 2008; Hunt, McKay, and Anderson 2014; Shepherd et al. 2013; Tee et al. 2012; Cao et al. 2019; Majidi 2019
	Diels-Alde polymer	4.4.1.				✓	2					Roels et al. 2019; Terryn et al. 2015; Terryn et al. 2017
Self-reconfigure	Modular robots	4.4.2.	✓				3					2014; Murata et al. 2001; Rubenstein and Shen 2009; Levi, Meister, and Schlachter
	Inflatable robot	4.4.2.	✓									Usevitch et al. 2020
Self-adapting	Robotic movement	4.4.3.	✓				3					Yu and Nagpal 2009; Bongard, Zykov, and Lipson 2006; Cully et al. 2015a; Yang et al. 2010
Self-replicating	Create new modules	4.4.4.	✓				2					Jacobson, Griffith, and Goldwater 2005; Zykov et al. 2007; Pelrine et al. 2016
Self-assembly	Modular assembly	4.4.4.	✓				3					Ishiguro and Maegawa 2006; Suzuki et al. 2009; Li et al. 2019; Divband Soorati et al. 2019

Key
Characteristic met
Characteristic partly met
Characteristic not met

a result of a breakdown in the elastomer layer, which allows voltage to penetrate. DE punctures will also cause a short circuit between electrode layers. Yuan et al. (2008) developed a coating which prevented the electrode layers moving into the elastomer layer when punctured: this enabled the DE to work even with a puncture. However, the healing efficiency is low, and each time the DE is healed the performance is reduced. Changes in performance can be evaluated by observing actuator deformation before and after damage. In another approach, an elastomer is made of silicone sponge and silicone oil (Hunt, McKay, and Anderson 2014); when the elastomer is breached, the oil flows into the gap keeping the electrodes separated, allowing the actuator to keep working. Punctures or even scissor cuts are healed, though the functionality of the actuator or sensor is reduced. Both these healing mechanisms are only tested in precise lab conditions, and it is unclear if they can work for all shapes and sizes of puncture or just the ones demonstrated. The process occurs without control and is triggered by damage to the elastomer.

Pneumatic actuators are another common soft robotic actuator vulnerable to punctures. Soft robotics pneumatic actuators which are puncture-resistant were developed with kevlar fibres built-in (Shepherd et al. 2013). When the actuators are punctured, the fibres help to seal the gap and prevent cracks growing larger. This is successfully applied to robotic grippers, however, only punctures and cuts below 1.6 mm were tested on the materials created.

Diels-Alder polymers are often used to create self-healing plastic components. Low temperatures below 100°C are required for the healing to be activated. Diels-Alder polymers were utilised to make a self-healing robotic gripper in a widely publicised study (Roels et al. 2019). Cables thread through the polymer to make the gripping mechanism. If the polymer is damaged or cut it can self-heal and retain its original properties after being heat treated; however, the actuating cable is not self-healing. Terryn et al. (2015) also utilised Diels-Alder polymers in an earlier application to make a self-healing mechanical fuse to prevent overloading and a simple cube pneumatic actuator, in later work, this is also used in a robotic

gripper (Terryn et al. (2017)). In these examples, healing and damage are controlled by the paper authors. To become a complete SE system, these processes would need automated monitoring and verification to control when heating for healing should start and end.

Many previous research projects have attempted to replicate skin-like materials which can sense touch, are flexible and can self-heal. Combining all these properties is difficult, though some authors have been successful (Tee et al. 2012). Recent work has even gone one step further, replicating a jellyfish's transparent and submersible skin (Cao et al. 2019; Majidi 2019).

Progress has been made toward self-healing robotic parts, though all of the concepts presented have only been validated in a laboratory environment. Previous reviews of self-healing electronics and robotics have also highlighted the slow healing process as an obstacle to further development (Bartlett, Dickey, and Majidi 2019), often healing takes place over days and require specific conditions.

4.4.2. Self-reconfiguring

Modular robots are smaller independent robots combined to complete a set function or task. Self-reconfiguring and self-adapting terms are often used interchangeably in modular robotics. Previous authors have investigated many different algorithms to help swarms of modular robots adapt by reconfiguring. Early work focused on self-assembling the groups of robots in 2D (x and y directions) then adding damage which triggers a pre-determined reconfiguration in response (Murata et al. 2001). This one-to-one solution approach is easier to implement but cannot cope with unexpected changes or unexpected damage.

The DASH (Distributed Assembly and Self-Healing) control method enabled groups of robots to re-size and reconfigure when robots are removed or added to a system (Rubenstein and Shen 2009). Modular robots are all given a map of the desired shape to help find their place. The approach was only tested in simulations, not with physical modular robots. More recent experiments with larger robot swarms looked at using evolutionary algorithms for the robots to enable them to adapt and re-configure to cope with challenges (Levi, Meister, and Schlachter 2014). Up to 100 modular robots of different types are used in the experiments to form an 'organism'. Different types of robots have different functions e.g. larger robots are used to assemble smaller ones. The swarm had a set reconfiguration programmed in, so it was not in response to damage or a loss in function.

Self-reconfiguration can be incorporated into individual robots (not modules); an example of this is the isoperimetric soft robot created by Stanford University (Usevitch et al. 2020). It uses inflatable tubes and rollers to change the length of its structural supports. This allows it to move but also reconfigure into new shapes to hold weight and move objects.

