SELF-OPTIMIZING AVIONICS: THE FUTURE OF AVIONICS

Mark M. Stephenson & Robert L. Harris

Air Force Wright Laboratory, Avionics Directorate
Wright-Patterson AFB OH 45433

Abstract

Numerous technologies are reaching a maturity level where they will merge and contribute to a new class of military weapons having self-optimization attributes of mission objectives at several levels. Among the technologies are integrated avionics, data fusion technology, data links, computer science, and computer engineering. An overview of self-optimizing concepts is presented along with operational implementation considerations including the network architecture, control of optimization decisions, aircraft configuration options, and affordability. Numerous payoffs within the context of leveraged technology are cited to support the expectations of major initiatives and investments in these concepts in coming years.

Introduction

As the Department of Defense (DOD) faces major reductions in assets over the next decade, there will be a critical need to compensate for dwindling physical reductions without weakening war-fighting capability. New economic and political pressures on the military avionics community are forcing nontraditional demands on systems. There is increasing pressure for avionics that is more affordable, more reliable, more maintainable, more adaptable, and more effective across multiple platforms.

In the recent past, new weapon system requirements translated into new weapon systems such as the stealth fighter (F-117) and the F-15E. The stealth bomber (B-2), and the advanced tactical fighter (F-22) are at the tail end of this era. With the significant funding limitations expected in the future, whole new weapon systems are unlikely. The avionics community will be required to continue to enhance system capabilities at a lower cost and within the constraints of existing weapon systems.

In any situation where resources are seriously constrained and increased performance and capability is demanded, there is only one acceptable alternative -- innovative use of existing resources to maximize capability. Even with the planned reductions, the Department of Defense possess many capable and diverse resources. The goal is to optimize there application and interaction to maximize mission effectiveness. A conceptual method to accomplish this is by integrating system assets with optimization. Through a synergistic use of elements treated collectively (none of which might be fully capable in and of itself), it appears possible to maximize mission-oriented functions by designing and employing systems based on principles of optimization theory.

A Definition Of Self-Optimizing Avionics

Self-optimizing avionics can be defined as avionics that: given the mission, goals, priorities, constraints, tactics, and resources, automatically takes the appropriate action to maximize effectiveness. The effectiveness can focus on a mission objective (e.g., destruction of a bridge), a functional application (e.g., blind in-weather landing of an airplane), a combat objective (e.g., destruction of enemy aircraft), etc. Theoretically, this involves optimization of some objective function, given input constraints such as a mission, available resources, a hierarchy of operational priorities, tactics, and physical limitations. Figure 1 summarizes this idea.

What is Self-Optimizing Avionics?

AVIONICS THAT:
- Mission
- Goals
- Priorities
- Constraints
- Tactics
- Resources
- Quantity
- Capability

Automatically takes the Appropriate Action to Maximize Effectiveness

Figure 1

Figure 2 illustrates some of the benefits of self-optimizing avionics. In this example, two F-16’s are in combat. One F-16 has a failed RADAR and one AIM-7 missile remaining. An AIM-7 missile requires an active RADAR for proper delivery. The other F-16 has a fully operational RADAR but no weapons. An enemy aircraft is in the area. Current avionics technology and procedures would force both F-16’s to return to their base.
With self-optimizing avionics, the current resources and mission could be assessed and a data link could be established between the aircraft. The data link would allow the aircraft with the operational RADAR to lock on to the target and fire the AIM-7 located in the other F-16. This capability would have the effect of providing avionics that is more affordable, more reliable, more maintainable, more adaptable, and more effective. This particular example is somewhat simplified and could be done with current technology for this very specific case. The difficulty comes when the problem is solved for the general case, taking into account multiple aircraft types and capabilities, possible failure modes, and various mission scenarios.

![Self-Optimization Example](image)

**Figure 2**

### Levels Of Avionics Optimization

Formulating the optimization problem, translated to avionics and weapon systems goals, can occur at many levels as shown in Figure 3. For example, at the pilot's level, optimization can maximize pilot-interfaces with the airplane, using displays that are "tailored" to the specific pilots experience and unique capabilities for a specific function (e.g., defensive avionics in an electronic warfare environment, acquisition of a ground target, perfect navigation, blind landing, or precision strike). Man-machine interfacing is a very important aspect of optimization at this level. Audio, visual, stimulus, and ergonomic designs have already greatly contributed to this level of optimization.

