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A COMPARISON OF SYSTEM RELIABILITY STRATEGIES IN LIVING ORGANISMS AND ENGINEERING

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Abstract

This paper describes system reliability strategies that are found in living organisms and compares these strategies with those used in engineering systems. There are several strategies used in nature that are not used much in engineering systems. One advantage of adapting reliability strategies from nature is that the natural world contains a wide range of species of living organisms that have been proven to function very reliably in harsh environments. A second advantage of adapting reliability strategies from nature is that engineering systems are becoming more and more complex and hence more 'biological' in concept. Since nature has a proven track record of system reliability, there is obvious benefit in adapting the features of natural systems.

Keywords: Systems engineering, complexity, reliability

1 Introduction

System reliability strategies can be defined as design features that enhance the ability of a system to maintain required functions over a specified period of time and for a specified set of general load cases and operating conditions. Reliability is a major issue for industry because accidents can lead to a poor reputation, expensive litigation and expensive remedial actions. Achieving high levels of reliability is very challenging because of the complexity of modern engineering systems.

Living organisms represent an important source of reliability strategies for engineers and scientists. The natural world contains millions of species of living organisms and these contain a great range of components and processes that have been proven to function very reliably in harsh environments. For example, a human heart can function as a self-maintaining sub-system for 75 years or more. During this time it beats the order of 2.5 billion times and pumps the order of 300 million litres of blood [1]. It is very difficult to design a man-made replacement heart with anywhere near the same capability as a living heart.

An important advantage of exploring biological systems is that many engineering systems are taking on more of the characteristics of biological systems. Characteristics of biological systems include a high number of parts, high integration, large hierarchy (nano-scale to macro-scale) and extreme complexity. Many modern engineering systems such as aircraft, process plants and motorcars are taking on these kinds of characteristics. As engineering systems become more biological in concept there is an obvious potential benefit in copying biological reliability strategies.

2 Simplicity

2.1 Minimal number of macro parts

In most cases, biological components are made up of a minimal number of macro parts. For example, a man-made positive displacement pump generally contains several different elements that are assembled together with various fasteners. However, the mammalian heart is largely a one-piece structure where the muscles and nerves are fully integrated. The use of a minimal number of macro parts is an important aid to reliability because there are a low number of interfaces where wear, misalignment and separation can take place [2]. A picture of the mammalian heart is shown in Figure 1.

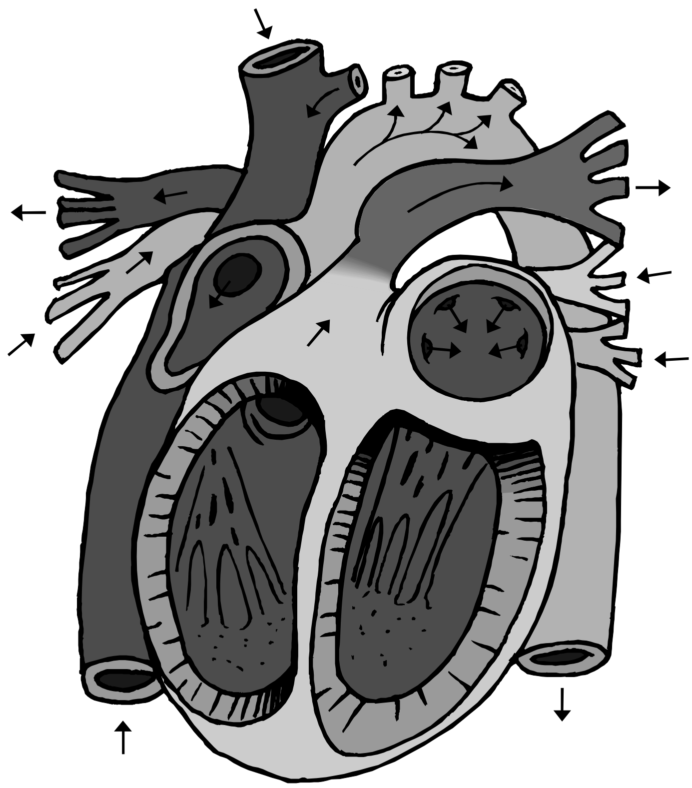


Fig. 1 Mammalian heart

Considering the functions that a mammalian body can perform, the number of macro parts and interfaces is remarkably minimal. Biological systems show that there is potential for reducing the number of macro parts in current engineering systems.