4.4.3. Self-adapting

Self-adapting robots aim to adapt to damage or a change in the environment. Previously, modular robots with sensors are combined with a control system to optimise their performance. Robots tested in one study included: cube modules which adapt to balance a supported weight more evenly using input from individual pressure sensors, a tetrahedral robot which moves towards a moving light source, and a robot gripping hand which can adjust to cope with different objects and orientations (Yu and Nagpal 2009). These self-adapting functions are normally in response to an input from one sensor and one type of response action, making the process straight forward.

Self-adaptation in robots can be tricky because it takes a long time for a robot to calculate all the possible ways it can adapt and identify the best one. Self-modelling is commonly used to help give the robot self-awareness so it can register when changes are made and adapt (Kwiatkowski and Lipson 2019). A starfish-like robot with four arms uses self-modelling and trial and error to determine the best method of movement. Damage is introduced and the robot uses actions it had already tested and new models to find a new way to move with the damage (Bongard, Zykov, and Lipson 2006). The starfish had to try many different models and movements which took hours to complete. Other researchers optimised a similar self-adaption process using a model, trial and error approach, but a wider range of scenarios are modelled, and models are more accurate (Cully et al. 2015b). A faster algorithm and better computing power also sped up computation time, enabling a six-legged walking robot to self-adapt to a loss or damaged limb within minutes. The robot can maintain its movement if it has four of its six legs, a further self-heal or self-repair design for damaged legs would help improve the robot's resilience. The self-adaption is triggered by a loss in the ability to move and stopped when the ability has been restored as close to the original as possible. Figure 10 shows pictures from Cully et al. (2015a) of the damage introduced and results of two self-adapting robots tested (Cully et al. 2015a).

Yang et al. (2010a) investigated neural oscillators (which create cyclic force and signals similar to ones used in our bodies) to make a robot resilient against interference. Central pattern generators are applied to a seven DOF robot arm and found to help improve its adaptation ability. However, applying neural oscillators to multiple limbs of a robot would increase the complexity of its control.

4.4.4. Self-assembly

Self-assembly using modular robots on a flat surface has been investigated previously, with simulations and small tests carried out using a few robots (Ishiguro and Maegawa 2006; Suzuki et al. 2009). The connection between robots was highlighted as a key area which can prevent easy assembly. The self-assembly of drones during flight (Li et al. 2019a), including attaching and detaching mechanisms (Saldana, Gupta, and Kumar 2019) has also been investigated; however, only small size swarms of drone have been tested. A recent project attempted to use modular robots with light sensors to replicate the growth of plants towards light found in nature, photomorphogenesis (Divband Soorati et al. 2019). The starting robot (or seeding point) is set at the beginning; robots then attach themselves to this seed or the robot closest toward the light, see Figure 11. Structures of robots appeared to resemble trees or roots. Further simulations also gave the robots the ability to self-repair when part of the tree structure is removed. These self-assembly processes allow modular robots to form groups, though currently, they do not restore a lost function. Self-assembly could form part of a self-adaption or self-reconfiguration response to damage.

