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THESIS

**SOFTWARE-DEFINED AVIONICS AND MISSION
SYSTEMS IN FUTURE VERTICAL LIFT AIRCRAFT**

by

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March 2015

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**SOFTWARE-DEFINED AVIONICS AND MISSION SYSTEMS IN FUTURE
VERTICAL LIFT AIRCRAFT**

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ABSTRACT

Integrated Modular Avionics, or IMA, has been a notable trend in aircraft avionics for the past two decades, promising significant size, weight, and power-consumption (SWAP) gains, radically increased sensors fusion, and streamlined support costs. Despite the demonstrated success of IMA systems in commercial airliners such as the Airbus A380 and the Boeing 787, military rotorcraft in the service of the United States Joint services have yet to benefit significantly from this technology. At long last, that may be about to change.

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This thesis assesses the maturity of IMA2G critical path technologies, validates the alignment between IMA2G benefits and desired FVL attributes, and describes the operational impact that software-defined avionics and mission systems might have on future rotary wing aircraft.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFDX	aviation full-duplex
AGL	above ground-level
AMP	asymmetric multi-processing
AMRDEC	U.S. Army Aviation and Missile Research, Development and Engineering Center
APEX	application executive
API	application program interface
ASCM	anti-ship cruise missile
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
ASM	application specific module
ATC	air traffic control
BAA	broad area announcement
BE	best-effort (referring to Ethernet)
BIT	built-in-test
CAS	close air support
CIP	common integrated processor
CNI	communication, navigation, identification
COTS	commercial off-the-shelf
CPIOM	central processing in-out module
CPU	central processing unit
DIVTACS	deployable integrated virtual tactical simulator (Proposed. See Appendix A.)
DODAF	Department of Defense Architecture Framework
DVE	degraded visual environment
EFB	electronic flight bag
ES	electronic support
EW	electronic warfare
FAA	Federal Aviation Administration
FACE	Future Airborne Capabilities Environment
FCF	functional check flight
FMN	future mission network
FOB	forward operating base
FVL	Future Vertical Lift
FVLFOS	Future Vertical Lift Family of Systems

GALS	globally asynchronous, locally synchronous
GCS	ground control station
GPM	generic processing module
HADR	humanitarian assistance and disaster relief
I/O	input-output
ICD	initial capabilities document
IEA	Information Enterprise Architecture
IMA	integrated modular avionics
IMA2G	second-generation integrated modular avionics
INCOSE	International Council on Systems Engineering
IOC	initial operating capacity
ISR	intelligence, surveillance and reconnaissance
JCA	Joint Common Architecture
JFOR	Joint forces
JMR-TD	Joint Multi-Role Technology Demonstrator
JSF	Joint Strike Fighter
kbps	kilobits-per-second
kts	knots (as in nautical miles-per-hour)
LOI	level of interoperability
LRIP	low-rate initial production
LRM	line-replaceable module
LRU	line-replaceable unit
MANPAD	man-portable air-defense
Mbps	megabits-per-second
MBSE	model-based systems engineering
MCP	multi-core processing; multi-core processor
MEDEVAC	medical evacuation
MFD	multi-function display
MILS	multiple independent levels of security
MOSA	modular open systems architecture
MUM-T	manned-unmanned teaming
NASA	National Aeronautics and Space Administration
NATOPS	Naval Air Training and Operating Procedures Standardization
NAVAIR	Naval Air Systems Command
NIAP	National Information-Assurance Partnership

nm	nautical mile
NR-KPP	Net-Ready key performance parameter
NSA	National Security Agency
O&M	operation and maintenance (funding)
OS	operating system
OTH-T	over-the-horizon targeting
PCI	Peripheral Component Interconnect
PEO	program executive officer
QOS	quality of service
RC	rate-constrained (referring to Ethernet)
RDC	remote data concentrator
RF	radio-frequency
RSD	recovery and securing device
RTOS	real-time operating system
SAE	Society of Automotive Engineers
SCARLETT	Scalable and Reconfigurable Electronics Platforms and Tools
SME	subject-matter expert
SMP	symmetric multi-processing
SWAP	size, weight and power
TDMA	time-division multiple access
TEL	transporter, erector, launcher
TRA	technology readiness assessment
TRL	technology readiness level
TT	time-triggered (referring to Ethernet)
TTP	tactics, techniques and procedures
UAS	unmanned (unpiloted) aerial system
UAV	unmanned (unpiloted) aerial vehicle
VM	virtual machine
VMM	virtual machine monitor
VMS	vehicle management system
VTOL	vertical take-off and landing

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I. INTRODUCTION

A. SOFTWARE-DEFINED AVIONICS AND THE FVL PROGRAM

The concept of *software-defined* avionics and mission systems is an emerging field with great promise for reducing size, weight, and power-consumption (SWAP), and life-cycle costs for modern aircraft, while simultaneously increasing reliability and providing new capabilities. It is a natural outgrowth of existing Integrated Modular Avionics (IMA) architectures introduced to many production aircraft over the course of the last decade, and is often referred to as Second-Generation Modular Avionics (IMA2G). First-generation IMA combines many system functions using shared processing resources but only makes limited use of virtualization to abstract (and thus eliminate) hardware components. Even so, the application of IMA-architecture to such aircraft as the Boeing 787 and Airbus A380, has demonstrated the ability to “reduce electronic control unit cost, improve the commonality of parts, minimize the number of computing modules, and reduce wiring, number of connectors and weight” (Jakovljevic & Ademaj, 2013, p. 1). The development of IMA2G is an attempt to continue progress along those lines via extensive virtualization and the convergence of critical vehicle management functions within a logically partitioned, software-defined, network computing environment.

