Delivered as a keynote address
Volga Conference on Complex Adaptive Systems, Samara, Russia, 2004.

DESIGNING COMPLEX ENGINEERING SYSTEMS

George Rzevski
Magenta Corporation Ltd
33 Glasshouse Street, London W1B 5DG
george.rzevski@magenta-technology.com

Keywords: complex systems, intelligent networks, design of artefacts

Abstract

Physical artefacts such as machines, vehicles, spacecraft and robots could be designed as intelligent networks rather than integrated units, giving them the feature of adaptability. Two examples of the new approach to the design of engineering artefacts are given: an intelligent variable geometry compressor and a family of space exploration robots.

1. Introduction

Traditionally, we avoid complexity. The aim was always to design well-structured systems, which exhibit predictable behaviour. Artefacts such as large ships, aircraft and process plants have elaborate control systems with explicit feedback loops that ensure that the artefact operates at an equilibrium point. It is considered necessary to ensure that the behaviour is stable, which means that the system, when disturbed, will return to its equilibrium, the sooner the better. The optimal efficiency of the system is tuned to coincide with the equilibrium. Armies, state bureaucracies and large businesses have also been designed as rigid organisations expected to obey commands of the leaders.

There are situations however where stability is undesirable. The classical example is a military aircraft that frequently needs to execute a rapid avoiding manoeuvre. Here the propensity to return to the equilibrium would make any effort to change the operating point more difficult and therefore must be designed out of the system. In fact, whenever the environment is frequently and rapidly changing in an unpredictable manner, the artefact should exhibit Adaptability, ie, the ability to rapidly adjust its behaviour to the dynamics of its environment, rather than stability.

The principle that in a dynamic, unpredictable world *Adaptation* is more important than stability applies equally to physical artefacts and social organisations.

To achieve a really effective adaptation we need to look for help beyond traditional control engineering and management science, which appear to have reached their limits. A good strategy is, of course, to imitate biological systems. To adapt to its environment living systems make use of *Sensory Perception* (detecting and anticipating changes in the environment), *Cognition* (reasoning about perceived changes and deciding on the best action) and *Execution* (controlling the implementation of cognitive decisions) [1]. In situations that require a really fast response, the cognitive stage is short-circuited. Instead of reasoning the system simply selects one of the patterns of behaviour which proved in the past to be effective in similar situations. We tend to call this type of reaction "intuitive".

Artificial Perception and Cognition systems, particularly advanced ones – like those in humans – are quite difficult to design, the major problems being the collection and formalisation of the essential domain knowledge and mechanism of reasoning under conditions of incomplete, unreliable or frequently changing information. An additional problem is the sheer size of a centralised artificial "brain" and a large number of fast communication channels required for very large artefacts such as jumbo jets or manufacturing plants. A huge intellectual effort has been spent during the last fifty years researching this area, under the name of Artificial Intelligence, albeit with patchy results.

Practical breakthroughs occurred only when the whole problem solving strategy was reviewed and the decision was made to imitate groups rather than individuals – colonies of ants, swarms of bees and, ultimately, human organisations. Note that societies (groups, teams) can be highly adaptive if their organisational structures and cultures are characterised by:

- Significant autonomy of their members, which allows each member to choose whether to co-operate with other members or to compete for limited resources
- Effective communication channels for a rapid exchange of information among all members
- Enforceable rules and/or cultural bonds, which keep the group together in pursuing common goals without unduly limiting autonomy of individuals

For a group to be effective there is no need for individual members to be of exceptional abilities, as long as there are ample opportunities for members to consult each other. For example, groups consisting of members of limited intelligence, like colonies of ants, are capable of quite a remarkable adaptation. This property is given the name Emergence, the creation of intelligent behaviour through the strong interaction among a large number of members rather than through actions of each member. Because of the paramount role of communication links between members of the group, such social structures are known as Networks, and to emphasise the importance of the group intelligence, I refer to them as Intelligent Networks [2].

Examples of social networks include: old-boy networks, drug-dealer networks, terrorist networks and the new breed of virtual enterprises [3].

A social network is a perfect model for the design of the new generation of intelligent software, known as Multi-Agent software, which has a similar configuration (a network with richly interconnected intelligent nodes) and displays adaptability similar to that of flexible societies.

In contrast, social groups with strong hierarchical control, restricted lines of communications between members, and governed by rules and traditions demanding submission to the authority of leaders are known to be rigid and to resist any change even when the change is imposed from the top. Such groups show similarity of structure with conventional software technology, which consists of a hierarchy (rather than a network) of passive software modules.

2. Designing Complexity into Engineering Systems

My contention is that physical artefacts, such as machines, vehicles, spacecraft and plants could be designed as intelligent networks rather than integrated units. By giving them distributed intelligence we make them adaptable to changes in their environments. Let me describe some of the projects in which I was involved that fall into this category.

