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Investigation of future applications of self-engineering using drones

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A B S T R A C T

Self-engineering (SE) systems aim to autonomously respond to a loss of function and take action to return functionality. Recently there have been a number of demonstrations of SE using multi-rotor drones to inspect and repair systems (such as repairing potholes), though many of these systems do not meet all the requirements of a SE system. This research identifies and explores new ideas for SE where drones could be utilised. Five ideas were successfully identified from consultations with experts and authors. The five ideas created are: 1) self-repair in enclosed spaces of ships, 2) self-cleaning roads, 3) self-repairing air conditioning systems, 4) autonomous underwater pipe repair, and 5) self-repair of damaged building cladding. Possible inspection and repair actions that a drone could perform are identified for each proposed system. From a short industry survey and further interviews, idea 1) (self-repair in enclosed spaces) was identified as the most promising for future development. The potential cost of building the system is discussed at the end of the paper; however, detailed cost estimation is too uncertain because of the difficulty in estimating the cost of developing autonomous capabilities.

1. Introduction

Maintenance, repair, and overhaul (MRO) are important activities that impact the cost and reliability of any system. Many maintenance processes are still performed by human workers. Brooks and Roy proposed the concept of self-engineering (SE) systems in 2020. A 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 availability and improve system resilience"* [1]. The four key characteristics of a SE system are: 1) it must restore or partially restore lost function or capacity; 2) it must be built into the system; 3) it should aim to avoid/reduce maintenance, prolong life and/or increase the system resilience; 4) there must be no human/user intervention, any process, response, and behaviour should be automatic. Key examples of SE systems include self-healing composite materials, self-repairing RAMs for computers, and self-adapting robots [2].

Unmanned aerial vehicles (UAV), also known as drones, have become increasingly common, with the technology available for commercial use. This research considers only multi-rotor drone UAV systems and their possible future applications. Many previous studies have investigated using drones to autonomously inspect key systems such as wind turbines [3], ships hulls [4] and power cables [5]. However, to be considered a SE system, it must autonomously inspect and take action such as repair. A number of key examples currently developed are highlighted in this section.

A prototype drone system at Imperial College London was designed to identify and repair leaking pipes carrying oil, gas, and hazardous chemicals [6]. The drone locates a leak before using expanding polyurethane foam to seal them; the system is only a prototype and still has to be fully tested. The Mine Kafon Drone (MKD) is designed to autonomously detect, map and detonate landmines with different modular attachments [7]. The first attachment is used to map the area, the second is a metal detector, and lastly, a robotic arm is used to detonate the mines. The limitation is that the drone requires an operator to change attachment, but this could be overcome with advancements. There has been extensive research by companies and academia using drones to autonomously inspect wind turbines [3]. The MIMRee project funded by Innovate UK aims to use autonomous drones to deposit a repair robot (Bladebug) onto an offshore wind turbine to perform repairs [8]. However, the system still requires human supervision. Researchers from the University of Leeds developed an autonomous drone that can detect, repair, and maintain potholes or road

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cracks [9]. This is a good example of drones used to make a self-repairing road system. Currently, it is being trialled in the UK; many of the tests are pilot operated or supervised and not fully autonomous.

This research aims to investigate new possible uses for drones in SE systems. Section 2 outlines the process used to create new ideas and the five SE systems designed. Section 3 shows a short industry survey conducted to gather feedback on the systems. Further interviews conducted with industry experts are outlined in Section 4. Finally, in Section 5, the most promising idea is chosen and outlined, with estimates for the build cost presented.

2. Phase 1 - identifying new industry applications

The process of developing the new ideas was cyclic; an overview can be seen in Fig. 1. The first phase was to review current academic research sand industry reports on drone capabilities and maintenance needs in industry; this helped identify unexplored application. From this information a brainstorming session among the authors was used to determine initial ideas for using drones in SE systems. A further review of the literature confirmed if the idea was unique and helped develop it to ensure it fits with the key characteristics of a SE system. Finally, the ideas were presented to two industry drone experts from a global engineering consultancy with experience designing and testing new drone systems. The industry experts were asked to indicate if the use was unique and realistically achievable with drones. If their approval was met, the idea was kept. The process was then repeated until five new ideas were generated.

This process does not guarantee that all ideas are unique because the authors and literature reviews may have missed existing systems. However, it was designed to create an efficient process for identifying and reviewing new SE ideas.