The promise of second-generation Integrated Modular Avionics has made it an attractive avenue of interest for the Department of Defense’s Future Vertical Lift (FVL) program. This ambitious initiative seeks to replace the current Army, Navy, Coast Guard, and Air Force rotary-wing fleets with an advanced new rotary-wing platform scalable from lightweight scout/utility aircraft to ultra-heavy transports (Defense Industry Daily, 2013). The resulting FVL Family of Systems (FVLFS) will include, manned, unmanned, and *optionally manned* aircraft, and all will share a “common open-systems” avionics architecture, intended to allow seamless interoperability (U.S. Department of the Army [USA], 2011, p. 1). In short, the FVL program’s Initial Capabilities Documents (ICD) describes a sum of characteristics unlike anything flying today, or even on the immediate

horizon. It seems reasonable then to propose that the optimum avionics architecture for such a system may *also* be beyond anything flying today.

B. PROBLEM STATEMENT

The majority of military aircraft in service today with U.S. Joint Forces are burdened with heavy, bulky, inefficient and often unreliable avionics and mission-systems designed under a Federated Architecture Model. The FVL will have to do better, if it is to live up to its lofty goals. The ground-up, fleet-wide reinvention of rotary-wing aviation proposed by the program is indeed a golden opportunity to break free of present limitations—and do so in a cost-effective manner.

Though the benefits of pursuing advanced IMA2G architectures in the civil aircraft field have been discussed in the literature, application to military systems has remained largely unspoken. We seek to address this shortcoming, within the specific context of the FVL—which may perhaps be the most significant aircraft-development program of the coming decades.

C. PURPOSE OF THIS PAPER

This thesis explores projected benefits of IMA2G and how they align with the desired characteristics and capabilities of the DOD’s next-generation helicopter fleet. We will also attempt to project upon possible downstream implications (both advantageous and otherwise) on FVL operations and support, based on the adoption of IMA2G. The intent is to develop a timely and relevant analysis and conclude with recommendations for development of FVL’s Joint Common Architecture (JCA).

D. RESEARCH QUESTIONS

This thesis will focus on answering the following questions:

- How might software-defined avionics and mission systems help achieve key operational requirements listed within the Future Vertical Lift Family of Systems ICD?
- Would an IMA2G-configured FVL Family of Systems be suitable for employment as envisioned by the DOD’s concept?

- What is the current level of technological risk associated with committing to an IMAG2-based systems architecture for FVL?
- Given the potential impacts, as well as the potential risks, is IMA2G (software-defined avionics)—the right fit for the FVL program?

E. ORGANIZATION OF THIS PAPER

The analysis of the advanced avionics architectures as applied to the FVL program will proceed as follows:

- Review As-Is state: The Federated Model, IMA.
- Introduce: IMA2G
- Survey: challenges to IMA2G implementation.
- Introduce: Future Vertical Lift program and proposals
- Survey: Joint Common Architecture (JCA) – current research directions
- Findings: technological maturity/development risk for IMA2G
- Findings: alignment comparison between IMA2G characteristics and FVL desired outcomes.
- Synthesis and Projection: operational vignette
- Conclusion: recommendations for the development of the FVL JCA

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II. LITERATURE REVIEW

A. TECHNOLOGIES

The history of aircraft avionics may well have begun with a simple lead weight, suspended on the end of a short length of cotton twine. This arrangement formed the rudimentary turn-and-slip indicator on a 1909 Wright Flyer, and within certain limits, it worked well enough (Curran, 1992, p. 7). Over subsequent decades, successive generations of technology have provided far more accurate and capable airborne systems, but that progress has been accompanied by its own ever-increasing trade-offs. The size, weight, power-consumption (SWAP) growth associated with complex, on-board equipment logically works in opposition to any efforts at increasing aircraft range, speed or payload. In multiple studies, it has also been convincingly correlated with swelling unit acquisition-costs (Dryden, Britt, & Binnings-Depriester, 1981), and support/maintenance challenges (USAF Science and Advisory Board [SAB], 2011).