Self-assembly in robotics can refer to the ability of a robot to assemble a system including itself (such as from modular parts) or the ability to assemble a copy of itself (such as self-replication). The ability to self-replicate is a key component of any living organism which many researchers have tried to develop using robotics. Initial work focused on using a swarm of modular robots given different 'colour' designation. A string of robots in a set colour sequence is used as the 'seed', the swarm then assembles a matching string of coloured robots (Jacobson, Griffith, and Goldwater 2005). When two identical strings exist beside each other, they separate, and the process repeats with two strings acting as new
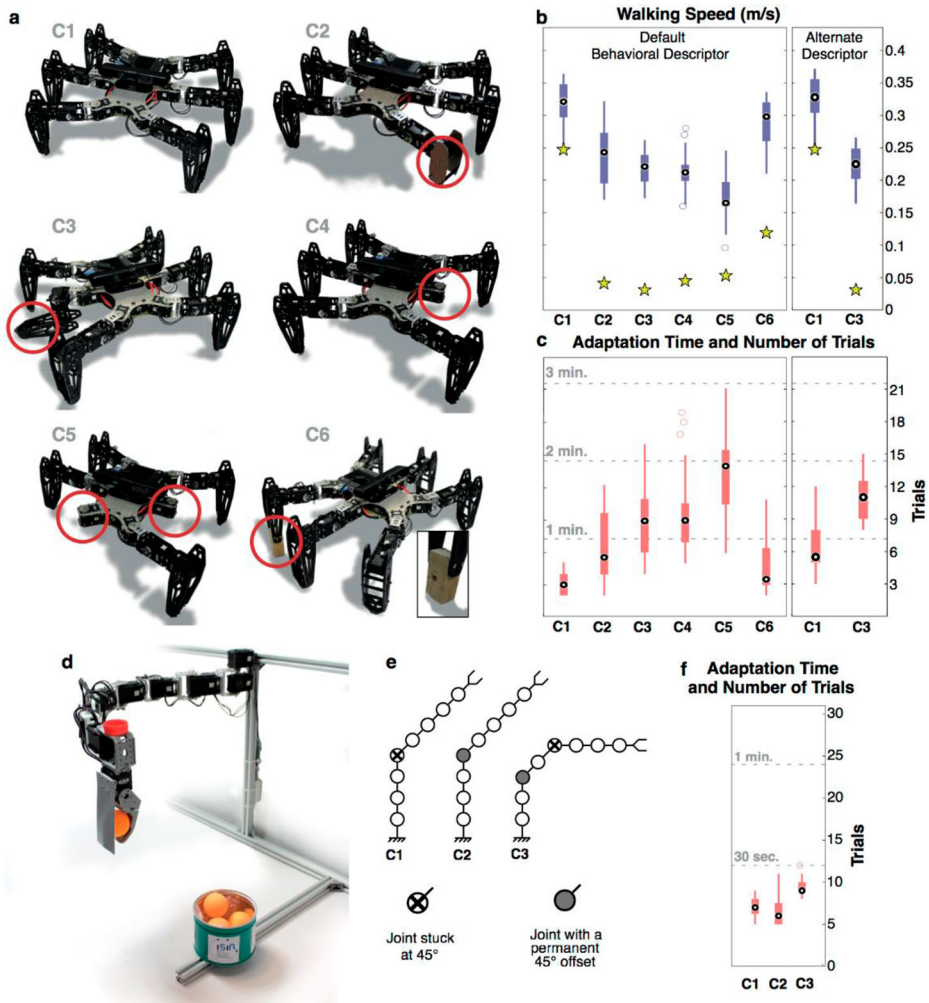
Figure 10. (a) Conditions tested on the physical hexapod robot. C1: The undamaged robot. C2: One leg is shortened by half. C3: One leg is unpowered. C4: One leg is missing. C5: Two legs are missing. C6: A temporary, makeshift repair to the tip of one leg. (b) and (f) Performance after adaptation. Box plots represent Intelligent Trial and Error. (d) Robotic arm experiment. The 8-joint, planar robot has to drop a ball into a bin. (e) Example conditions tested on the physical robotic arm. C1: One joint is stuck at 45 degrees. C2: One joint has a permanent 45-degree offset. C3: One broken and one offset joint. Image from (Cully et al. 2015b) ©Antoine Cully/Pierre and Marie Curie University. Licensed under CC By 3.0. (Creative Commons Attribution 4.0 International 2020).

seeds and growing to become four strings. The process requires spare modules to be available. Similar work presented later used a robot made of modules to assemble a twin robot from spare modules (Zykov et al. 2007). The robot can coordinate the 3D assembly quickly, but again the parts (spare modules) must be provided and placed within reach. Small simple Diamagnetic Micro Manipulation (DM3) microbots which levitate using permanent magnets are coordinated to assemble a new identical DM3 bot (Pelrine et al. 2016). However, DM3 bots are relatively simple robots and only require a few materials to make. All these
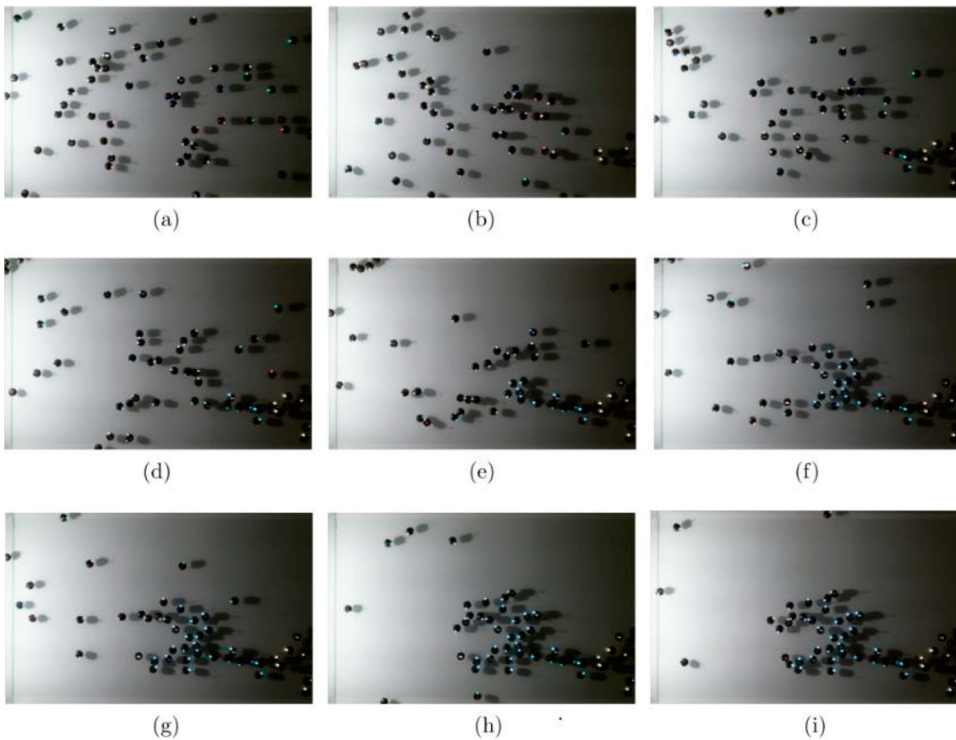
Figure 11. Photomorphogenesis self-assembly process over time in one experiment with Kilobot swarm. Reproduced from Divband Soorati et al. (2019), CC By 3.0. (Creative Commons Attribution 4.0 International 2020).

systems discussed are self-replicating, but they require a human to input and materials or parts to do this.

