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SciVerse ScienceDirect

Procedia Computer Science 00 (2014) 000–000

Procedia
Computer Science

www.elsevier.com/locate/procedia

1st International Workshop: From Dependable to Resilient, from Resilient to Antifragile Ambients and Systems (ANTIFRAGILE 2014)

Engineering Antifragile Systems: A Change In Design Philosophy

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Abstract

While technology has made astounding advances in the last century, problems are confronting the engineering community that must be solved. Cost and schedule of producing large systems are increasing at an unsustainable rate and these systems often do not perform as intended. New systems are required that may not be achieved by current methods. To solve these problems, NASA is working to infuse concepts from Complexity Science into the engineering process. Some of these problems may be solved by a change in design philosophy. Instead of designing systems to meet known requirements that will always lead to fragile systems at some degree, systems should be designed wherever possible to be antifragile: designing cognitive cyber-physical systems that can learn from their experience, adapt to unforeseen events they face in their environment, and grow stronger in the face of adversity. Several examples are presented of on ongoing research efforts to employ this philosophy.

Selection and peer-review under responsibility of Elhadi M. Shakshuki.

Keywords: Antifragile, Autonomous systems; Autonomy; Complex Systems, Design, Intelligent Systems, Cognitive Systems

1. Introduction

America's development of aeronautical vehicles and systems since their inception not much more than a century ago is one of the greatest success stories in human history. However, many problems have arisen that may not be solvable with current methods. The costs in money and time of designing, testing, delivering, operating and maintaining new systems is accelerating at an unsustainable rate, and systems often do not perform as they were intended. Maintenance and operations have a relatively new and growing problem that is not unique to aviation but is also experienced in the automotive, computer, and other industries. Systems may initially perform as designed and may do so for some time but when they fail, it is often difficult or impractical to correct problems. The complexity of

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designs increases the probability of intermittent problems. Much of the added complexity, and exacerbating this problem, is the integration of information technology into mechanical systems, cyber-physical systems[1]. But problems transcend cost schedule, and performance. Our Air Traffic Management (ATM) system for the National Air Space (NAS) is nearing saturation and is not scalable to reach required capacities. New technologies are being developed at a rapid pace for Unmanned Aerial Systems (UAS) that are now operating in limited applications as remote piloted vehicles. However, much research remains to advance these to truly autonomous systems. Also, modification of the current ATM for our NAS will be required to fully integrate these vehicles.

Thus, addressing future challenges in aeronautics is not simply to do what we know how to do now better: *we need to do things we currently do not know how to do*. What is needed to address these challenges is a transformation of engineering practice that infuses new methods being developed in the discipline of *Complex Systems*. Federal research and engineering organizations have recognized this need and are beginning to take steps to a realization. Specifically here, application of a new concept of *antifragility* to engineering practice will be presented as a means of solving some of these problems.

2. What is different about complex systems?

The source of the approaching limits to what has been an astounding progression of technology in aviation may be found in an underlying philosophy of design: *Reductionism*. Since the beginning of design there has been an assumption that any system, no matter how complicated, can be completely understood if reduced to elemental components. By fully understanding the elements, system behavior can be predicted and therefore controlled: *a system is the sum of its parts*. In 1984, a group of scientists formed the Santa Fe Institute (SFI) in the belief that *a complex system is more than the sum of it parts*. They believed behavior of a complex system is determined by the interactions among components and their interaction with their environment. Through such interactions, behavior of the system *emerges*. Since that time, other academic institutions, such as the New England Complex Systems Institute (NECSI), have been founded or adapted to study behavior of complex systems and to develop an understanding of this behavior to solve real world problems. Most of the research has centered on the study of biological and ecological systems, social organizations, and economic policies.

In 2011, The National Science Foundation (NSF) partnered with NASA Langley Research Center (LaRC) over a concern that, while academic interest in complex systems science was growing, the research was not being effectively transferred into engineering practice. It was proposed that academic institutions needed to work more closely with engineering organizations such as NASA to develop tools and methods that can be evaluated in practical applications within the design process. Out of this partnership, the InterAgency Working Group (IAWG) on the Engineering of Complex Systems was formed in 2012[2]. Comprised of representatives of key Federal agencies including NASA, NSF, Office of the Secretary of Defense (OSD), Army, Defense Advanced Research Projects Agency (DARPA), Department of Energy (DOE), National Institute of Standards and Technology (NIST), and Federal Aviation Administration (FAA), this group is dedicated to facilitating the transition of academic interest in complex systems science by transforming the practice of engineering for large complex systems.