1. The Scope of the Challenge

With the advent of digital technology and integrated circuit microprocessors, the focus of aircraft avionics development turned increasingly toward software. A 2009 NASA report on the increasing complexity of avionics software explains that “in a period of forty years, the percent of functionality provided to pilots of military aircraft [through software] has risen from 8% in 1960 (F-4 Phantom) to 80% in 2000 (F-22 Raptor) ... The F-22A is reported to have 2.5 million lines of code” (Dvorak, 2009, p. 30). Despite the perception that software is faster and less expensive to develop than commensurately complex hardware, this upward-trend in code-derived functionality has done little or nothing to arrest costs. According to a paper published in 2009 by Navy analyst Henry Eskew, inflation-adjusted fly-away costs for fixed-wing fighter aircraft increased 600% from the Korean War vintage F-86 Sabre to the 80’s-delivery F-18C. (Eskew, 2000, p. 211) By the early 1990s, data from contemporary military aircraft acquisition programs indicated that up to 50% of program costs were related to avionics. (Curran, 1992, p. 7). There is no indication that this upward trend has abated. Meanwhile,

sustainment and service-life-extension phases helped perpetuate a vicious cycle. Expensive aircraft require long-service lives to justify their development costs and hold the line until their replacements achieve full operating capacity. In order to facilitate that long service life, they must be built from the outset with redundant capacity and leading-edge systems—which of course, make them more expensive to begin with.

2. Modularity and the Federated Systems Approach

Most aircraft in current U.S. military service today feature avionics built along a Federated Systems Model. This architecture dates back to the late-Vietnam era, and grew out of an approach described as “Form, Fit, Function” (Helfrick, 2000, p. 315), which was intended to contain costs and streamline maintenance. The analogy to the household lightbulb detailed in Albert Helfrick’s *Principles of Avionics*, provides a ready illustration. It is easy to replace a failed light bulb with a new one or even a new type of light bulb because prevailing standards ensure that the socket dimensions are the same, and the current-draw within limits. The “form” and “fit” are compatible, and the “function” is specified within the standard in terms of output – not how that output is achieved within the unit itself. Clearly, an LED “bulb” produces light in a completely different manner than an old incandescent bulb, but the standards governing light sockets or household electrical wiring did not have to be re-written to accommodate the new technology (Helfrick, 2000, p. 316). Consequently, one does not have to re-wire one’s home in order to switch to new lightbulbs, reducing cost of ownership.

In terms of federated aircraft avionics, these standardized, interchangeable “light bulbs” are LRUs, or Line Replaceable Units. LRUs are the so-called “Black Boxes” that make up individual function-based avionics-components. The “line-replaceable” appellation requires three things:

- The component can be removed or installed by a single maintainer with minimal or no tools.
- A replacement LRU can be installed in the place of a failed unit without extensive testing or calibration.
- The LRU itself must be sufficiently rugged to endure rough handling prior and during installation. (Helfrick, 2000, p. 315)

In the Federated Model, the arrangement of LRUs mirrors the functional decomposition of a given aircraft's avionics suite. Each function-area will be served by a series of interconnected devices that perform sub-functions in series. Most of these devices are micro-processor controlled, and as many as practical are built into LRU-form, to facilitate maintenance, and simplify airframe design. *Replication* and *coordination* are hallmarks of Federated Systems. Standardized form, fit, and function prevails down to the level of physical interface between sub-components. *Integration* between functional branches is intentionally limited, and generally only occurs at a very high level.. Processing resources are not shared.

There are advantages (Hagen, Hurt, & Sorenson, 2013) to this loose federation of compartmentalized systems:

- There is no single point of failure for the entire system.
- The performance and reliability of a functional branch is not dependent on the system as a whole, simplifying both certification and trouble-shooting.
- The need for high-performance computing assets is reduced, since system tasks are distributed across many individual processors.

These advantages, however, are mitigated (Fuchsen, 2009) by some notable drawbacks:

- Lack of integration between functional branches means that each branch has *many* potential single points of failure.
- Decomposing the system into standardized LRU's increases wire-count, system weight, and power-consumption, and inhibits efficient resource pooling.
- Unneeded memory or processing capacity in one functional unit or branch is essentially "trapped" – it cannot be leveraged to increase the performance of another unit or branch which may be over-burdened at the moment. As a result, a large amount of excess capability must be designed in to every component from the outset, increasing cost, complexity, and weight.

Perhaps the most salient shortcoming of the federated systems model (as it has historically been implemented) is the fact that "Form, Fit, and Function" was only applied as far as the physical level. Differing network protocols, bus connections, and

software languages limited reuse across platforms. This means that, in practice, the majority of LRU's are unique components, specific to a single type-model aircraft. SYSGO AG researcher Rudolf Fuchsen describes the resulting impact: "The increasing number of separate devices, each with its own development, certification and update process and the need to maintain spare parts for all these devices in all configurations became more and more a logistic and economic problem." (Fuchsen, 2009, p. 7.B.5-1)

For a deployed military force, reliant on the support of complex aircraft, maintained in austere forward environments, such "economic" problems can easily translate to operation shortcomings.

3. First-Generation Digital Data Bus Standards

With the advent of micro-processor-equipped Line-Replaceable Units in military and civil aviation, it was clear that a standardized network protocol was required to allow the dispersed system components to exchange data. The military solution was designated MIL-STD-1553B. First conceived in the late sixties and fully implemented by 1973, this standard describes a half-duplex digital data bus utilizing time-division multiple-access (TDMA), command-and-response protocol between up to 31 remote terminals (IE: LRUs or other system components). Communications are regulated by dual-redundant bus-controllers with dual-redundant bus cables that specify the sending unit and the receiving unit for each transaction. A minimum throughput of 1 Mbps (megabit-per-second) was called for. ("MIL-STD-1553," n.d.) If more than 31 terminals are required, separate 1553B data buses are added, and linked via controlled gateways.