At the weapon system level, optimization can maximize integrated avionics system resources for performance at each operational phase such as takeoff, climb, cruise, engagement, descend, land, or taxi, even with avionics component failures. Integrated Communication Navigation Identification (CNI) avionics can be optimized to maximize radio communications functions such as UHF, VHF, or HF.

As illustrated in figure 2, flight level optimization can provide automated co-operative weapon system operations in which multiple aircraft fly as a single synergistic system. Utilizing optimization, the overall capability of the flight could drastically exceed the sum of the capabilities of the individual weapon systems with or without avionics system failures.

The mission level represents the ultimate in self-optimizing avionics and would require support from all the other optimization levels. At the mission level, optimization principles apply to the continuous automatic coordination of forces from many services to optimize global objectives. The mission level may be too complex and expensive to fully realize in the foreseeable future.

**Optimization Levels**

![Optimization Levels](image)

**Figure 3**

### Technical Feasibility

Five emerging technologies have made the self-optimizing avionics concept a practical consideration.

**Integrated Avionics**

First, the demonstration of integrated avionics principles has established a baseline for theoretical departure for higher levels of optimization.\[1\] A collective optimization among signal processors, data processors, memory, central processing units, and control implemented by software, has been demonstrated performing many discrete CNI functions that were formerly implemented by discrete hardware boxes. Integrated avionics can be characterized by three distinguishing features: a) a collective optimization of on-board aircraft sensors, signal processors, data processors, and computer memories; b) high-speed processor interconnects such as data busses; and c) software that represents the "intelligence" or "glue" that makes the system operate. Switching of data among processors within an integrated avionics node might be aided by GaAs technology. This technology has resulted in an off-the-shelf crosspoint switch with 64 independent outputs, each operating at 200 million bits-per-second. Crosspoint devices are typically used for data distribution in telecommunications and automatic test equipment, but this speed is fast enough to also serve in fiber-optic serial backplanes, such as those being designed for the Air Force's PAVE PACE program.\[2\] A prototype switch is currently housed in a 344-pin ceramic lead chip carrier, and can be cross-connected with up to
Fiber Distributed Data Interface (FDDI) links. They might be capable of also being cascaded to create a larger crossbar.

**Data Fusion**

Second, data fusion represents an evolving science that will enable the concept demonstration of optimized avionics. This is the process by which multi-source and multi-modal data are combined to produce interpretable information through data reduction, synthesis of new information constructs, and optimized decision-making. Data fusion includes the process of acquisition, integration, filtering, correlation, and synthesis of data from diverse sources for the purpose of situation/environment assessment, detection, verification, diagnostics, and improving system performance and utility. The essence of data fusion is the process by which multi-source and multi-modal data are collectively exploited for shared self-optimized avionics. Individual nodes must enable secure, potentially covert, real-time voice and data transfers at minimum rates of several megabits per second in support of both offensive and defensive avionics. The aim is to improve aircraft identification, formation positioning, and a global situational awareness. An important Government initiative expected to aid data linking is the High Performance Computing and Communications effort, a $1.9 Billion effort that would create high-speed data links and computers capable of sustaining speeds up to 1 trillion calculation-steps-per-second. The goal of the effort is to accelerate significantly the availability and utilization of next-generation high-performance computers and networks. Components of this effort include: High Performance Computing Systems; Advanced Software Technologies and Algorithms; A National research and Education Network; and Basic Research and Human Resources.

**Computer Science**

Fourth, computer science and software technology have advanced to where “software first” is a viable alternative for system design. This concept focuses on software as the driving engineering requirement for hardware development. Software applications, support tools, software engineering environments, and software engineering practice would represent the underpinning for planning, organizing, and controlling the system development. Traditionally, system design has been approached from a hardware perspective. Hardware would be designed around software network requirements, functions, and software architectures as parallel-processing programming evolved. Domain-specific software architectures, represented by the Defense Advanced Projects Agency’s initiative, could represent a significant contribution to this approach. [3],[4],[5] Engineering has historically been limited by what existed in hardware. With a “software first” concept this limitation no longer needs to exist. Suboptimal parts can be specified and produced to perform at a system level in accordance with a global view.