4.4.5. Summary

As shown in Table 4, most mechatronic technologies identified are applied at a system level, and none have developed beyond TRL3. As in the previous sections, many processes are not fully automated. Processes such as robotic self-assembly and self-replication mechanisms do not return a clear function; however, they could be adapted to do so.

5. Maintenance robots

Robots that can perform inspection, maintenance, repair or servicing tasks are of interest across many different sectors. It has been a research subject of interest for industry and academics for many years, especially when an area is expensive, dangerous or difficult to access. The earliest known example of a robot used for maintenance is in Japan in 1979 (Yoshikawa 2014); a robot was designed to perform tasks to reduce human workers' exposure to radiation in a nuclear plant. However, this early example still required human control. A fully autonomous robotic system which can inspect, register damage and perform a repair without human intervention would fall under the category of SE with control. The repair robot should either be integrated into or automatically move between systems

Table 5. Table of robotic maintenance projects, including the industry it is used in, robot type, and project name (if given) and the automated processes shown in the project.

Industry	Project	Type	Automated tasks performed			Extra info	Reference
			Movement	Inspection	Repair		
Shipping	[Drones]	UAV	Yes	Yes	No	Vulnerable to weather	Bonnin-Pascual et al. (2015)
	HISMAR; AURORA	AUV	Yes	Yes	No	Can also clean hull	Narewski (2009), Akinfiev, Armada, and Fernandez (2008)
Aircraft	FLARE ('snake' robot)	–	Yes	Yes	Yes	Only grinding repairused so far	Dong et al. (2017, 2019)
	CompInnova	WR	Yes	Planed	Planed	Repair and inspectionnot added yet	Papadimitriou, Andrikopoulos, and Nikolakopoulos (2019)
	[Robotic trolley]	WR	No	Yes	Yes	Only in design phase	Negri et al. (2019)
Power cables	LineScout	CR	Yes	Yes	Yes	Needs to be placed on	Pouliot, Richard, and Montambault (2015)
	[Drones]	UAV	Yes	Yes	No	Vulnerable to weather	Pagnano, Höpf, and Teti (2013)
Wind turbines	CONCEPTS; LEeCH; BladeBug	CR	Yes	No	No	Needs to be placed on	Sahbel, Abbas, and Sattar (2019), Bogue (2019)
	[Drones]	UAV	Yes	No	No	Vulnerable to weather	Shihavuddin et al. (2019)
	[Rope guided]	CR	Yes	Yes	No	Rope needs to be attached first	Hayashi et al. (2018), Rope-Robotics (2019)

UAR, Unmanned Aerial Vehicle; AUV, Autonomous Underwater Vehicles; WR, Walking Robot; CR, Climbing Robot.

it is repairing and not be reliant on humans to add it when needed. Currently, many robots used for inspection or repair still have to be transported to the site, activated and controlled by an operator.

In this section, robots designed for use in planes, ships, overhead cabling and wind turbine inspection has been discussed (a summary is shown in Table 5), though many other sectors also employ robotic maintenance.

5.1. Shipping

Ships have a vital function in global trade, allowing goods to be transported between continents cheaply. Classification societies require regular inspection of hulls (twice every 5 years). Currently, the ship is removed from the water for cleaning, visual inspection, repairs and application of a protective coating, taking it out of operation for weeks. There are some attempts to automate these processes by using drones with laser, visual or thermal inspection techniques (Bonnin-Pascual and Ortiz 2019). Completion of these processes underwater would prevent the ship from being removed and could be completed while the ship was unloading. Some robotic systems developed can use sonar or visual inspection to observe damage in ships hulls (Zereik et al. 2018), though currently, these are all human-controlled and not fully automated; maintenance and repair tasks done on ships in water is

completed with ROVs (Remotely Operated Vehicles). The Hull Identification System for Maritime Autonomous Robotics (HISMAR) project built a fully automated underwater robot, but it is only able to perform inspection and cleaning duties (Narewski 2009). Similar robots, such as AURORA, attach onto a ship's hull and perform similar cleaning functions (Akinfiev, Armada, and Fernandez 2008) or measure hull thickness. However, both are unable to perform a more complex task, such as maintenance and repairs, which require human assistance.

5.2. Aircraft

Safety of aircraft is of the utmost importance, regular inspection, servicing and maintenance is required on all aircraft to maintain high safety standards. Airlines are increasingly looking to automate these processes to reduce the time planes are inactive and costs. A snake-like robot developed at Nottingham University can inspect inaccessible areas of jet engines (Dong et al. 2017); tools added in later tests can be used for maintenance and repair (Dong et al. 2019). The CompInnova project uses vortex adhesion to create a robot which can move around all of a plane's outer shell (Papadimitriou, Andrikopoulos, and Nikolakopoulos 2019); an infrared thermography inspection technique will be combined with this robot to inspect composite materials for damage or degradation (Gray et al. 2018). The project aims to include an automated repair process, making a complete SE system. Lastly, a design is presented for a robot for inspecting the inside of a composite wing. The robot moves on a trolley system and is currently only semi-autonomous (Negri et al. 2019).