Envisioning more modest requirements and wishing to keep costs in line, the civil aviation sector arrived at its own 1st-generation standard: ARINC 429. This schema did without the multiplexing specified in the military standard, relying instead of parallel communication paths between all networked devices for separate sending and receiving channels. This one-way data-bus architecture limited the speed and throughput, and could only integrate 20 devices on a single network backplane. The double-weight of wiring required for separate send and receive channels also contributes to system overhead – a shortcoming avoided by the 1553's time-division multiple-access (TDMA)

communications protocol. Even with these inherent limitations, the 429 bus was broadly adopted and has remained a common standard. The follow-on technology, ARINC 629, developed by Boeing in the 1980s, finally adopted TDMA with collision avoidance, but does without the 1553B's bus-controllers by employing priority message algorithms. (Curran, 1992, p. 22)

The development of the both civil and military digital data bus standards paralleled the evolution of ground-based network computing and there was close interaction between the emerging fields. Fiber-optic transmission media was subsequently integrated into both (the revised MIL-STD-1773 was the result), increasing data throughput to as much as 50 Mbps.

As network throughput increased and parallel advances were made in processor speed and memory capacity, aircraft system designers were tempted to begin integrating more capability into fewer and fewer discrete hardware modules. The SWAP advantages of integration still had to be balanced, however, against the ruggedness and ease-of-maintenance afforded by loosely federated modular architecture. These seemingly divergent strategies lead eventually to the development of an entirely new model in the 1990s: Integrated Modular Avionics or IMA.

4. Integrated Modular Avionics (IMA) – Generation One

How exactly can an avionics system be both integrated *and* modular? The key concept is the LRM, or Line Replaceable Module. This differs from the previously described LRU inasmuch as it is a *generic* processor, capable of performing a variety of functions depending on installation and software. (Curran, 1992, p. 24) Otherwise, the standardized form-factor concept from the LRU is retained, although the intent of IMA architectures is to co-locate many LRMs in a central location (advantageous to the design of the aircraft) and link them upon a shared backplane. Connectivity to the distributed sensors and effectors is provided by Ethernet-based fiber-optic cable network. The architecture allows for what European researchers Mirko Jakovljevic and Astrit Ademaj describe as “embedded resource sharing” (2013, p. 7D5-1). In addition to the SWAP

benefits of such an arrangement, they also assert that IMA “supports design of new integrated functional capabilities which could not be implemented in a federated system.”

Given the real-time (or near-real-time) performance requirements present in many aircraft avionics and mission systems, *time-partitioning* of some order determines the extent to which resource-sharing can be applied. Effective time-partitioning provides for efficient multi-tasking with deterministic Quality of Service (QOS) provided to all concurrent processes. In absence of adequate prioritization controls (including memory), a shared processing environment might allow multiple low-or-medium-priority functions to dangerously draw resources away from the smaller subset of mission-critical or safety-of-flight functions.

The issue of adequate time-partitioning and guaranteed QOS for high criticality functions led to the development of the ARINC 653 standard, initially released in 1996 (as a joint project of Boeing and AEEC). This specification describes a Real Time Operating System, with associated Application Executive (APEX) and Application Programming Interface (API). The API calls for 51 routines, allowing time and space (memory) partitioning, health monitoring (error detection and reporting), and communications via “ports.” (IEEE, 2008, p. 14). Individual APIs have been developed for both C and Ada languages, to allow use in both military and civil applications.

With ARINC 653 providing for deterministic cross-functional resource-sharing, another standard, ARINC 664 describes the way nodes within the network are connected. Also known as AFDX (Avionics Full-Duplex network), ARINC 664 is a profiled, switched Ethernet-based network standard for high-speed digital avionics communications. Utilizing these two standards together, IMA architecture was implemented by Airbus in the A380 passenger liner. As described by Jakovljevic and Astrit Ademaj, the system “replaces multiple LRUs by a smaller number of more generic Core Processing and Input Output Modules (CPIOMs) integrated into an Avionics Bay sharing the power supply and the communication connection.” (Jakovljevic & Ademaj, 2013, p. 7.B.5-2) The CPIOMs consist of a physically distinct CPU (running AFDX) and various I/O modules (all implemented as LRMs) that provide tailored interface with

various peripherals serviced by the module (IE: sensors, displays, control actuators, etc.). The CPIOMs are connected via a star-topology AFDX network. (See Figure 1).