2.1. Idea 1 – Self-repair in enclosed spaces of ships

Ships have a complex inner structure, including small and confined areas known as enclosed spaces. These enclosed spaces have limited openings, insufficient air circulation, and are not designed for continuous worker occupancy. Toxic atmospheric gases, lack of oxygen, risks of falling or slipping, and flammable gases all make it dangerous for workers [10]. However, on-board crew members must get in to perform routine inspection, repair, cleaning, and repainting of tanks or holds. Unfortunately, several injuries and fatalities in confined spaces have been documented [11]. It is difficult to eliminate all the hazards of enclosed spaces and better to minimise the human exposure. A drone-based SE system is proposed to perform automatic inspection and repair of enclosed spaces.

1) The drone would autonomously fly around the enclosed space and inspect for toxic gas leaks, pipe damage or leaks and loss of corrosion coatings, using a visual camera, thermal camera, or toxic gas detector.
2) The drone returns to its base plate to charge and store data retrieved, if no problems are detected it inspects a new section.
3) If problems are noted, it returns with the appropriate tools to perform the repair. For example, a coating reapplication would require an airbrush attachment for spray-on coatings.
4) Once the repair is complete, the drone would return to the base to recharge and collect the inspection tools.

A basic diagram of the system is shown in Fig. 2 a). The drone would reduce the need for human works to spend time in these parts of the ship. The drone would form part of a complete self-repair system built into the ship. One key benefit is that the drone does not have to avoid humans, animals, or commercial aircraft as in other applications.

2.2. Idea 2 – Self-cleaning roads

A recent report revealed that in 2019–2020 councils all around the UK spent £694 million on picking up litter on roads, almost as much as they spent on collecting bins [12]. Some councils like Haringay spent £9.4 million, almost four times more than they spent on collecting household bins (i.e., £2.1 million). A smarter technology solution could be used, especially for high speed or dangerous roads which workers cannot safely access. A self-cleaning road system is proposed utilise drones to remove rubbish or debris; a basic diagram is shown in Fig. 2 b).

1) The drone will inspect roads within a set range using a visual camera. The drone can use AI and existing database images of rubbish to identify common rubbish items on roads, trees, and pathways.
2) The drone will analyse the type of litter. If it is predicted to be up to 0.5 kg, the drone will register it under 'Self Pick'. A robotic hand or gripper will be needed to remove rubbish along with an extension cable or arm. For bulky or heavy items, it will send the local council a message with the location for a human worker to collect.
3) The drone will return to the base station next to the bin to deposit rubbish or recharge

2.3. Idea 3 – Self-repairing air conditioning

As a result of the changing climate, there is predicted to be another 10.9 billion air conditioning (AC) units functioning by the end of 2050 [13]. Dirty and damaged outside condenser coils are common problems of AC repair [14]. Accessing the condenser unit for repair can become costly because of the difficulty accessing them on tall buildings A drone could be used to inspect the condition of outer AC condenser units and perform automated repairs. A drone could be included within each building or a set of buildings to inspect and maintain condenser units.

1) The drone inspects condenser coils with a camera (or thermal camera) and decide if cleaning or a repair is required and how intensive the work needed is.
2) The drone returns to the base station to get a compressed air canister or a brush attachment.
3) It returns, landing on top of the unit to perform cleaning or repairs required.
4) After cleaning, another inspection is completed to check for signs of damage to the coils and fins that could lead to a leak. Significant fouling or damage can be communicated to a human worker for further servicing.

A basic diagram of the system is shown in Fig. 2 c). Currently, air conditioning unit placement is often chosen to be easily accessible, using a drone for servicing could enable a wider range of placements in hard-to-reach areas.

2.4. Idea 4 – Autonomous underwater pipe repair

In June 2021, the ocean around the Gulf of Mexico was on fire. The tragedy occurred because of gas leakage from an underwater gas pipeline [15]. Other similar incidents include oil flow from Ixtoc 1 into the ocean in 1979 [16], the 2015 Russian oil pipeline blast [17], and the 2015 explosion in the Gulf of Mexico [18]. An