2.1. Intelligent Compressor

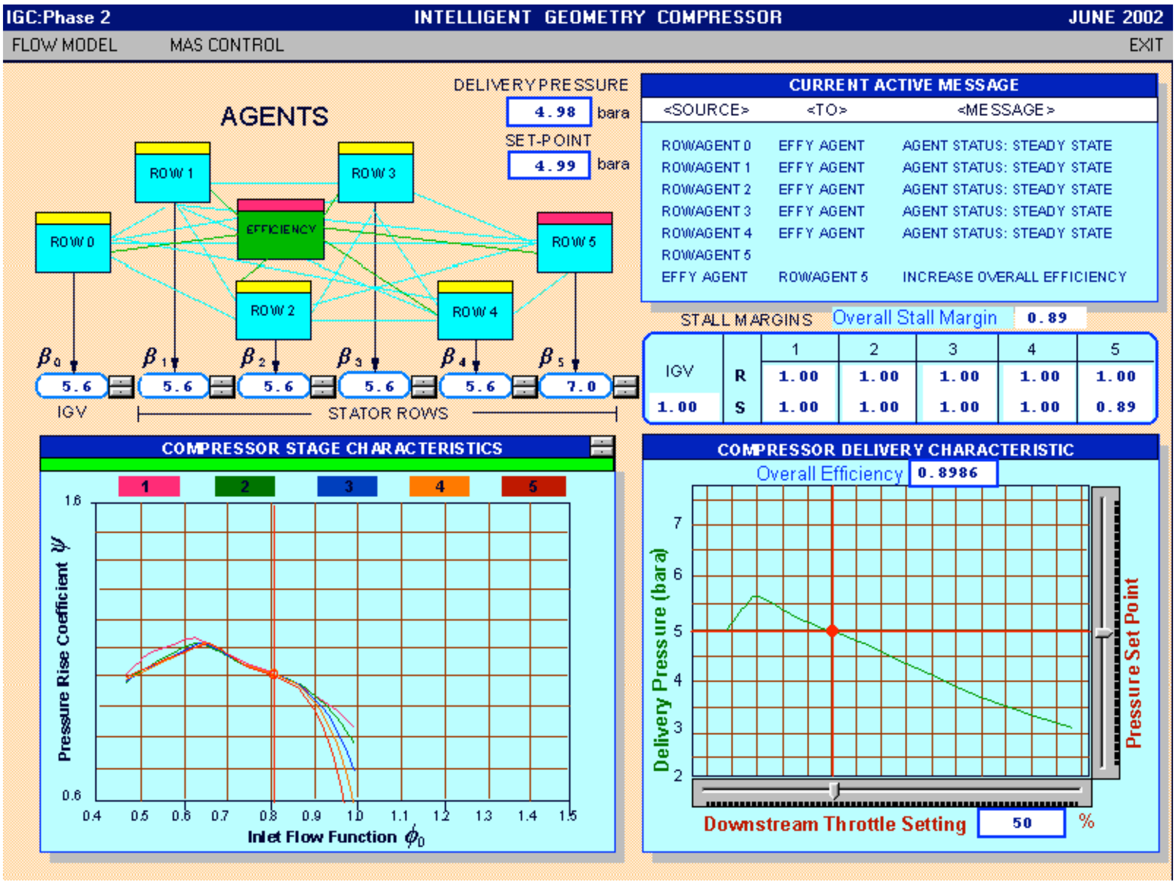
Axial turbo compressors are used in many areas of industry where large quantities of air or gas have to be moved or compressed. Typical examples are in jet engines, large gas turbines, gas-line pumping and in many process plants. All turbo compressors are limited in their performance by the aerodynamic phenomena of stall and surge, where the flow of the gas becomes unstable and can reverse in direction. Stall and surge, if allowed to develop, can cause significant mechanical damage to the compressor.

Present designs of axial compressors use fixed geometry rotor blades and fixed geometry stator vanes, with a limited capability to vary vane angles against pre-set limits, using simple control algorithms. The operating point for the compressor is designed to give an adequate safety margin from the surge line, therefore avoiding the possibility of stall or surge in operation. This surge margin puts a limit on both the work that the compressor can do and its efficiency. For example, large industrial turbo compressors can absorb powers of the order of 50 MW, with annual operating costs of between £5M and £20M, depending on the duty cycle and power charges applied. It is understandable therefore that the costs for even a small drop in efficiency due to a provision for pressure and/or flow with adequate surge margin, is very significant. The avoidance of surge has important safety implications in aerospace. Surge under extreme manoeuvres has resulted in the loss of aircraft.

Supported by a group of industrial organisations and experienced turbo-machinery designers, the author's team decided to tackle the problem of aerodynamic instability in compressors in a novel way. The decision was made to reconsider the fundamentals of compressor design by removing the usual assumption of fixed or partially variable geometry and to apply concepts from the intelligent network paradigm.