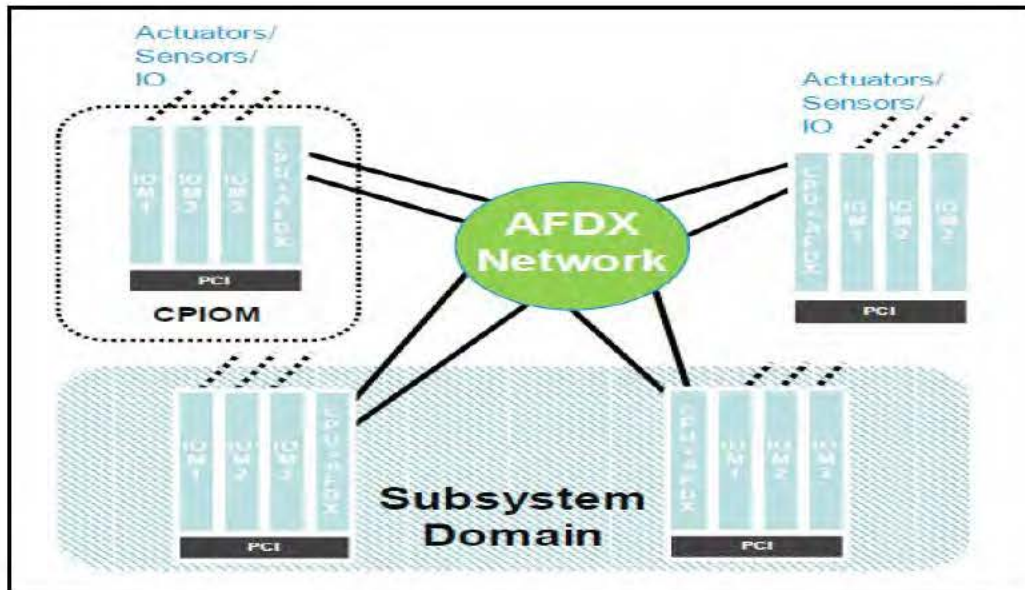


Figure 1. Airbus A380, domain-based IMA
(from Jakovljevic & Ademaj, 2013)

Apparent from this description: resource-pooling in the Airbus A380's IMA architecture is not system-wide. The number of stove-pipes has been greatly reduced however by incorporating many individual functions into just three subsystem domains: “cockpit (electrical flight control, communications and warning); cabin (air conditioning and pneumatics); and utilities, including energy, fuel functions and landing gear functions.” (Ramsey, 2005) Rockwell-Collins, the firm that designed the system claims that 100 unique LRUs were eliminated as a result of functional integration (Mairaj & Tahir, 2014, Table 4).

A somewhat more aggressive application of the IMA principals can be found in the Boeing 787 “Dreamliner.” Rather than domain-based partitioning of computing resources, the 787's architecture implements a Common Core Systems Approach (CCS), where the entire spectrum of assigned domains is serviced by a single, Common Computing Resource (CCR) consisting of multiple General Processing Modules (GPM) –

which are all identical LRMs – and a minimal number of Application Specific Modules (ASM)s linked via an AFDX backplane. (See Figure 2.)

The key enabler of this and other IMA systems is the distributed network of standardized Remote Data Concentrators. RDCs act as a connection point where discrete, or analog signals from I/O peripherals are converted for transmission within the AFDX Ethernet network. They are located in close physical proximity to the sensors or other devices they serve, and one RDC can serve as many devices as its ports and processing capacity allow. This eliminates the signal corruption issue of sending non-digital information across long-transmission lines, and combats latency by off-loading the signal-conversion task from the centralized CCR. (Jakovljevic & Ademaj, 2013, p. 7D5-5). Of note, RDC's will also allow the re-use of older digital devices designed for the legacy ARINC 429 network, if such is desired. (For DOD Applications, where weapon systems have long been standardized under MIL-STD-1553B, the use of such RDC's is a vital enabler for integration.)

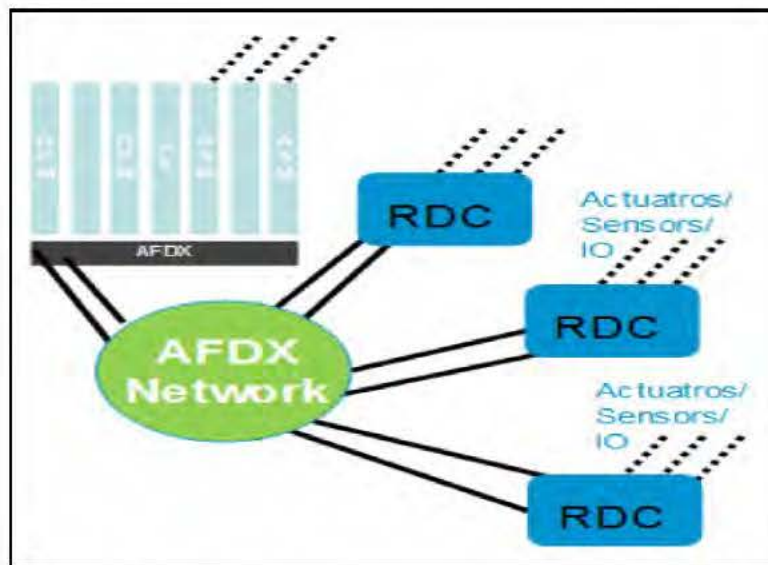


Figure 2. Boeing 787. CCS-based IMA (from Jakovljevic & Ademaj, 2013)

According to Boeing press reports, system engineers on the 787 were able to integrate 80 different functions—from anti-icing systems to passenger Internet access—while at the same time, eliminating over a hundred unique LRUs. (Ramsey, 2005) Furthermore, data fusion and sharing across domains allows for enhanced on-board

diagnostics, event-logging, and maintenance reporting. Flight crews are provided with Electronic Flight Bags (EFBs) which are fully tied into the aircraft's navigation equipment and displays and communication's suite. In other words, the aircraft's avionics system is now capable of performing much of the integration and processing feats that pilots, flight engineers and maintenance personnel previously had to do themselves in converting data to information to understanding, and finally, to action.