2.2 Minimal number of sliding parts

As well having a minimal number of macro parts, biological systems also have a minimal number of sliding parts. The advantage of minimising the number sliding parts is that sliding parts are vulnerable to excessive wear and movement and this can lead to poor reliability. The human heart valve is an example of a component that has a design that avoids sliding parts. The human heart valve has flaps that act as a non-return valve. These flaps hinge through flexing without any sliding taking place. In contrast, engineering non-return valves usually contain a bearing device to allow relative movement at a hinge. Relative sliding does occur in the joints of mammals. However, considering the functions that a mammalian body can perform, the number of sliding joints is minimal.

2.3 Continuous joints

Continuous joints are yet another way that living organisms achieve simplicity at a macro level. Examples of continuous joints include the connection between tendons and bones and ligaments and bones. At the junction between these different types of tissue, the living cells merge together to form a continuous joint. In addition, fibres such as collagen fibres, extend continuously from one part to the next.

For example, collagen fibres in the bone extend right into the tendon, thus producing a very tough connection. A continuous joint is generally more robust than a mechanical joint because there are no mechanical fasteners that can become loose. Also, continuous joints are generally lighter and this leads to lower loads due to self-weight being imposed on the system.

An engineering analogy to the continuous joints found in creatures is that of the welding of two dissimilar materials to form a permanent continuous joint. These permanent joints can enhance reliability because they are simple and cannot be shaken apart. It is generally accepted that simplifying interfaces in engineering systems helps achieve better reliability.

Continuous joints are also feasible with advanced bonding techniques and this is now beginning to be used in the automotive industry in the joining of aluminium structures. The use of continuous joints presents a dilemma for designers because there is a conflict between the advantage of a simple light joint and the disadvantage of a design that is difficult to disassemble and repair. However, nature shows that there are important reliability benefits in using continuous joints.

3 Redundancy

Examples of redundancy in non-essential organs include the eyes and ears. Examples of redundancy in essential organs include the kidneys and lungs in the human body. The human body has two kidneys and two lungs but is quite capable of surviving, albeit with reduced capacity, with one kidney and one lung.

Living organisms generally have live redundancy, i.e. the redundant elements are all fully functioning in parallel and the load is shared between them while they are all working. The fact that redundancy is seen widely in nature gives support to the principle that this is an important reliability strategy in engineering systems.

Large-scale redundancy is defined here as m out of n redundancy where n is the total number of elements and m is the number of elements that must work in order for the system to survive. The advantage of large-scale redundancy is that very high levels of reliability can be achieved even though individual elements may have a modest level of reliability. An example of large scale redundancy in the human includes skin sensors (pressure, heat, cold etc) and brain cells.

Another example of large-scale redundancy in nature is found in the flight feathers of birds. Birds have between 30-88 flight feathers in their wings [3] but only a certain proportion of these are required to be in place and functioning for the bird to fly. The reliability of a system where m out of n parts must be working is given by:

$$R_{system} = R^n + q_{n-1} R^{n-1} F + q_{n-2} R^{n-2} F^2 + \ldots + q_m R^m F^{n-m}$$

where $q_p = n!/[(n-p)!p!]$

$F = Probability\ of\ failure$

The advantage of maximising *n* where *m/n* is a constant, for elements that have an individual reliability of 0.9, is shown in Table 1. The Table shows that having 1 in 2 redundancy (i.e. parallel redundancy) improves the reliability from 0.9 to 0.99, which is a large improvement but does not produce a very high level of reliability. However, by making *n* very large, the reliability becomes very high indeed. Since flying birds have over 30 flight feathers on their wings, they achieve high levels of reliability even though the reliability of an individual feather may not be that large.

Table 1 Advantage of large-scale redundancy ($R_i = 0.9$)

m out of *n*	Reliability of parallel elements
1 in 2	0.99
2 in 4	0.9962
3 in 6	0.9983
15 in 30	0.9999

One example of *m* out of *n* redundancy is sometimes found in the lighting systems of large work areas that are served by a large number of individual lights. In such cases the lighting system is often tolerant of several individual light failures and, therefore, the overall reliability is high.

Another reliable feature of a bird feather is that it has a robust design. A flight feather is shown in Figure 2. The feather has individual hooks which will break apart when subject to high loading. However, the hooks can be re-zipped by the bird so that the feather can be repaired. This feature makes the feather tolerant of high loads.