5.3. Power cables

Power cables enable electricity to reach homes all over the world. Unfortunately, there are 1000s of miles of cables which have to pass through difficult to access environments; this is a problem in Canada where wet and cold weather increases the chance of cable degradation. This led to the creation of LineScout an automated power line inspection and repair robot which has evolved from 10 years of research. The robot has to be attached to a cable but is then able to autonomously inspect and re-join lose cables (Pouliot, Richard, and Montambault 2015). Other approaches have looked at using UAVs unmanned aerial vehicles with thermal imaging or ultraviolet cameras to inspect power lines (Pagnano, Höpf, and Teti 2013).

5.4. Wind turbines

Maintenance and repair of wind turbines is a key problem which impacts the cost of energy production. Turbines are getting larger to facilitate greater efficiency and are moving to more remote locations, such as out to sea. The constant rain, wind and snow can slowly erode the wind turbine blades reducing the overall energy generated. Advances in drone and image processing research have led to the creation of many visual inspection drones which are utilised on wind turbines (Shihavuddin et al. 2019; Bonnin-Pascual et al. 2015). Other robots have focused on climbing the tower or the blades directly for inspection (Sahbel, Abbas, and Sattar 2019; Bogue 2019), or using a rope attached to the tower to guide the robot up and down (Hayashi et al. 2018). Currently, all these robots have focused on

inspection and identification of damage to the outer side of the wind turbine. Recently funded projects aim to go further and include repair mechanisms; these include WindT-TRo (Wind Turbine Repair Robot) funding from EU Horizon 2020 fund (Rope-Robotics 2019) and the MIMRee (Multi-Platform Inspection, Maintenance and Repair in Extreme Environments) project (Madigan 2019; Bernardini et al. 2020), a collaborative project between UK universities and industries.

The summary shown in Table 5 highlights that the key area missing in robotic maintenance and servicing systems is the automated repair. Currently, most industries have focused on moving to and inspecting the damage. Most of the systems also focus on the visible outer areas, not internal problems which are designed to be repaired by a technician.

6. Discussion and research gaps

In this review, SE systems have been evaluated against the definition and characteristics presented at the beginning. However, a more detailed design methodology is required to help validate future SE systems. The definition and characteristics presented here may need to be extended to provide a more comprehensive list for validation and testing of new systems. As a TES, more research is needed into total lifecycle assessment, how does adding different types of SE system affect the lifecycle of the product or system?

As highlighted in Section 2.2, two distinct streams are developing in SE, with and without control. Different SE technologies will drive developments in each of these areas. Initial systems without control will likely use self-healing and self-sealing methods at a material level which are well developed and have already made it into commercial products. Reducing the need for control in a SE system could have many benefits, such as reducing the complexity and cost of running a SE system. However, it limits the SE responses to one mechanism responding to one type of damage. SE systems with control will initially develop from work on predictive maintenance, continuous maintenance, and machine learning. These are all mature research fields, but the repair and maintenance procedures which follow them still need to be automated and integrated into systems, which will be the key challenge; from reviewing current SE work it was clear automation is a missing area in many SE processes.

Another categorisation of SE system which has yet to be discussed in this paper is integrated vs externally added. Many systems already in continuous use or high-value long-life systems could benefit from SE methods. The addition of an integrated SE system may not always be feasible, but an external system could be added, such as a repair robot, a new reconfigurable part or a system level controller. External systems added to existing systems are easier to implement and test and requires no redesign of the original system making it more appealing in the short term to many industries. To classify as a SE system, an externally added system should still monitor and respond to degradation; crucially it should also be operable before a loss of function and not be added just when degradation or a failure has occurred. A SE repair robot could be separate from the main system but activated by a monitoring signal and autonomously transported to take action to repair the main system. An integrated response offers a greater range of SE responses which could address more complex situations. For example, many maintenance robots can only access the outer system components as the insides are designed to be traversed by humans. Integrated SE systems need to be built-in at the design phase of projects and will take longer to develop and reach the market as a result. Designers and engineers should consider both externally

added and integrated systems as potential solutions. Further research is needed to identify the benefits and limitation of these types of SE systems.

Different types of redundancy will have different impacts on the SE system; for example, component redundancy requires spare components and is likely to be more costly than functional redundancy, which aims to utilise parts or components which are already present. When designing SE systems, cost and complexity will be key consideration; the cost of including redundancy will have to balance against the reduction in MRO costs and the life extension provided. This could be done by using existing methodologies and tools developed to optimise the cost or reliability of a system using redundancy (Mohamed, Leemis, and Ravindran 1992; Tillman, Hwang, and Kuo 1977; Coit 2003), or using new methodologies specifically for SE system design optimisation.

Other considerations for researchers, engineers and designers specific to the monitoring, trigger, response and validation stages of SE systems are discussed in the following sections. The five questions proposed originally at the beginning of the paper are evaluated under each relevant section and research gaps identified.

6.1. Self-engineering – without control

6.1.1. Monitoring and trigger

SE systems identified without control do not monitor actively for damage; instead, they are designed so that a loss of function directly triggers a response (such as self-healing microcapsule materials). There is often no set level of function lost which triggers the response; damage often releases a built-in reaction. The system design has a big impact on what triggers the SE response and its repeatability. For example, the depth microcapsule are placed within a material will have an impact on what cracks will trigger healing and how far the healing agent can spread within the material. In studies relating to SE without control, the design parameters, and impact on the response and when SE is triggered, is not studied in detail. Understanding system design parameters and the impact they have on performance will be key to ensuring reliability and use of these systems in critical functions.