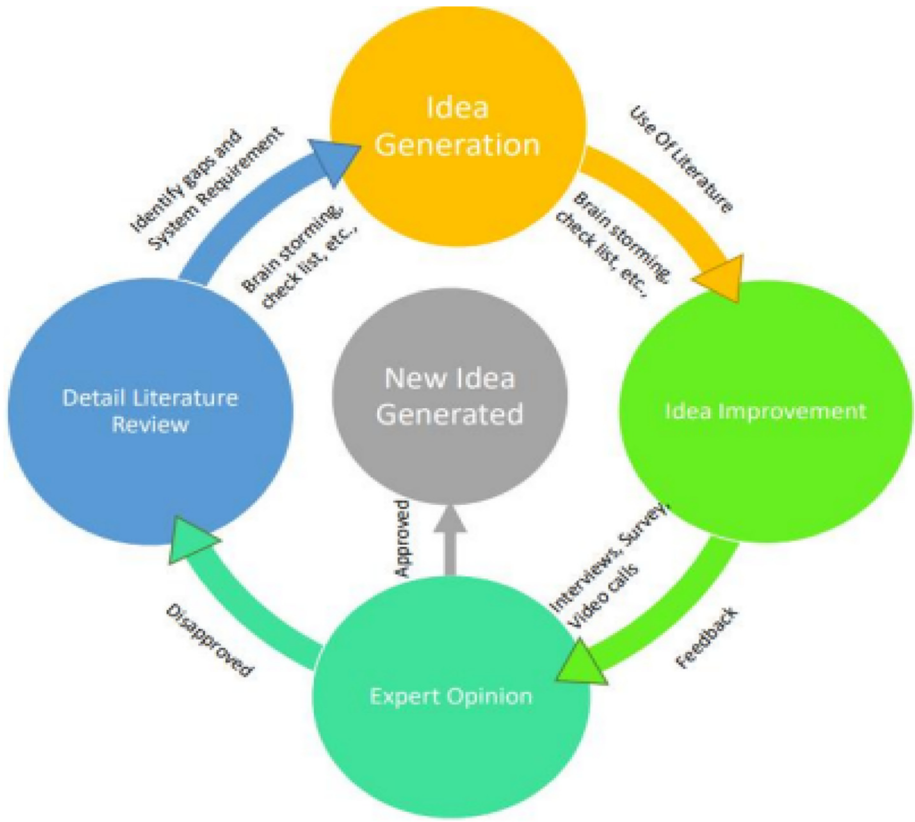

Fig. 1. Initial method used to identify new SE system using drones. The process was repeated in a cycle until five new ideas were created for use in the study.

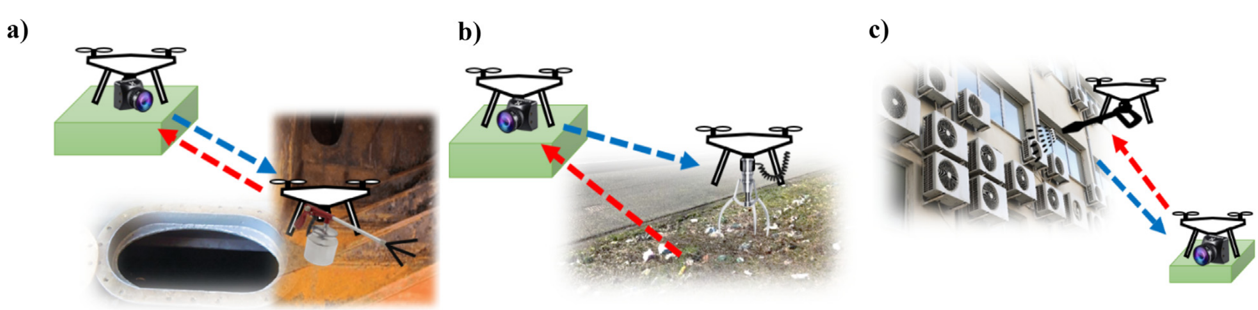

Fig. 2. Diagram of three of the proposed ideas, a) self-repair of enclosed space, b) self-cleaning road with drones and c) self-repairing air conditioning.

integrated drone-based system for underwater pipeline inspection and repair could be used to avoid direct human interaction and improve safety of inspections processes needed for these oil and gas plants. The proposed system work as follows:

1) Drones will carry a smaller autonomous underwater ROV (remotely operated vehicles) to the location of the pipe being inspected and deposit it in the sea.
2) The ROV will go and inspect the pipeline for leakages and send location coordinates to the drone.
3) The drones will pick up the repairing robot and drop it at the location where the repair is required.
4) The underwater repairing robot will fix the leakages before being retrieved by the drone.

The use of a drone to transport could allow the system to cover a wide area quickly. The drone, and inspection and repair robots could be included onboard an autonomous ship as used by the MIMRee project currently [19].

2.5. Idea 5 – Self-repair of damaged building cladding

External house cladding's primary function is to protect the underlying structural walls from the elements such as moisture, temperature changes, and oxidation. Cladding damage adversely impacts the appearance of property and risks safety [20]. For instance, corrosion can spread to the structure of the building, compromising its strength. Typically, cladding is repainted or repaired to overcome these issues; however, it is often costly to install scaffolding required and risky for the workers who must operate at dangerous heights. A building could have a drone-based repair system with the following steps to make the job safer:

1) The drone will perform a visual inspection of the building with a camera. It will identify and classify the damage. The drone will be looking for corrosion and damaged paint or coatings.
2) After identification, it returns to the resting position to fully charged and collect repair tools.

