A Complexity Framework for Self-engineering Systems

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Abstract. To ensure extended useful life of systems during pandemics such as Covid-19, systems independent of traditional maintenance, repair and servicing will be required. Ambitious new designs are needed, such as self-engineering (SE) systems to automatically respond to return lost functionality and improve product resilience without human intervention. Development in SE has focused on self-healing materials, self-reconfiguring electronics and self-adapting robotics. There has been little work to evaluate SE systems holistically and develop new design tools for creating new SE systems. This paper presents a framework for evaluating the complexity of SE systems and the validation of the framework with expert interviews. There was agreement between experts and the authors for 21/24 of factors for the eight SE examples (four biological and four engineering) evaluated using the framework. Disagreements in results were caused by a lack of knowledge on the system being evaluated or misunderstanding about the system operation.

Keywords: Self-engineering; manufacturing; repair; complexity; bioinspired; design

1. Introduction

New systems are being designed with increasing useful life, however, nothing engineered is immortal, and it will eventually break. Maintenance Repair and Overhaul (MRO) services can delay and extend product life and fix problems that occur; however, MRO is reliant on safe systems access, which is difficult during the Covid-19 pandemic with limitation on access to all but essential system to avoid further contaminations. To deal with this new ambitious self-engineering (SE) technologies are needed. SE is: *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 availability and improve system resilience*;[1]. Systems should improve resilience and robustness, automatically taking action and preserve functionality without human intervention. Many SE systems can also be considered autonomous systems and will have autonomous behaviour; however, not all autonomous systems will aim to return functionality lost as in SE systems. SE could be combined with, or part of, an autonomous systems in the future to help keep them going (such as self-healing material parts in an autonomous robot). Three possible areas of manufacturing during Covid-19 and immediately after where SE could be utilised include:

1. Within new products – New healthcare robotics used clean to prevent human-to-human contact [2] will need to be highly self-sufficient; regular MRO may not be possible without contamination risks
2. To develop new responsive manufacturing systems – SE techniques such as self-adaption, self-reconfiguring and self-optimising can be used within automated manufacturing procedures to maintain high quality or volume production.
3. To support urban factory development – Decentralised smaller factors [3] will not have specialist technicians on-site to repair machines and pandemics make visits from them difficult; therefore new SE systems could help maintain production despite failure or damage.

Over the last 40 years, there has been an increase in new technologies with SE abilities, including self-healing materials[4], self-adapting robotics[5] and self-repair electronic[6] systems; however, many systems have failed to develop beyond TRL 1-3. Further work is needed to evaluate SE methods in biology and engineering, to generate new design tools for SE system development.

The addition of SE capability can increases the complexity of a system; however, there has been no focused study of SE systems and complexity. Axiomatic Design theory presented by Suh [7] was used by Brooks and Roy[8] to evaluate five biological SE systems. It was noted that SE returned degraded functionality repeatedly similar to what Suh referred to as time-dependent periodic complexity. Three key factors contributing to SE system complexity were identified: redundancy, repeatability and control [8]. These factors make up a framework which is validated in this paper using interviews with experts in research related to SE and design complexity.

2. A proposed Complexity Framework

The framework for evaluating complexity of SE systems contains three factors, Redundancy, Repeatability and Self-control which are outlined in detail in this section; an overview of different levels is displayed in Fig. 1.

Repeatability

This refers not to how closely the process can be repeated (as defined in scientific experiments) but a system's capability to respond to a loss of function multiple times. The system ideally should return to its original state and functionality, though it may only be partially restored. The number of times a SE system can respond may vary depending on the severity or type of functionality lost.

Highest level – A SE system can respond indefinitely to functionality lost at the same location and/or of the same type.

Medium level - A SE system can respond multiple times to functionality lost at the same location and/or of the same type.

Lowest level – A SE system can respond once or only a few times, at the same location and/or of the same type. Further responses are either not possible or will not significantly return functionality.

Redundancy

The definition of redundancy used here is: *the provision of additional capacity in a system, so that system function is maintained despite partial system failure* [9]. Different classifications of redundancy can be used for different types of systems. Redundancy could be component based (multiple spare parts) or functional (parts that can perform different functions). Redundant components can also be either passive (inactive) or active (in use) in a system.