5. Military IMA

The development of IMA architectures has not been confined to civil aviation. The F-22 Raptor's avionics architecture was built along a domain-based IMA approach that technically predated that used in the Airbus A380. The aircraft features two separate Common Integrated Processors (CIPs) to provide centralized computing resources, split across three functional domains: Mission Management, Sensor Management, and Vehicle Management. (Spitzer, 2001, Chapter 32) Each CIP is actually a cluster of individual, modular processing units, with identical form-factor, but differing capabilities. Seven different types are employed to control the full set of domain functions. Up to 66 of these processing cards can be installed in each self-contained CIP rack, but currently 19 slots remain open in CIP #1 and 22 are unused in CIP #2, allowing for future growth. Provisions were made within the airframe for the installation of a third CIP, should that become necessary (Lockheed-Martin, ND).

Much of the processing power of the F-22 (and other modern tactical aircraft) is dedicated to presenting high-fidelity, graphic-intensive cockpit displays to the pilot. MIL-STD-1553 data busses offered inadequate throughput for such data-heavy applications; indeed, fourth-generation fighters with glass cockpits, such as the F-16 and F-18, had been forced to rely upon a patchwork of multiple 1553 busses to achieve the necessary capacity. (Kopp, 2001) At the same time, the newer, faster, fiber-based 1553 standard (MIL-STD-1773) did not offer the deterministic isochronous performance that the F-22 design team needed in order to integrate time-critical functions into the common avionics network. At the time, ARINC 653 (AFDX) was still in development (by Airbus), and Lockheed decided to go with another emerging standard: IEEE 1394, better known by its

consumer-electronics trade name “Firewire.” This solution provided the necessary performance and characteristics but has not achieved any wide-spread use in other aircraft besides the F-22. Subsequent developments of IEEE 1394 have demonstrated that gigabit transfer rates are possible (Baltasar & Chapelle, 2001, p. 15), and it may yet emerge as an important standard for military avionics, but enthusiasm for Firewire seems to have cooled in the last decade—perhaps because of the success of AFDX in the Airbus A380/350, and Boeing 787.

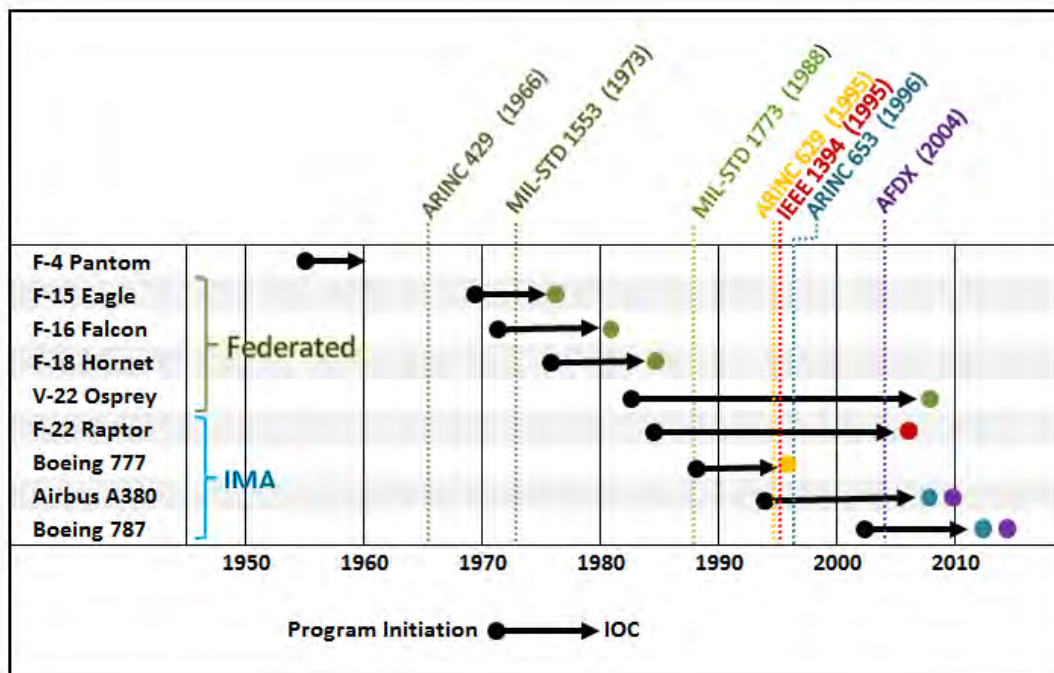


Figure 3. Timeline: avionics standards versus aircraft technology adoption

B. SIZE-WEIGHT-POWER BENEFITS OF IMA

With the recent proliferation of IMA-style avionics in commercial aircraft, it has finally become possible to quantify the size-weight-and-power reductions that are typically achieved with such an architecture. A 2014 study by two Pakistani researchers, Aamir Mairaj and Rohail Tahir, compiled manufacturer-supplied data from twenty-eight different aircraft to determine what, if any, real gains had been realized. A few of these aircraft, such as the Boeing 787, were designed from the ground-up as IMA platforms but had a history of very similar aircraft from which to draw comparisons. The majority of

study subjects, however, were aircraft that had initially been equipped with federated systems, and then later upgraded to IMA. The results demonstrated conclusively that the logical efficiency of deconstructing the domain-stovepipes and sharing system resources translates into very real SWAP benefits. (Mairaj & Tahir, 2014) Select data from the study are depicted in Table 1.