Computer science is expected to contribute to integration of mathematical optimization theory and practice, algorithms, computations, computer visualization, simulation, and its use of more powerful and fast computers as the basis for system design. Visualization of algorithms, and use of virtual reality to design system capabilities and performances could be augmented by object-oriented programming. As an intense software system, this new avionics would exploit “Megaprogramming” techniques for its implementation. [6]

**Computer Engineering**

Fifth, computer engineering holds the key for hardware implementation of the concepts. This will likely be driven by commercial interests, however it is expected that faster, smaller, more efficient processors and “computer systems on a chip” will become the norm during the next decade. Trends today point to gigaoperations per-second processors with a continuing escalation of processor-power/dollar. Recent hardware advances offer the potential for a thousand-fold improvement in useful computing capability and a hundred-fold improvement in computer communications capability by the year 1996. The Defense Advanced Research Projects Agency expects to coordinate much of this R&D, culminating in initial demonstrations of billion-bit-per-second capability. As part of the total effort, very high-speed switches, protocols, and computer interfaces will be defined. Other technologies that are evolving within computer engineering are optical computing and “systems” on a single chip. Each are expected to play a singular role in self-optimizing avionics systems.

**Optimization Technology**

Optimization technology represents the pervasive underpinning of self-optimized systems. It can be argued that this is as much a branch of mathematics involving numerical solutions to finding optima, as it is a technology. Technology implies the theory is not used by itself, but rather it is combined with elements of engineering, science, software, and management. By using various optimization techniques for various situations, decision rules for system behavior and performance can be integrated into the system’s design. Many aspects of optimization theory have been known to mathematicians for years, however their tedious and voluminous computations prevented their practical application. With development of powerful and inexpensive computers, these computations are now routine and
the study of transportation systems, and the planning and engineering, however it may be possible that some of its concepts have been extensively applied in the discipline of operations research used in industry for organizational analysis. [7] Operations research typically involves finding solutions to systems of simultaneous equations within some defined boundary conditions. Usual steps of attacking an operations research optimization problem are the following:

1. Formulating the problem.
2. Constructing a mathematical model to represent the system under study.
3. Deriving a solution from the model.
4. Testing the model and the solution derived from it.
5. Establishing controls over the solution.
6. Putting the solution to work.

In optimization, one seeks to maximize or minimize a specific quantity (an objective), which depends on a potentially vast but finite number of input variables. These variables can be independent of one another, or they can be related through one or more constraints. A mathematical program can be an optimization problem in which the objective and constraints are presented as mathematical functions and functional relationships such as:

\[
\text{optimize: } z = f(x_1, x_2, x_3, \ldots, x_n) \\
\text{subject to:} \\
\quad g_i(x_1, x_2, x_3, \ldots, x_n) = A \\
\quad g_j(x_1, x_2, x_3, \ldots, x_n) = B \\
\quad \ldots = C \\
\quad \ldots = \text{etc.}
\]

Each of the constraint relationships involves one of three conditions, "equal to", "less than or equal to", or "greater than or equal to."

Associated with mathematical optimization is network analysis which might be applied to self-optimizing avionics. Network analysis has long played an important role in electrical engineering, however it may be possible that some of its concepts and their tools can be used in the conceptualization and design of self-optimization avionics systems. Important applications of network analysis have been made in information theory, cybernetics, the study of transportation systems, and the planning and control of research and development projects. Additional application areas include social group structures, communication systems, production schedules, chemical-bond structures, and language structures.

A distributed "resource allocator" which focuses the network resources onto a given mission objective can be expected to result in the most effective maximization or minimization of a given objective. For example, "software-focusing" on various hierarchical "phases" of an airplane's flight, could for each phase maximize this function at the expense of other unneeded phases at the same instance in time. As the "hierarchy" of the phase-objectives change, so also would the resource allocator change its focus, thereby causing a dynamic reconfiguration of avionics resources that focus on an updated objective. Airplane flight phases such as taxi, takeoff, climb, cruise, etc. could thereby be optimized. This "robbing Peter to pay Paul" provides the concept behind optimized avionics' allocation and reallocation.