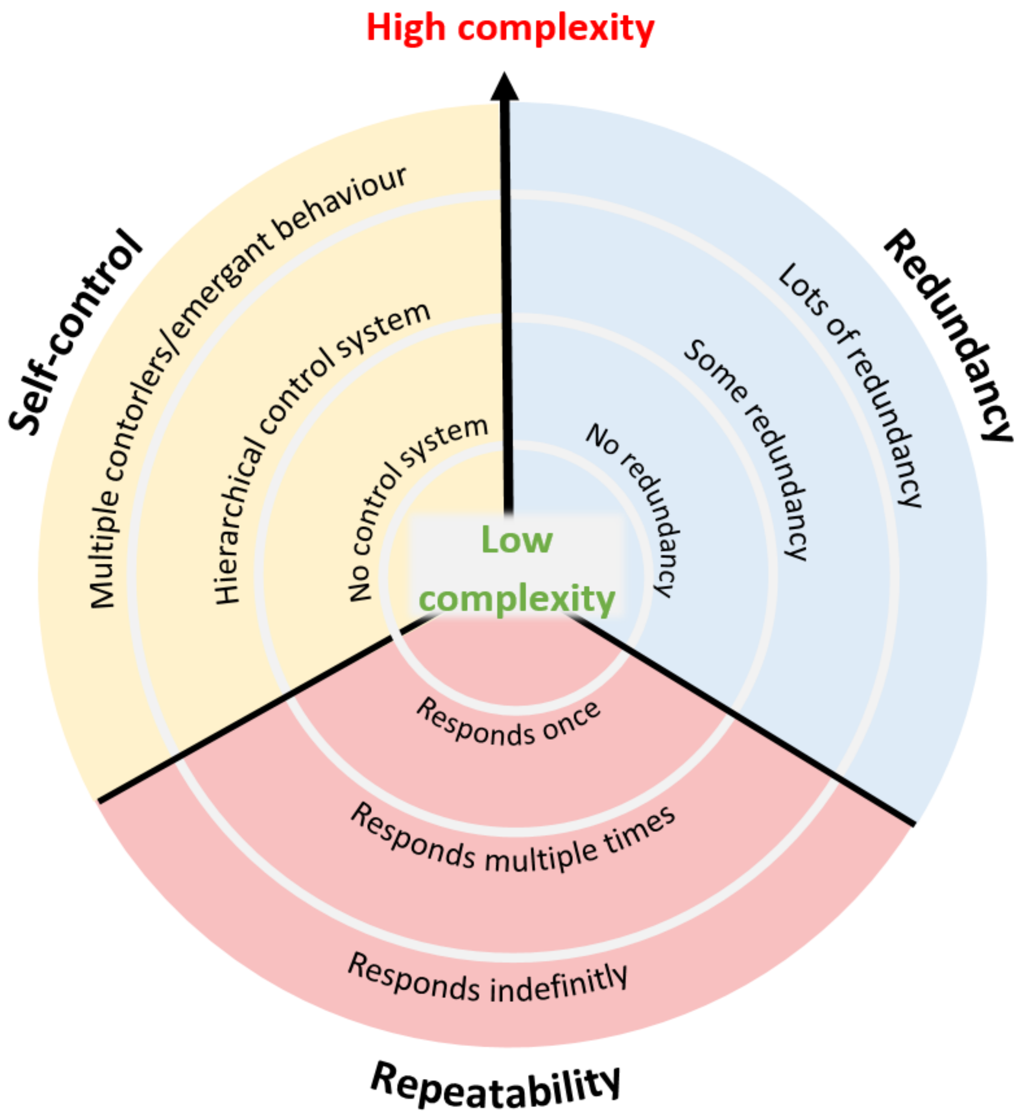

Figure 1 – Overview of the framework for evaluating complexity. Three key factors: Redundancy, Repeatability and Self-control and the different levels of complexity for each factor.

Highest level – A SE system has many redundant material, components, sub-systems or functionality that is utilised for the SE response.

Medium level - A SE system has some redundant material, components, sub-systems or functionality that is utilised for the SE response.

Lowest level – A SE system has no redundant material, components, sub-systems or functionality that is utilised for the SE response.

Self-control

This refers to the complexity of the self-control of the SE system. Some SE systems are a reactionary response with no control; more complex ones can evaluate, plan and execute using inbuilt control.

Highest level – There are multiple methods of control and/or multiple interacting control systems. Individual controllers might be simple but the interacting control systems create a highly complex system with lots of connections and potentially unpredictable or emergent behaviour.
Medium level - There is an overriding control system used to manage the SE system. It coordinates and makes decisions on the SE process, creating a hierarchical structure rather than many individual actors.
Lowest level – The lowest level of self-control in when there is no active control present, a SE system is designed to act as a response to a stimulus or change caused by loss of function (such as autonomous self-healing materials).