The challenge for designing complex systems are many but a focus for NASA is to develop tools and techniques where interactions of massive numbers and types of components are understood such that emergent behavior can be more predictable and controlled than is currently possible with a reductionist approach. Also uncertainty in the environment must be better managed. It is clear that solutions require more than technical excellence: they must include social, political, and economic considerations. Thus, another focus is infusion of other sciences by blending knowledge bases from diverse communities in non-engineering sciences.

NASA LaRC has recently formed a team, the Complex Aeronautics Systems Team (CAST) to begin the process of researching methods and affecting the transformation of engineering by infusing complex system science. The team is multidisciplinary in composition as its members are representatives of the Research Directorate (RD), the Engineering Directorate (ED), the Systems Analysis and Concepts Directorate (SACD), The Aeronautics Research

Directorate (ARD), the Space Technology & Exploration Directorate, and the Office of Chief Technologist. One of the members is also a member of the IAWG.

The first step NASA needs to take to infuse new methods from complexity science into engineering practice in the Agency is to build a bridge between the researchers in academic institutions and the practicing engineers within the Agency. The benefits to the Nation and NASA include engineering design approaches for *more resilient systems* that can self govern behavior and adapt to unpredictable circumstances, *more adaptable systems* that will behave appropriately in uncertain and unknown environments, *more reliable systems* that will behave as intended, *new kinds of systems and applications* that are currently intractable (e.g., intelligent and learning machines), *reduced cost and time* for large scale system development for entire product life cycle (research to operations), *comprehensive science in design* where societal, political, and economic considerations are incorporated into and addressed in the design process, *better workforce organization and utilization* by capitalizing upon advancements in non-engineering sciences to organize for more productive and cooperative workforce, and *opportunity for significant innovation and creativity* enabled at the intersection of knowledge bases.

3. Opportunities for Antifragile Design in NASA Missions

A change in design philosophy to address many of these challenges is presented in Nassim Taleb's book, *Antifragile: Things That Gain from Disorder*[3]. Current systems are designed to be fragile at some degree: requirements for performance are specified and the system is designed to meet those requirements. If the system is stressed beyond the design requirements, it will fail. Current efforts are focused on how to design more *resilient* systems but the result is systems that are less fragile. Taleb defines the opposite of fragile as *antifragile*: a system that becomes stronger when stressed. The best examples are found in biological systems. Muscle, for example, becomes stronger when stressed through activity and exercise and, ironically, atrophies when it is not used.

Current methods of designing to requirements by definition produce fragile systems. Requirements constrain the design and concentrate on what is known about the system and its operational environment. What is needed are new methods producing systems that can adapt functionality and performance to meet the unknown. In the following sections are brief descriptions of ongoing research that adopts this philosophy. It is not an exhaustive list but presents examples of how a change in design philosophy can lead to antifragile systems. In these examples, systems are not designed for what is expected and anticipated but designed to access the environment in realtime operation and adapt in response to current events that need not be completely know at design.

3.1. Communal Sensor Network

Noise abatement in aircraft engine nacelles is conventionally accomplished by massive numbers of Helmholtz resonators arranged behind the nacelle liner. These resonators are passive as they are of fixed and homogeneous impedance. The impedance is selected as a tradeoff to achieve acceptable noise reduction throughout all periods of the flight regime (e.g., take-off, cruise, and landing), though realizing optimal reduction in none. Also, there are problems in translating design into operational systems. Designers use approximations, the design is not perfectly implemented in manufacturing, and properties can change during use.