3) Once charged, it will use an airbrush to spray paint new coatings as required. A portable sanding mechanism could also be added to remove loose paint and prepaid surfaces for coatings.
4) The drone can return to its base to charge, reload with paint or change paint type.

3. Phase 2 - initial validation of application

The next phase of the research was to validate the ideas with industry experts (different from those used for initial idea generation). Workers in each sector of the five ideas were identified on LinkedIn and sent a survey. Responses were kept anonymous, but experts were only sent the survey if they had at least five years' experience in a related industry. The number of responses is shown in Table 1. Participants were presented a with description of the drone system proposed for their industry and asked to indicate what impact they thought the new system would have on safety, cost and quality of data obtained to inform future work. Three options were presented for each question; the results can be seen in Fig. 3. It should be noted that the answers given are subjective and based on a description of the system, not the final system. These questions were intended to get insight from people who might use these systems.

For all five ideas, nearly all participants thought that the safety of the current process could be improved by using the drone system. For ideas one, two and three, most participants thought better quality data could also be obtained, while for ideas four and five, participants were split. The cost was where the largest difference in answers was. This question is also the most uncertain because it would depend heavily on the final cost, which is not indicated in the description. For ideas four and five, most participants felt there would be no reduction in cost. For the other three ideas (one, two and three), at least half of the participants felt the cost could be improved by implementing the drone system.

Idea one, two and three were investigated further with interviews with industry experts to develop the ideas further. These three were chosen because they had more positive responses in this initial survey phase.

Table 1
List of industry participants in each sector who responded to the survey and the idea number they were presented with.

Industry of participant	Idea number	Idea presented	Number of responses
Shipping industry	1	Self-repair in enclosed spaces	5
Council waste management	2	Self-cleaning roads	3
HVAC	3	Self-repair air conditioning	4
Underwater ROV inspection	4	Autonomous pipe repair	4
Construction Industry	5	Self-repair building cladding	3

4. Phase 3 - further expert validation

For the remaining three proposed SE systems using drones, self-repair in enclosed spaces, self-cleaning roads and self-repair air conditioning, an industry expert was identified and interviewed in a semi-structured interview. Details of each expert are shown in Table 2. Participants were sent the system idea description before the interview. Questions related to existing practices in the industry, existing uses of drones, suitability of proposed design, and any possible problems with the idea. A summary of key comments made by each expert is shown below.

Idea 1 – Self-repair in enclosed spaces of ships: The expert indicated that there is currently some use of drones in hull and tank inspection, but they had not heard of it being used in enclosed spaces. The expert was excited by the idea and noted, "*It will save many lives that are being lost annually due to accidents related to enclosed spaces*". However, the cost of a fully autonomous system was noted as possibly too expensive for the industry. Finally, the expert highlighted interesting possible onshore applications for the system include in "*power plants, tunnels, wells*".

Idea 2 – Self-cleaning roads: The expert mentioned the existing use of drones for "*garbage inspection, mapping landfills, [and] monitoring methane emissions*" but not currently collecting garbage. The current collection system relies on reports by phone or email, which are then coordinated by the council before sending out manual labourers and trucks to collect the rubbish. Generally, the expert was positive about the idea and suggested expanding it to include "*shorelines, natural areas, and other places where it's hard to reach*". This is a good suggestion as many of these areas may be less populated and safer to operate in.

Idea 3 – Self-repairing air conditioning: The expert indicated that there are some commercial operations using drones for inspection of buildings and ductwork, but these are in the early stages. The expert noted tasks such as "*straightening fins and intensive cleaning*" might be difficult for a drone to complete effectively. The expert indicated it had the greatest potential for older buildings where air conditioning has been added and is not built-in; newer buildings have a central unit for the whole building, which is easier to reach, reducing the need for a drone. A potential addition could be detecting gas leaks from AC units because these leaks can be hard to spot early and contribute to global warming. The expert did also note that using cameras near the building may infringe on privacy.

All experts indicated they thought ideas were unique and could be used in their industry in the future. However, more critical feedback would have been beneficial to help with the design of the system. There was little insight gained into the rules, regulations, and dangers of using these drone systems in individual industries. Regulations and privacy are two key barriers preventing drone use identified in previous studies [21] which needs further investigation.