Implementation Considerations

There are four primary implementation considerations for achieving a full self-optimizing avionics capability. They are 1) the self-optimizing avionics network architecture, 2) the operational control of optimization decisions, 3) the aircraft configuration options, and 4) the affordability of the implementation.

Self-Optimizing Avionics Network Architecture

For a full mission wide implementation of self-optimizing avionics, the network architecture infrastructure must be in place. The network architecture will place strong demands on data-link technology by requiring networks that are as secure, high data rate, jam resistant, hard to detect, fault tolerant and adaptable as possible. The networking architecture will resemble a ground based network with large numbers of local area networks, each with gateways to higher level networks. The higher level networks will be linked to other higher level networks to effectively allow information to flow between any of the nodes on any of the networks. The overall network will be somewhat more dynamic than ground based networks as nodes enter and exit the network, and portions of the network are jammed or fail. The network will have to be highly adaptable to reroute messages around inoperable portions of the network in a timely and efficient manner.

The network architecture will support multiple types of messages between and within optimization levels. Here is an example of some possible message types.

**Higher level to lower level messages**
- Commands directing some action
- Requests for status or other information

**Lower level to higher level messages**
- Responses to higher level commands and requests
- Requests for assistance
- Notification of unique events/information

**Within level messages**
- Cooperative data sharing
- Requests for assistance
- Status sharing

The message passing approach will use a standard hierarchical approach with problem/issues handled at the lowest possible level. If an issue cannot be dealt with at the lower level then it will be elevated with a message passed up to the next level. Higher levels will direct lower levels. With this approach, messages between
levels will tend to be shorter and less frequent; messages within a level will tend to be larger and more frequent.

Within a local network there is an endless potential for sharing and cooperative functions. Systems can share information to improve situational awareness and overall knowledge. The information could include information about threats, or even terrain data. Cooperative functions have a great potential for drastic improvements in capability. Systems could use their RADARS to illuminate different portions of an area, and by sharing the information, achieve a scan of a much larger region. In the future, systems could even share processing resources to execute very complex algorithms. Cooperative functions can also be very useful in the event of a subsystem failure. If a subsystem such as a RADAR or a navigation system fails, another aircraft could provide supplemental data to allow the mission to continue.

The self-optimizing avionics network adds significant capability to a full up self-optimizing avionics implementation, however, it also adds vulnerability if the network capability is totally depended on. The concept of self-optimizing avionics is always to do the best with what is currently available. If the network is currently being jammed, then an aircraft can operate autonomously similar to the way they operate now. During that time the aircraft should try various approaches to reestablish communications. Once the jamming stops or is overcome the network should immediately begin operating again. In the case of stealth operation, an aircraft may not be able to transmit during portions of the mission, but the aircraft may be able to receive throughout the mission. The purpose of the network is to provide a means for additional optimization of resource and information sharing, and like any resource, it should be used wisely and appropriately.

**Operational Control of Optimization Decisions**

Operational implementation of self-optimizing avionics would be surprisingly similar to current operations and decision making. Today, the actions and decisions a pilot makes can be thought of as manually controlled optimization. For example, during a mission, a pilot attempts to constantly monitor the mission, goals, priorities, constraints, tactics, and resources and then, to the best of his/her ability, take the best possible action. As the situation changes (e.g. an enemy aircraft approaches or an avionics subsystem fails) the pilot automatically makes adjustments. In essence, through the use of the cockpit controls, the pilot is constantly adjusting the optimization criteria for the aircraft.

In a realistic scenario there are potentially thousands of optimization criteria. Two examples of optimization criteria might be safety and mission. Suppose an optimization criteria value of 0 signifies unimportance and 1.0 signifies maximally important. In the case of a safety value of .75 and a mission criticality value of 1.0, the aircraft would try vigorously to perform the mission but would avoid some risk. A safety value of 1.0 might not allow the aircraft to take off because of the risk. A safety value of 0.0 and a mission value of 1.0 might represent a Kamikaze.

The role of the mission commander, the flight commander, and the individual pilot, which correspond directly to the optimization levels, would be the constant adjustment of their specific optimization criteria values based on feedback from the environment. Some very unique user interfaces, perhaps using virtual reality technologies, will have to be designed to allow rapid, intuitive control of optimization criteria values. Many of the actual individual decisions and actions will be performed automatically by the self-optimizing avionics based on the optimization criteria.