Table 1. SWAP Benefits for IMA (after Mairaj and Tahir, 2014)

PERCENTAGE VOLUME REDUCTION		LRU ELIMINATED	
aircraft	volume reduced %	aircraft	number eliminated
Boeing 777 ER	50.0%	Boeing 787	100
Airbus A380	50.0%	Airbus A380	100
Rafale	50.0%	Embraer 170/190	15
Cessna Citation	40.0%	Raytheon Hawker	13
Challenger 601	28.3%	Challenger 601	15
Falcon 20	28.3%	Falcon 20	15
King Air 350	50.0%	King Air 350	15
King Air 300	28.3%	FD 728	14

WEIGHT REDUCTION		POWER REDUCTION	
aircraft	weight shedding (lbs)	aircraft	% power reduced
Boeing 787	2000	Boeing 777 ER	50
Cessna Citation	300	Rafale	60
Embraer 170/190	550	Challenger 601	38
Gulfstream G350	300	Falcon 20/50	38
Raytheon Hawker	341	King Air 350	38
FD 728	462		
Challenger 601	500		
Falcon 20	340		
King Air A350	100		
King Air 300	348		

Mairaj and Tahir summarized their results as follows: “The analysis reveals that in all these projects SWAP efficiency was achieved: a size reduction ranging 28.28 %–50 %, a power reduction ranging 38%–60 %, and a weight reduction ranging 25 %–50 % was attained. Moreover, the transition appears to be more advantageous on large-size aircraft” (para. V.).

It follows intuitively that the more complex an aircraft is (in terms of desired avionics functionality) the more opportunities exist for component integration and resource-sharing; thus is no surprise the biggest “gainers” in Mairaj and Tahir’s survey are the large airliners (Boeing and Airbus) and the multi-role fighter (Dassault Rafale). Logically, the ratio of an aircraft’s dry, empty weight to the weight of its avionics systems would determine what sort of performance gains an aircraft might see from a given reduction in the latter. The larger the ratio, the more significant the effect.

Medium-size, multi-role military aircraft (such as the Rafale, or more germane to this thesis, the FVL) likely have the highest such ratio of any manned platforms flying today. The implication is that this class of machinery stands to gain the most by transitioning to an advanced integrated architecture.

C. INTEGRATED MODULAR AVIONICS—GENERATION TWO

Despite the demonstrated advantages of IMA-based systems and the clear success of the Boeing 787, the Airbus A380/A350, there is ample room to develop follow-on architectures that move beyond these first-generation designs and achieve even greater SWAP gains—primarily through extensive virtualization. In an ideal Second-Generation Integrated Modular Avionics (IMA2G) system, there are no LRUs or even physical ASMs. (See Figure 3.) An aircraft-wide network of Common RDCs would link sensors and effectors to the digital data bus, and application specific *software* modules—virtual ASMs—reside and carry out their tasks within an abstracted environment created by an avionics “cloud” of GPMs. The total aggregate resources of that cloud would be available for subdivision into any imaginable combination of requirements.

It should be emphasized that the computing and memory resources of the avionics cloud need not physically be located in a central location within the aircraft. In a civil

aircraft, they almost certainly would be, simply for the sake of practicality and maximizing passenger and cargo space. For a military application, where resiliency against battle damage and tight packaging constraints might apply, the Centralized Computing Resources might actually be highly *decentralized* physically. The physical separation of processing from input/output is a key aspect of all IMA, but especially the proposed second-generation standard. For that reason, IMA2G is sometimes referred to (or associated with the concept of) Distributed Modular Electronics, or DME. (Fuchsen, 2009)