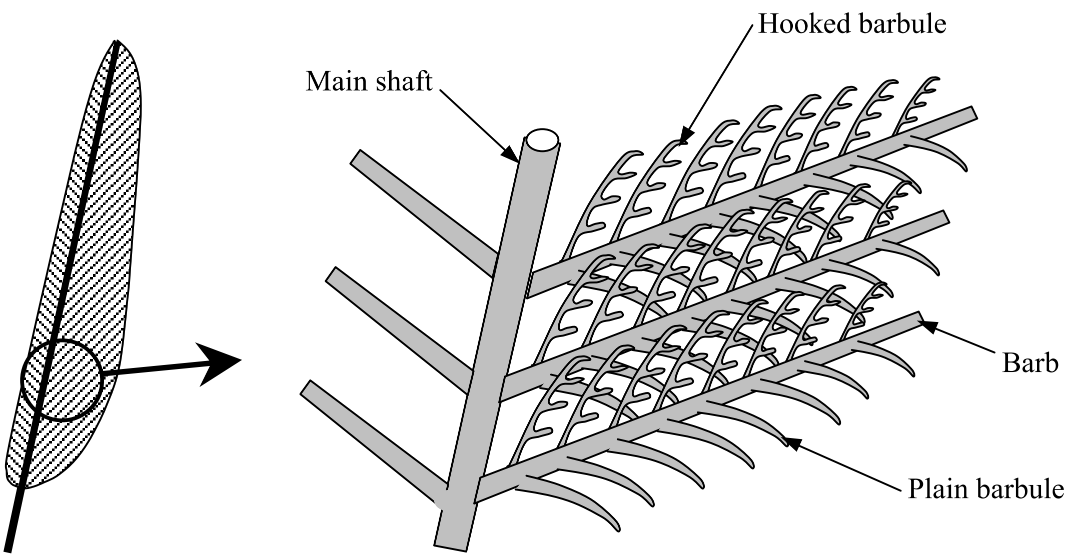


Fig. 2 Flight feather

4 Control

4.1 Automatic control

Living creatures generally have an autonomic nervous system that controls involuntary actions in the body including beating of the heart, movements in the gut and secretion of sweat. A great advantage of having an autonomic nervous system is that voluntary part of the brain can be free to think about high-level actions such as movement and planning. Also, automatic control allows a speed and consistency that is difficult to match with voluntary control. The speed and consistency of the mammalian autonomic nervous system undoubtedly is a key reason why mammals function very reliably. Automatic control has had a dramatic influence on the efficiency of engineering systems over the last few decades, enabling large increases in efficiency, productivity and reliability.

4.2 Adaptive control

The autonomic control system within living creatures has a remarkable ability to perform adaptive control. One example of adaptive control is the control of the mammalian heart rate. The heart is able to beat at widely varying rates depending on the particular demand. The advantage of adaptive control in this case is that the power generation of the system is always set at an optimum level. Adaptive control has recently been applied to the control of aircraft by developing algorithms that take into account the changes in the aircraft due to fuel loss and other factors [4].

5 Maintenance

5.1 Planned maintenance

An example of planned maintenance in nature is found in the flight feathers of birds. The activities of birds in flight and nesting mean that feathers are prone to damage, so the replacement of feathers is vital to the birds' survival. It is remarkable that birds replace their feathers whilst maintaining normal flying activity. Flight feathers are usually replaced in late summer. This is an ideal time because the bird has finished the important job of raising new born but there is still a good supply of food around. Feathers generally are replaced one by one in a strict sequence so that at any one time there are not more than two feathers completely missing. Planned replacement is common in engineering systems.

5.2 Planned inspection

Many creatures carry out self-inspection to maintain a high standard of fitness. Birds pass their beaks through their feathers to repair unzipped barbs and to lubricate the feathers. Humans inspect for all kinds of problems from teeth ailments to cancerous growths. The great advantage of inspection is that dormant problems can be identified and dealt with before they cause significant problems. Planned inspection is common in engineering systems.

5.3 Self-healing

Living tissue has the remarkable ability to perform self-repair. In the case of a cut to human flesh, a self-repair process is carried out including blood clotting, scab formation and skin growth. The clotting process is remarkable because it only occurs at wound sites and would be dangerous anywhere else. The principle of self-healing has recently been applied to composite materials with the use of a large number of distributed and embedded glue capsules [5, 6]. In this system, if there is a crack in the material, a local capsule or capsules will burst and release a healing agent. The liquid molecules come into contact with a catalyst that is also embedded within the polymer matrix, causing the healing agent to polymerize.

6 Flexible structures

Engineering structures are generally designed for stiffness. In contrast natural structures are designed for strength and flexibility. For example, the ligaments and muscles around joints are very tough and can withstand significant stretching and distortion. The flexibility of natural structures often plays a key role in achieving a robust design.