6.1.2. Response

Most SE systems without control are only tested for a single response. A good example of this is self-sealing materials, often only one sealing response is shown in research, but a material could be damaged multiple time. Neglecting further tests with multiple response cycles makes it harder for engineers to utilise these new materials in designs. Without control, it is also harder to account for external factors like resource availability, time, damage severity and environmental conditions. One example where damage severity is accounted for is self-healing microcapsule materials (White et al. 2001); a deeper crack in a material with microcapsules will break more capsules and release more healing agent to fill a bigger crack. However, without control monitoring and verification, the healing agent could overfill or not fill a crack, and the response will differ for each crack position.

6.1.3. Verification

SE systems without control do not verify that damage has been repaired and do not monitor the system function to verify how much functionality has been returned . However, they can be designed so that the response continues until a set point is reached. For example,

vascular self-sealing tires will continue to bleed sealing agent until it solidifies and blocks the puncture. As noted in Section 6.1.1., the design has an impact on the performance of these processes and further understanding of design parameters is needed. Effectiveness measures of SE are discussed further in Section 6.3.

6.2. Self-engineering – with control

6.2.1. Monitoring

Industry 4.0 is used to describe the current shift to more automated manufacturing, including utilising new data processing, connected sensors and improved machine-to-machine communication (Lasi et al. 2014). With the development of Industry 4.0 well underway, maintenance and repair processes are changing, with more connectivity and cyber-physical systems being utilised. The decreasing cost of sensors and monitoring systems has enabled manufactures and operators to have more detailed data about products and systems. Research conducted over the last decade has focused on using this data to predict failures, diagnose problems and optimise MRO procedures. This can form the foundation for future SE monitoring systems (or self-monitoring, self-diagnosing and self-modelling systems).

SE system using control tend to monitor one function of the system. Often this is done by monitoring one parameter such as a force (Korkmaz, Bel Hadj Ali, and Smith 2010; Peairs, Park, and Inman 2004) or electrical signals (Braaten et al. 2013; Nishiwaki et al. 2006). Measuring multiple parameters such as voltage, current and resistance (Huston and Hurley 2010) can enable more verification of when a loss of function is occurring. Existing systems often only measure parameters which indicate a potential failure or degradation of the part to be repaired; the condition of other parts, subsystems or the overall system could also be considered in case a repair causes accelerated degradation elsewhere in the system.

One area where monitoring systems need to be developed further is compound degradation; this is the interactions of more than one failure mechanism to accelerate the degradation process. One example is corrosion fatigue where the presence of corrosive fluids (such as salt water) reduces the strength of materials undergoing loading (Adedipe, Brennan, and Kolios 2016; Wang et al. 2016; Chapman et al. 2017). Physical phenomena (such as impacts, fatigue, stress or high temperatures), chemical phenomena (such as corrosion) and biological phenomena (such as bacteria, termites or fungi) can all interact to accelerate degradation (D'Amico et al. 2019). Many current monitoring systems still only focus on modelling and assessing single degradation mechanisms; future monitoring systems should aim to incorporate knowledge on compound degradation.

6.2.2. Trigger

As with monitoring, the SE trigger can draw on many previous areas of research such as continuous maintenance and predictive maintenance. In existing systems, a response is triggered when parameters monitored reach a set limit, or tests can be performed comparing differences in system performance from previously recorded sates to identify the set limit. Often the signal triggering a response is a binary (on or off) signal, but there are examples where the data from monitoring is used directly to inform the type of response, such as self-adapting robots in Section 4.4.3.

As a system ages performance is degraded, leading to more frequent SE systems triggers. Further research could look at adjusting a SE system trigger in line with a system's age. False triggers could also be a problem as a system ages and more sensors degrade. Very few systems identified actively verify a SE trigger, or use alternative or spare sensor readings to check for sensor faults.

6.2.3. Response

The SE response is a key component of a SE system. As identified throughout this review, there are many materials or methods which can be classified as a SE response. Repair and maintenance procedures are becoming more automated but not at the same rate as monitoring procedures. Many maintenance tasks are still complicated and rely on technical experience. Developing automated maintenance and repair procedures is a key area needed to increase SE system development. A complete redesign of our MRO and servicing methods may be needed to better suit robotic or autonomous workers rather than traditional human workers. The advances in artificial intelligence and machine learning have helped to create systems capable of learning advanced repair skills. However, a large quantity of data is often required to train the system, which is often not available.

No SE systems identified (with or without control) account for all the factors mentioned in the introduction (resource availability, time, damage severity and environmental conditions). System level controlled SE examples record and account for the state of the whole system; examples include self-reconfiguring manufacturing systems (Li, Nassehi, and Epureanu 2019b) or RAM device (Nair and Bonifus 2018). The trial and error method used for self-adapting robots (Bongard, Zykov, and Lipson 2006) could also take account of changing environment and quantity of damage, though they do not monitor these factors. Interestingly, there are no examples of SE systems identified that adjust their response to fit a set time available or account for the system's age. However, this could be because researchers do not discuss these factors and the impact on SE response. Future research could look at accounting for multiple factors, creating a framework to prioritise important factors and investigate how to control the length of or when a response starts and ends.