As a result, a design of an axial compressor with variable geometry emerged, where an intelligent agent individually controls each movable element. Agents are then connected into a network and empowered to negotiate among themselves relative positions of movable elements with a view to achieving a performance as close as feasible to the optimum under continuously changing aerodynamic conditions. The overall behaviour of the compressor emerges from the interaction of agents.

The proposed intelligent geometry compressor will operate by using sensors to monitor the aerodynamic conditions at each movable element. Sensor information will be used by local agents, which, through the process of negotiation, will make control decisions and instruct actuators to incrementally adopt the flow path geometry that ensures optimum performance for current aerodynamic conditions.



DELIVERY PRESSURE 4.98 bara

SET-POINT 4.99 bara

β_0 5.6 β_1 5.6 β_2 5.6 β_3 5.6 β_4 5.6 β_5 7.0

CURRENT ACTIVE MESSAGE

<SOURCE>	<TO>	<MESSAGE>
ROWAGENT 0	EFFY AGENT	AGENT STATUS: STEADY STATE
ROWAGENT 1	EFFY AGENT	AGENT STATUS: STEADY STATE
ROWAGENT 2	EFFY AGENT	AGENT STATUS: STEADY STATE
ROWAGENT 3	EFFY AGENT	AGENT STATUS: STEADY STATE
ROWAGENT 4	EFFY AGENT	AGENT STATUS: STEADY STATE
ROWAGENT 5		
EFFY AGENT	ROWAGENT 5	INCREASE OVERALL EFFICIENCY

STALL MARGINS Overall Stall Margin 0.89

IGV		1	2	3	4	5
	R	1.00	1.00	1.00	1.00	1.00
1.00	S	1.00	1.00	1.00	1.00	0.89

Overall Efficiency 0.8986

Downstream Throttle Setting 50 %

Fig.1 A multi-agent model of an intelligent geometry compressor

Simulation results indicate that an axial compressor designed as a network of movable elements could be operated over a significantly enlarged envelope without risk of stall or surge [4]. The project has now reached the stage of experimental tests on a variable geometry compressor in Cambridge University Turbomachinery Lab [5].

Utilising embedded processing power it becomes feasible to design into the compressor:

- Self-diagnosing (monitoring compressor conditions and identifying faults when they occur),
- Self-repair by reconfiguration (isolating faulty parts and thus making them harmless)
- Graceful degradation of performance (repositioning remaining healthy parts to achieve a reduced but acceptable level of performance; also, in case of a serious failure of critical elements, such as actuators, agents can revert to the fixed geometry mode of operation)

2.2. A Family of Space Robots

A robot was recently launched by a UK team to explore Mars. Unfortunately, it got lost. It disappeared without a trace among speculations that it landed into a crevice on the Mars surface and lost the communication link with the control station. This disaster could have been avoided by sending to Mars a "network" of smaller robots. In fact, just before the unfortunate Mars robot project started, I joined another team of researchers, involving three universities and two spacecraft manufacturers from the UK, concerned with the development of technologies for the autonomy and robustness in space. Following the design principles described in [2] and briefly outlined in this paper, our team concluded that a family of five much smaller intelligent robots would do a better job under uncertain conditions in space than a single big robot. Each member of the robot family had a limited intelligence and was potentially able to undertake simple tasks such as placing scientific instruments onto a correct location and to provide a variety of services to other members of the family, e.g., cleaning their solar cells if they get covered by the space dust and helping them to get out of cracks in the Mars surface. Multi-agent control system provided intelligence to the robot family without having to rely on "world model" of the Mars environment; just a manageable ontology. The cost and weight per unit performance for the family was estimated to be below the cost and weight of an equivalent single robot. In addition, five smaller robots offered an important advantage in packaging for launch and delivery. The results of this project were ignored with catastrophic consequences.

3. Conclusions

Only two practical examples out of many available are given here to illustrate the new approach to the design of physical artefacts based on the premise that, for environments characterised by uncertainty, it is advantageous to design complexity into artefacts rather than making them fully predictable.

4. References

[1] Rzevski, G (ed), "Mechatronics: Designing Intelligent Machines", Butterworth Heinemann, 1995.

[2] Rzevski, G.: "On conceptual Design of Intelligent Mechatronic Systems". Mechatronics 13 (2003) pp. 1029 – 1044

[3] Rzevski, G, Skobelev, P, Batishchev, S, Orlov, A.: "A Framework for Multi-Agent Modelling of Virtual Organisations". In Camarinha-Matos, L M and Afsarmanesh, H (eds), Processes and foundations for Virtual Organisations, Kluwer Academic Publishers, 2003, pp. 253-260

[4] Morgan, Gwyn: "Intelligent Geometry Compressor - The Application of Multi-Agent System Technology to the Design of Intelligent Machines". PhD Thesis, Brunel University, 2002

[5] Morgan, G, Rzevski, G., Wiese, P.: "Multi-Agent Control of Variable Geometry Axial Turbo Compressors". Journal of Systems and Control Engineering, issue I3 vol. 218 (2004), pp. 157-171