Techniques have been developed to adjust the impedance of a resonator in situ[4], thus mitigating these problems in design, production, and maintenance while allowing for better noise reduction as acoustic conditions change. Furthermore, it has been proven that heterogeneous liners can achieve better noise attenuation than the optimal homogeneous liner[5]. The question then becomes, how is the decision made to set impedances of each resonator to achieve optimal nose attenuation throughout the flight regime? A conventional approach is to predetermine, through modeling, simulation, and experimentation, the best combination of impedances for all resonators under differing acoustic conditions. Once determined, the resonators could be centrally instructed to adjust their impedance as conditions change (i.e., a table lookup). The table could be large but is discrete and finite and, thus, instructions would always be an approximation. Rather than specify the expected, an alternate approach has been examined[6] that would have the resonators act as a community: assess acoustic conditions locally, share information with each other when necessary, and make local adjustments in response to these conditions. From a combination of local decisions and actions, impedances would be adjusted locally to affect a global optimal attenuation. It is not necessary to predetermine conditions: the community would assess and respond to conditions as they change.

3.2. Morphing Wing

The shape of conventional wings on aircraft is fixed with small variability in foil shape through ailerons (increasing curvature increases lift at cost in drag). Aircraft design is a tradeoff between stability (needed for safety) and instability (needed for agility). The more stable the aircraft, the safer it is but the less agile it is. Fighter and acrobatic aircraft are less stable but more maneuverable than passenger liners. But, the stability of aircraft is fixed at design, except for small variability of control surfaces. Possible now by improvements in multi-functional, smart materials and structures, a morphing wing[7] can improve ability to vary the characteristics of the wing in flight, providing greater flexibility and adaptability of shape, thus opting for increased stability or agility as needed.

Conventional design uses modeling, simulation, analysis, and ground test experimentation to optimize wing design for few design points in anticipation of expected conditions of flight for a specific mission. A morphing wing, with its greater flexibility of shape could assess conditions in situ, respond to those conditions within its increased limits of flexibility, and adjust its characteristics appropriately. This would not only lead to higher performance and efficiencies in flight but would also allow greater flexibility so that a single aircraft could easily be adapted for multiple missions.

3.3. Learn To Fly

NASA has developed a “Learn-to-Fly” concept[8], where techniques are being explored to rapidly and autonomously develop vehicle characterization and control strategies during flight with minimum human interaction. Early results have developed efficient and rapid flight test capabilities for estimating highly nonlinear models of airplane aerodynamics over a large flight envelope. Used in conjunction with fuzzy-logic system identification algorithms, flight maneuvers result for flight conditions ranging from cruise to departure and spin conditions.

As with the morphing wing, this philosophy differs from conventional methods for defining control laws. Rather than specify all control strategies and vehicle characteristics in design, methods are being developed whereby these can be evolved, adapted, and optimized in flight. The biomimetic approach is drawn from the way baby birds learn to fly. While they are born with genetic capability and predisposition for flight, their early flights are erratic and inefficient. From these experiences, better techniques are rapidly developed and adopted until the bird is able to fly efficiently with skill. These techniques go beyond initial determination of rules but will be continually used to adapt for new situations resulting in improved flight.

3.4. Autonomy

The race is on for autonomous systems and articles appear daily in newspapers and magazines describing the latest capabilities in autonomous automobiles and UAVs. However, the definition of autonomy varies greatly. At some level autonomous systems have been available since the industrial revolution began (e.g., looms were directed by punched tapes). Automation was greatly advanced with the arrival of computer controllers of electro-mechanical systems: cyber-physical systems. This revolution has rapidly accelerated with miniaturization made possible by Micro-Electrical Mechanical Systems (MEMS) and will soon move into the nano scale. The variability in defining autonomy may be understood by where the system lies along a continuum. At the beginning of the continuum are automated machines: those that follow a fixed and finite script. In a progression along the continuum, the script becomes more complicated resulting in more capabilities of the machine. The promise is that at some point along the continuum, autonomous machines will approach or even exceed the intelligence of humans. But for this to occur, a giant chasm must be crossed. Instead of following fixed, predetermined, and therefore limited, scripts that can only respond to an anticipated environment, machines must be programmed to observe their environment, make decisions, and take action, but more importantly must learn from their experiences, adapt to new circumstances, and take actions that were not preconceived at design.