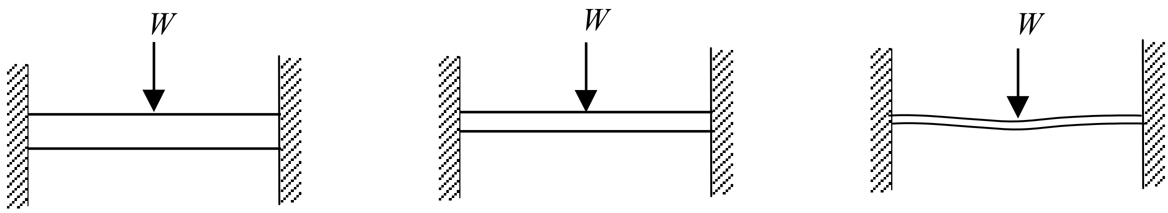
In general, the objective in structural design is one of three things:

(i) design for stiffness;

(ii) design for strength;

(iii) design for flexibility.

Figure 3 below shows a beam that is designed for each of these three design goals. In general, a stiffness design goal leads to a design that deflects the least distance for a given load, whilst the flexible beam deflects the most.



(a) Stiffness design (b) Strength design (c) Flexible design

Fig. 3 Different structural design strategies

In terms of resistance to a given load it can be argued that the stiff beam in Fig. 3(a) is the most robust of the three designs because it deflects the least. However, a flexible beam (Fig. 3(c)) actually has several advantages:

(i) It deflects so much that it may become supported by a secondary structure
(ii) It is tolerant of significant enforced displacements
(iii) It is tolerant of significant thermal loads
(iv) It is tolerant of significant misalignments in assembly.

Therefore, depending on the nature of loading, flexibility can be a source of robustness rather than weakness. In the case of enforced displacements and thermal loads, the stiff beam is actually the most vulnerable to breakage because the resulting internal loads are very high.

7 Large-scale sensing

A living organism like the human being contains millions of microscopic sensors scattered throughout the living tissue. Human skin contains millions of fully integrated sensors including cold, heat and pain sensors. The fine level of granularity means that problems can be detected when they are very small and localised and hence dealt with before they get too large. Large-scale pressure sensing by massed arrays of micro-mechanisms is being investigated for aircraft wings, where detailed information about the pressure distribution can provide important information for the aircraft.

8 Learning and instinct

One of the key activities of living organisms is that of learning. Activities like walking involve fine control of actuators and large amounts of sensory inputs such as vision and touch. Animals are able to quickly recognise the meaning of signals and the best way to control movements. The concept of machine learning is the subject of current research. Neural networks have recently been used to learn touch patterns in a tactile sensing system [7].

Living organisms often perform complex actions based on instinctive knowledge, i.e. knowledge that is somehow embedded in the DNA which is passed on to offspring. Bird nest-making, bird song and bird migration are examples of actions that require instinctive knowledge. Many birds make nests without actually ever seeing how it is done and many birds fly on very complicated migratory routes without ever having done it before. An instinct like migration involves the existence of detailed information in the genes, such as star patterns for navigation and timing instructions for the timing of migration. The presence of instinct means that creatures carry out their complex tasks without any worry and with high levels of reliability. There is no doubt that instinct is one of the key reliability strategies used in nature.

In contrast to creatures with instinct, humans must be trained in order to carry out complex tasks such as operating machinery and constructing equipment. The fact that humans are not restrained to instinct can obviously have great advantages in some situations. However, the fact that humans need to be trained to carry out complex tasks and that human behaviour can be unpredictable means that humans can often be one of the weakest links in a complex system. Unpredictable behaviour can result from inadequate training but can also be caused by personal problems or just simply an adventurous spirit. Nature does not suffer from these problems because almost all of the activities of wild creatures are controlled by instinct. To design a system based on instinct ultimately means eliminating the human operator. However, such a strategy would appear to be unfeasible at present.

9 Conclusions

Nature provides a powerful insight into how to achieve simplicity in an optimum way in complex systems. In nature, simplicity does not mean avoiding complicated processes or even reducing absolute number of individual parts. In nature, simplicity is maximised at the macro level by using a minimal number of macro parts, a minimal number of sliding parts and by having continuous joints. These strategies lead to a small number of simple macro interfaces with the obvious benefits in reliability. To achieve this extreme simplicity on a macro-level, there is incredible complexity of functions on a micro-level with very sophisticated smart materials. This design philosophy in nature shows that simplicity is a design goal that must be carefully defined by design engineers.

The fact that so many reliability strategies can be identified in nature demonstrates that strategies can be an important means of achieving high reliability in complex systems. Many of the reliability strategies used by modern engineers are seen in nature. However, there are several strategies used in nature that are not used much in engineering systems. As engineering systems take on more of the characteristics of biological systems, there is potential benefit in copying the reliability strategies of nature.

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