**Aircraft Configuration Options**

Self-optimizing avionics opens up new possibilities for aircraft avionics configurations. Depending on the likelihood of full autonomous operation, aircraft could be configured with less than a full capability. Groups of aircraft may be configured to provide a full compliment of sophisticated avionics with no one system having a full capability. In the future, many avionics subsystems may be loaded and unloaded according to the current mission. This is done now to a limited extent using pods.

Self-optimizing avionics also supports the concepts of remotely piloted systems and unmanned systems to assist piloted vehicles. Perhaps piloted weapon systems could be fully equipped with a sophisticated set of avionics, while unpiolted systems could act as weapons haulers to fire weapons as directed by the pilot. There are many options that can be considered as tradeoffs are made between cost, mission requirements, and vulnerability. It is likely that a combination of approaches will be used depending on the specifics of a given mission.

**Affordable Implementation**

Near term implementation of a full self-optimizing avionics capability across all DOD systems would obviously be too costly, however, some of the benefits can be realized immediately with only a few systems implementing the capability. As more systems undergo retrofits the overall capability will increase. The actual aircraft modifications required to support self-optimizing avionics would consist primarily of a massive increase in computational capability and possibly an additional or enhanced communication system. There is a potential to use existing communication systems. The computational power could be added as part of planned computer reliability/maintainability upgrades. With computer technology available in the next few years, massive computational power could be added that would provide increased reliability within the current size, power and cooling constraints. The major cost drivers would be in the development of the self-optimizing avionics infrastructure and the enormous quantity of software to implement it.

**Payoffs/ Expectations for Self-Optimizing Avionics**

Self-optimizing avionics systems have the potential to provide new capabilities to commanders. They potentially could permit users to maintain existing effectiveness levels of mission-completion success with even with reduced-capability resources. By synergism one can envision use of many low-cost
avionics combined by a flying local-area-network into a system whose total capability exceeds that of a far more sophisticated and expensive alternative. A reasonable design goal for such a system might be 10 to 1 reduction in elemental costs comprising the avionics while sustaining a given mission-completion-success-probability.

Self-optimizing avionics can be expected to improve the performance of its users by leveraging computer science and technology against human effort, with the result that a given number of people greatly multiply their capability to achieve a given objective. During times of reduced manpower allocations for the military, this capability could provide the military means to maintain their war fighting strength in spite of fewer personnel.

Self-optimizing avionics could encourage joint-service planning and interoperability of resources by pooling requirements to define optimization objective functions. Its most effective use could involve multi-service assets at the mission-planning level. Currently, a large number of people within the military known as "operations researchers" are engaging in tactical planning for requirements and use of weapon systems, as well as the larger problems of joint-service allocation and integration of effort. Optimization theory can be applied to engineering of avionics systems with an advantage of each service using a common theoretical approach (operations research and mathematical optimization) to design and implement airborne electronics.

Self-optimizing avionics leverages computer technology, our country's leading technology, against limits of hardware engineering. By using modeling and software science, one escapes the bounds of traditional hardware engineering. New visualization techniques can be applied during concept formulation to arrive at design specifications for hardware.

Self-optimizing avionics can be made inherently fault-tolerant. Modeling and optimization algorithms, plus design of hardware to support them can guarantee "fail-soft" behavior by providing equations to define alternate "paths" throughout these avionics networks, along with backup "nodal" redundancies.

It is expected that reduced costs will result from self-optimizing avionics, when compared with conventional full-up complements of avionics hardware required to perform a given mission. Mission aborts that could be expected due to failures in a given aircraft would not occur when many aircraft are cooperatively pursuing a common objective, utilizing a self-optimizing avionics system.

The basic concepts of self-optimizing avionics are currently being implemented to solve specific problems today. As this basic capability evolves to full self-optimizing avionics, we will likely realize capabilities far beyond what could ever be conceived of only a few years ago.

Conclusion

Self-Optimizing avionics represents the next generation of conceptual systems with huge potential payoffs in cost, effectiveness, and operational efficiency. A combination of technological innovations, along with ideas from operations research appear to be at the threshold of providing the impetus for this next generation of airborne electronics.

References