Advances are currently being made in autonomous systems by increasing and improving automation. However, for a fully functional and trusted autonomous automobile, to replace pilots in aerial vehicles operating in the NAS, to have robotic vehicles explore unknown environments on other planets with maximum effectiveness, or to succeed with deep space missions requires cognitive machines that are designed to adapt for the unexpected.

3.5. Swarming

A swarm is another term that has a variety of definitions. For this discussion, a swarm is a collection of autonomous vehicles operating for a common purpose that are not centrally controlled. Thus, they must self-organize and cooperate to complete a mission. Another characteristic is that a swarm is composed of large numbers of relatively inexpensive units that are expendable: 80% failure of individuals may still result in 100% mission success. Swarms present great potential for applications such as exploration, direct sensing and surveillance, and disaster relief. For maximum effectiveness swarms cannot be preprogramed for all action but, must be programed such that, as they self-organize and cooperate, they learn from experience and their behavior is adapted to best complete the mission.

3.6. System Health Management

Currently aerial vehicle systems health assessment and management is dependent on direct human decisions and action. Limited information is provided to cockpit displays as input to humans for decision and action. Much dependence is placed on periodic human inspection for fatiguing components or systems needing maintenance or replacement. Scheduled end-of-life replacement is designed to replace components before failure but may result in premature replacement.

Integrated Vehicle Health Management (IVHM)[9 10 11] was conceived to collect data relevant to the condition and performance of a vehicle's sub-systems and automate its transformation into information that can be used to support operational decisions. The concept of IVHM has been made possible through the development of inexpensive and small Size Weight And Power (SWAP) electromechanical sensors and communication technologies that allow their pervasive distribution throughout the vehicle to collect data. Such a sensor network enables continuous monitoring and real-time assessment of vehicle functional health. But beyond collection of information, recent advances in information fusion and artificial intelligence facilitate autonomous decisions. The IVHM vision goes beyond the collection and presentation of data for diagnosis of system health. It includes system prognosis for prediction of remaining useful life of components, recommendations on preventative maintenance, and fail-safe decisions on continued operation. Maintenance operations are improved by reduced occurrences of unexpected faults and by early identification of failure precursors. Condition-Based Maintenance (CBM) is enabled, enhancing mission reliability and safety and optimizing component lifetime.

Ubiquitous sensing enables real-time diagnostics. Machine intelligence enables prognostics that improve maintenance and mitigate system failure. But increasing cognitive ability, adaptability, and autonomy of machines leads the way beyond identification and prevention of system failure to systems that can compensate for failure through system resource reallocation and adaptation towards systems that can adapt to unexpected environmental conditions.

3.7. Self-healing Materials

Aircraft structural design is a tradeoff between strength and weight. Structures such as wings and fuselage must be strong enough to withstand consistently variable stresses yet any more weight added to the structure than necessary decreases performance. Because of uncertainty, the minimum required level is exceeded and yet there is still failure. Exceeding strength to guarantee against failure would result in an aircraft that would not fly efficiently, if at all. Thus, aircraft structures are designed knowing that fatigue will eventually cause failure. Failure is determined largely by visual inspection.

Inspired from biological systems that self-heal after injury, research is now ongoing into self-healing materials[12] that can autonomously repair damage without human intervention. Such materials could increase lifetime of mechanical systems thus reducing cost and demand for raw materials. If determined early, damage is easier and cheaper to correct. More importantly, these could improve safety of operations.

But what if materials could do more than heal damage? What if they could adapt for strength: borrow from areas of less stress to fortify areas under more stress? What if materials could grow in strength in response to stress, similar to how muscles build strength? Such a system would not be designed for resilience to expected stress but would instead be designed to adapt to undetermined stress as it is encountered.

4. Conclusion

Despite the fantastic advances made in technologies for aerospace vehicles and systems, the aerospace community is facing many unsolved problems. Continuing conventional design methods of specifying requirements that produce systems to perform as expected in an anticipated environment may not solve these problems. Complex Systems concepts may solve problems with component interaction and mitigation of uncertainty. A change in design philosophy is needed that will produce antifragile systems: systems able to learn to perform in the face of the unexpected and improve performance beyond what was anticipated. Several examples are presented of ongoing research towards this goal.

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