5. Final design cost discussion

From further consultation with drone experts used at the start of the study and the feedback from the interviews conducted, the most promising idea chosen was self-repair of enclosed spaces system (idea 1). All experts were positive about the ideas making it difficult to choose; however, drones in enclosed spaces do not have to consider complex interactions with humans or animals, or invading someone's privacy.

The most uncertain part of any of the ideas is the autonomous capability. Currently, there are projects using drones for inspection and monitoring autonomously but not for autonomous repair. The second area of uncertainty is the development of new actuators required. These two factors made it difficult to realistically predict the cost of the drone system. However, a build cost was estimated based on commercially available drone systems, materials and parts required. Initially, a list was compiled of all the required components by the authors. This was then sent to two drone experts used in the earlier phase of the project (Section 2). They recommended additional parts which may have been missing. From the final list, a maximum, minimum and most likely cost was found for each part. The maximum cost was formed of the highest cost suitable parts found and the minimum was the lowest cost suitable

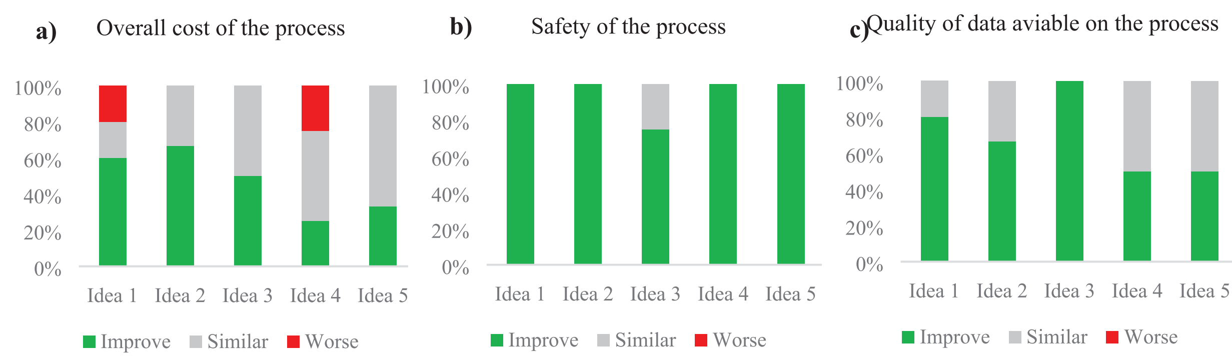

Fig. 3. Results from initial survey with industry of the five ideas created. Graph (a) indicates the view of experts on impact of the new proposed idea on overall process cost, (b) shows the views of impact on safety, while (c) shows the views on impact on the quality of data collected about the processes.

Table 2
Experience and role of the three experts interviewed further about Idea 1, 2 and 3.

Industry	Interviewed on	Profession/Rank	Experience
Marine shipping	Idea 1	2nd Engineer	6 Years
Council waste disposal	Idea 2	Waste Management	11.5 years
HVAC Research	Idea 3	Research in Refrigeration systems	5 Years

Table 3
Maximum, minimum and most likely build cost for Self-repair drone system.

	Minimum	Most Likely	Maximum
Total cost (£)	2909	4,555	7,512

parts. For the most likely cost, a price representative of the most common price for the component was used. The final costs can be seen in Table 3.

This build cost does not consider the extra research and development cost. The development of autonomous capabilities of the systems will likely require a much larger investment. An indication of this can be found by looking at previously funded research projects within the UK. For example, the Engineering Physical Science Research Council (EPSRC) funded the development of the University of Leeds road repair drone in 2016; this cost approximately £1.406 million[1] but does not include further work required to get regulatory approval and get the system ready for commercial use. Creating autonomous capabilities for the proposed self-repair of enclosed spaces system is likely to be similar, though costs could come down with more research and development in drones and regulations.

6. Conclusion

This research provides five potential ideas for new SE systems using drones. The five ideas created can be seen in Section 2. The ideas were evaluated using surveys and interviews with experts in each industry. SE system using drones to repair exist for wind turbines and roads, but there are still many potential areas that could be explored. Future work should focus on the automation of drone systems as many current systems are still designed to be supervised or operator controlled. Research could also focus on automation of the repair responses, such as creating a drone actuator and controllers to spray an even surface coating. One of the major limitations was the limited number of experts used in interviews and surveys. Meaning only a limited viewpoint was collected. More experts might have given a more diverse and representative view or information. A prototype demonstration of the final idea (self-repair of enclosed spaces) would demonstrate the ideas' feasibility and help identify the cost of implementing and running the system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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