Most SE responses identified in this research are in the early stages of development (TRL 1-3) and only tested for one repair cycle. SE found already in use commercially such as self-reconfiguring RAM devices have been designed to work for multiple repairs cycles without a loss of performance. SE research needs to focus on long-term testing with multiple responses if more SE systems are to be utilised in industry.

6.2.4. Verification

Most SE system with control identified do not perform checks or verification after a SE process has occurred. When checks are performed, the initial sensors and parameters used to trigger the SE are used to verify its effectiveness. If a faulty monitoring system causes a trigger, then the same system is unlikely to successfully verify a SE response, which could lead to needless responses being triggered. Further research could investigate reliability of different SE verification sub-system designs. As with the response the verification should also account for other factors in the system such as resources and system age because even if

a further response could return more of the functionality, it might not be in the best interest of the whole system. Different measures of effectiveness for SE systems are discussed in more detail in the next sub section.

6.3. Effectiveness of self-engineering systems

It is important to consider the effectiveness of SE systems and how effectiveness can be evaluated. An effective SE response will return all or most functionality lost, while a less effective response will restore less functionality. This section explores previous research on evaluating the effectiveness of SE, though a tested framework for evaluating effectiveness is beyond this paper's scope.

Brown et al. (2004) recommended four dimensions for evaluating autonomic computer systems at IBM: (1) the automation level of the response, (2) the quality of autonomic response, (3) the impact of the response on the system's users, and (4) the cost of any extra resources needed. Brown and Redlin (2005) evaluated two software application systems with two of these dimensions. Firstly, quality was measured using the number of correctly completed requests when a set disturbance was added. Secondly, the level of automation was measured for different tasks using a survey and scoring system. The second metric is less useful in SE systems as they must be fully autonomic; however, SE systems will eventually require some human input. The time between human input needed or Mean Time between failures (MTBF) could be used as an alternative measure.

Another well-advanced area is the evaluation of self-healing materials. The efficiency of self-healing materials (η_H) is defined as the percentage of an original property (P_o), or original functionality (F_o) returned after healing (F_H or P_H) (Diesendruck et al. 2015), see Equation 1.

$$\eta_H = \frac{F_H}{F_o} * 100 = \frac{P_H}{P_o} * 100 \tag{1}$$

Effectiveness of a material healing (e_H) is defined as Equation 2 (Akrivos et al. 2019); unlike efficiency, it also takes account of material properties after damage before healing (P_D). Equation 2 is also used to evaluate the effectiveness of self-sealing concrete in Ferrara et al. (2018), with properties of sorptivity, visual crack size and max loading used to evaluate material performance.

$$e_H = \frac{P_H - P_D}{P_o - P_D} \tag{2}$$

Cseke et al. (2020) introduced life cycle healing efficiency (L_H) to account for multiple healing cycles. The healing function $f(H)$ is the changing healing efficacy with each healing cycle until the final healing cycle (H_C). L_H can be used to indicate the self-healing material maintaining higher functionality for longer, as shown in Figure 12. However, it would require detailed knowledge of the material performance and does not account for damage severity.

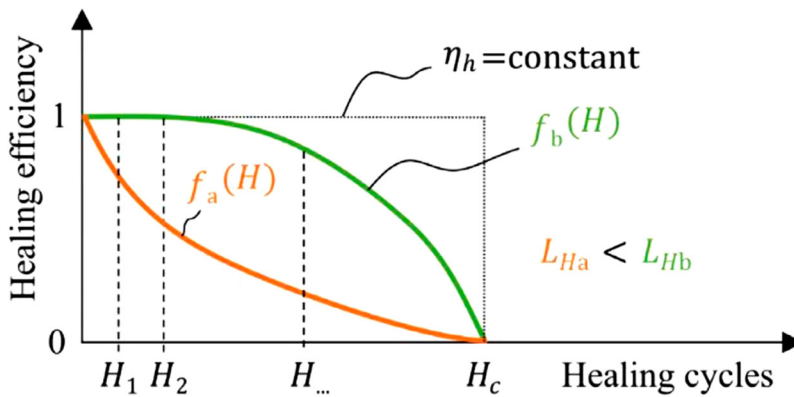$$L_H = \frac{\int_0^{H_C} f(H) dH}{H_C} \tag{3}$$

Figure 12. Examples of change in healing function and healing efficiency over the use phase in self-healing product life, reproduced with permission from Cseke et al. (2020).

Many previous authors note that metrics of effectiveness and efficiency are limited to only one property. This is hard to avoid, and it is likely that SE effectiveness will not be accounted for by only one property and one metric but instead a combination of them, similar to Brown et al. (2004). The functionality being returned in each SE system differs, meaning metrics might have to be tailored to specific systems and their key functionality.

There has been significant work in information and defence systems to create frameworks for evaluating the effectiveness of systems; common attributes these systems use include availability, reliability, maintainability, dependability, capability or performance (Tillman, Hwang, and Kuo 1980). Reliability, availability and maintainability (often abbreviated as RAM) are often used to evaluate system effectiveness or identify where improvements can be made. The best metric of reliability, availability and maintainability to use can change depending on the system being evaluated but some common ones used are outlined below (Tsarouhas 2012; Department of Defense 2005).