3. Methods

To validate the framework, interviews with eight experts (academics and researchers) were conducted; experts ranked the complexity of four engineering and four biological SE systems using the framework, and their reasoning was discussed. Eight experts were interviewed, with an average experience of 28 years, 12 years being the lowest and 40 the highest. Many of the experts were selected because they have researched system design, complexity or had expertise relating to at least one of the examples used in the interview. Experts were asked to rank complexity for each framework factor (redundancy, repeatability and self-control) either high, medium or low. For each example experts were presented with a description of the system, an image and a link of the information source before the interview. Other key questions put to experts at the end of the interview were: 1) Can you rank the importance of each factor with regards to complexity? 2) Do you think the framework is effective for evaluating complexity of SE systems? 3) Are there other factors or considerations that you think should be included in the framework?
The four engineering examples evaluated were: 1) Self-healing vascular material [4], 2) Self-adapting robot limb [5], 3) Self-reconfiguring RAM (built-in self-repair) [6], 4) Self-assembly robots [10]. The four biological examples evaluated were: 5) Self-sharpening teeth [11], 6) Wet skin wrinkles [12], 7) Self-sealing Latex plants [13], and 8) Self-reconfiguration of jellyfish [14]. The engineering examples cover a range of system levels and engineering sectors, while the biological systems all utilise distinctly different mechanisms and respond to different types of degradation. All the systems have been presented in journal papers and cover a range of complexity levels. The key aim was to avoid evaluating similar systems (such as all self-healing materials).

4. Results and discussion

For all but three of the individual factors in Example 3 and 8, the experts' and authors' complexity ratings agreed after the discussion and evaluation of the interviews; this is shown in Table 1 results. With Example 3, experts scored repeatability lower than the authors, because the self-reconfiguration reduced the RAM performance, however the repair could occur 1000s of times before this happens and there are often spare cells included for this purpose. The final score was chosen as high, the same as the authors and three other experts who all had expertise and experience related to these systems. With Example 8, many experts misunderstood the mechanism used by the jellyfish to heal and assumed it must be controlled when actually the response occurs purely due to mechanical forces (tension and compression). The author's and key experts' choice of low self-control and medium repeatability was considered more accurate after evaluation.

Detailed discussion with experts about each factor led to the evolution to the final definition outlined in Section 2. In discussion on importance of each factor, two experts noted the importance varied depending on the system evaluated. Self-control was most often noted as the most important, followed by repeatability and redundancy; however, all rankings varied significantly depending on the expert; no conclusive ranking could be made. Experts noted that redundancy and repeatability were often linked; increasing redundant parts available directly increased repeatability in Example 3, 4 and 8. Further studies of the interaction between factors is needed.

Table 1 – The most common (Mode) expert ratings and authors' final rating after interview discussions with experts, are shown. Where two ratings (e.g. high/medium) are shown there is a tie between two ratings.

Example	Factor	Experts view (Mode)	Authors Final Decision
1	Repeatability	Medium	Medium
	Redundancy	High	High
	Self- control	Low	Low
2	Repeatability	High/Medium	High/Medium
	Redundancy	Medium	Medium
	Self- control	Medium	Medium
3	Repeatability	Medium	High
	Redundancy	High	High
	Self- control	Medium	Medium
4	Repeatability	High	High
	Redundancy	High	High
	Self- control	High	High
5	Repeatability	High	High
	Redundancy	High	High
	Self- control	Low	Low
6	Repeatability	High	High
	Redundancy	Low	Low
	Self- control	High	High
7	Repeatability	High	High
	Redundancy	High	High
	Self- control	Low	Low
8	Repeatability	High/Medium	Medium
	Redundancy	Medium	Medium
	Self- control	Low/Medium	Low

Suggested other factors to consider were: 1) Time, either taken or available, for a response to occur; this has been noted previously in self-healing materials research [15]. 2) Constraints on a system such as weight, resources or cost; Summers and Shah [16] similarly noted size as a key complexity metric in mechanical systems. 3) Uncertainty in a system, its SE response, or environment was also noted as contributing to complexity of a system. Further work would be needed to evaluate the sources of uncertainty and how to account for in the framework. Factors such as repeatability could be expanded to include the range of functional losses a system can respond to as well as the quantity of times it can respond.

The good level of agreement between the authors and experts verifies that the framework produces consistent repeatable ratings. The majority of experts (6 out of 8) thought the framework was effective for evaluating complexity of SE systems. Further research would be needed to verify if the framework does effectively rank complexity of systems. The study is limited to simpler SE systems because these are the current ones that exist, as more complex SE systems are created and integrated into other systems further validation of the framework may be required.

Complexity in design can be a problem to be solved or a source of inspiration. This framework will not necessarily lead to less complex SE designs but highlights where complexity in SE system is concentrated. Reducing factors such as repeatability is not desirable as a SE system with high repeatability is needed to extend system life. The framework could also be applied to biological or engineering systems to provide insights to help with future smart manufacturing systems.

5. Conclusion

SE offers a method of reducing reliance of human maintenance and repair to extend product life, which is particularly advantageous in a pandemic. A framework is presented for evaluating complexity of SE systems under three key factors, Redundancy, Repeatability and Self-control. This paper demonstrates that the three factors and different levels can be used to explain complexity of SE systems. The framework was validated with expert interview, the most common expert and authors' rating consistently agreed for 21/24 factors. No factor was highlighted as most important; although, there was a marginal preference for self-control as the most important.

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