- Availability – The measure of at items operable and useable state or the total uptime over total time. Availability is often defined using mean time to failure (MTTF) and mean time to repair (MTTR) in MTTF/(MTTF + MTTR).
- Reliability – The probability a system will perform its set function adequately under set conditions. Mean time between failure (MTBF), mean time between maintenance (MTBM), mean time between repair (MTBR) and failure rate are metrics used.
- Maintainability – The probability that a system can be repaired or restored in a defined environment and set time. Increased maintainability implies shorter repair times. MTTR, max time to repair and maintenance ratio can be used.

Table 6 summarises the different metrics discussed and the key strengths and weaknesses of each metric for use in SE. These are all possible metrics of effectiveness that could be used but there is no one method that is perfect for SE. Further investigation would be needed to find the most suitable metric or combination of metrics. Effectiveness properties could be linked to the three SE complexity factors identified in previous research (Brooks and Roy 2020): repeatability, redundancy and self-control.

Table 6. Table of pros and cons of relevant effectiveness metrics for the SE systems.

Measure	Reference	Strength	Weakness
Autonomic Computing evaluation	Brown et al. (2004), Brown and Redlin (2005)	Uses multiple dimensions to account for lots of factors including response quality, automation and resource cost.	Accounts for automation level and user response, which are not needed. Quality of the response is also not clearly defined.
Healing efficiency (η_H)	Diesendruck et al. (2015)	Simple, easy to use matric for effectiveness of response, requires only two measurements	Only accounts for one function or property/function, damage severity not accounted for, requires a measurable property, and only applied to one healing cycle
Healing effectiveness (e_H)	Akrivos et al. (2019), Ferrara et al. (2018)	Relatively simple, accounts for damage and quality of response	Only accounts for one function or property, requires a measurable property/function and only applied to one healing cycle
Life cycle healing efficiency (L_H)	Cseke et al. (2020)	Accounts for the whole life and multiple healing cycles	Requires knowledge of system performance after each response, does not account for damage severity before each healing.
Reliability, availability and maintainability (RAM)	Tsarouhas (2012), Department of Defense (2005)	Accounts for many different aspect of maintenance and failure rates of the whole system	Knowledge of whole system life performance needed, changing conditions, damage and individual SE responses are not accounted for.

7. Summary

This review provides a detailed overview of the concept of a SE system which can be applied at multiple levels in a system being designed (material, component, sub-system and system level). Two categories of SE systems are highlighted, those with and without control. The taxonomy presented outlines definitions for different SE methods such as self-healing, self-repair, self-reconfiguration, self-sealing, self-adapting, self-optimising and self-organising. The use of most (but not all) of these terms in patents and academic papers has increased over the last 50 years.

The development of new self-healing materials has been the primary area of research in SE mechanical systems. The main focus has also been on polymer materials, though some success has been shown with metals, concrete and fabrics. However, despite numerous success in lab research, few technologies have developed further. Self-healing coating and paints have made it to market but not bulk materials which require more stringent testing. There is a need for the development of mechanical self-repair or self-reconfiguration systems to emulate those seen in other engineering sectors. Current work in these areas is still in its early stages (TRL 1).

The need for reliable integrated electronics in many products has led to significant developments in SE electronics. Built-in self-reconfiguration with redundancy (both component and functional) has been implemented in a range of electrical sub-systems. More recent work has also investigated integrating self-healing abilities into particular components and materials, though this work has yet to be developed into a commercial system. The use of control systems and software to make self-adapting, self-managing or self-optimising systems is well advanced because these systems are relatively inexpensive compared to physical systems.

Research within mechatronics and robotics has focused on system level self-reconfiguration with swarms of modular robots working together, or self-adaptation of

individual robots. At a component and material level, self-healing soft robotic actuators and self-adapting grippers have been created. Maintenance robotics is an expanding area of research, but few systems are close to meeting all the characteristics needed for a SE system. Most focus has been on the initial challenges of identification and moving to areas of damage, some have developed repair capabilities, but more automated and integrated MRO and verification capabilities are needed.

SE systems offer a challenging area of research with many questions which need addressing. More mappings of possible technology and processes for specific sectors is needed to help inspire future development. A structured design methodology for combining existing mechanisms and technology into new SE systems is also needed. Often the tools needed for each stage exist but have yet to be combined is a complete SE system or automated fully. New mechanisms and repair techniques need to be developed, which can be automated and controlled easily.

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Appendix

Self-engineering Method	Trigger	Processing/evaluation	Implementation	Verification

Response

Built-in Redundancy — Damage causes a change in the system: microcapsules may be broken and liquid released, a change in surface Ph level or removal of material. — The damage normally automatically triggers the response. No processing or evaluation stage as the response is autonomic. — Failure of system automatically leads to implementation of redundant system.

Self-sharpening — Material is eroded from the softer surface and not the hard one causing it to sharpen.

Self-sealing — The joint material swells or moves into the punctured area, blocking the leak.

Self-healing — Healing response initiated, liquid material is released or bonds reform due to stimuli either internally or on external surface.

Verification — Verification, is automatic, is the trigger still registered. If the trigger repeatedly occurs so will this cycle. If trigger happens once the cycle will end when the pre-planned response does.

Automatic No Control

It should be noted that location differs for each action, e.g. material occurs normally in the material itself while other occur in assemblies or components.