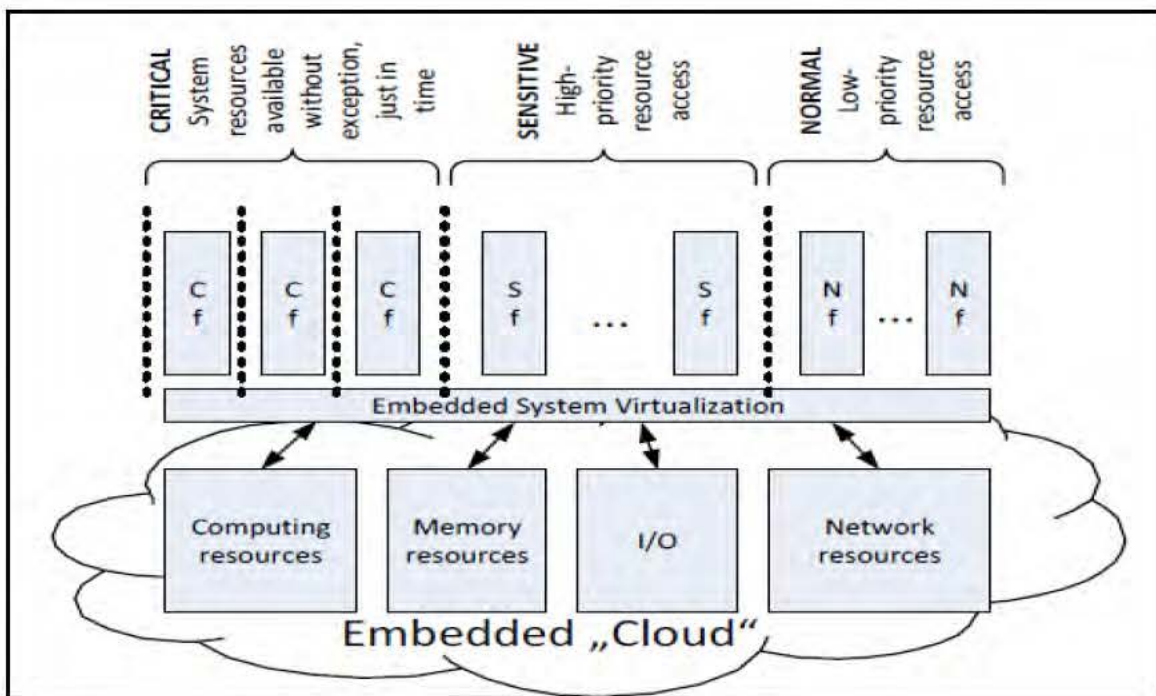


Figure 4. IMA2G - Distributed Embedded System Virtualization
(from Jakovljevic & Ademaj, 2013)

IMA2G encompasses a wide range of technologies and approaches, with myriad potential benefits. Most obvious is the chance to build further upon the SWAP and life-cycle cost reductions already evident where first-generation IMA has supplanted federated systems. More significant perhaps in the long term, however, is the opportunity to change the way aircraft (especially military aircraft) are designed, tested, certified, operated, maintained, and re-developed.

1. Challenges

Current challenges to advanced IMA implementation are well-documented. (Jakovljevic & Ademaj, 2013; Fuchsen, 2009; Wolf, 2008, etc.) For the purpose of this study we will focus on five specific areas:

- High-speed networking—required to connect distributed, embedded processors.
- Multi-Core processing—required to facilitate high-performance system demands.
- Secure virtualization—to enable reliable functionality within the avionics cloud and defend against malicious agents.
- Open standards software integration—to streamline development.
- Model-based development, verification and certification—to ensure that the right system is built for the requirements, and that testing and certification delays do not impede system life-cycle.

D. CURRENT IMA2G INITIATIVES

1. SCARLETT

According to their organizational website, Project SCARLETT is a European consortium with members from 39 countries, organized under the auspices of the EU's 7th Framework Program (FP7) for advancing research in innovative high-tech fields. SCARLETT is said to stand for "SCALable and ReconfigurabLe Electronics plaTforms and Tools." Their stated goal is to bring about the next generation of Integrated Modular Avionics. Since 2008, they have been perhaps the most vocal driver of research in the field. Indeed, the term IMA2G used throughout this paper seems to have been coined by this group, and it strongly associated with them. By no means, however, do they hold a monopoly on the concept. SCARLETT researcher Rudolf Fuchsen describes the bottom-line of what they seek to achieve with their work: "reduction of development and maintenance costs, reduction of certification costs by means of incremental certification, reduction of energy costs and an increased availability." To that end, he further identifies seven areas of focused research. (Compare these to the challenges listed in the prior section):

- Separate I/O From Computing Modules.
- Support Increased Computing Performance.
- Provide Abstraction Of Platform Level Services.
- Implement Reconfiguration Mechanisms.
- Provide Integrated Processes And Tool-Sets.
- Technological Survey Of Packaging Solutions.
- Support Definition Of Associated Standards. (Fuchsen, 2009, p. 7.B.5-2)

2. FACE

The Future Airborne Capabilities Environment (FACE) is a public-private-sector consortium, organized in 2010 for the express purpose of defining a new, open, avionics standard for airborne military systems. (The Open Group, n.d.)” FACE Consortium members are a “who’s who” of the U.S. aviation and avionics segment, including Lockheed-Martin, Boeing, Bell Helicopter, Sikorsky, Honeywell, Rockwell-Collins, etc. DOD partners, meanwhile, include Navy Air Systems Command (NAVAIR) and the Program Executive Office (PEO) for Army Aviation. In other words, FACE appears to have the both the resources and the influence to truly establish a broadly-supported standard for a Modular Open Systems Architecture (MOSA). Although the term “IMA2G” does not appear in the group’s self-promotion materials, their espoused goals of developing an open, modular, standard for horizontal and vertical software interfaces in military identifies them as part of the same trend-line. Their technical standard is currently in its version 2.1 iteration, and divides the computing environment in five layers: Operating System Segment, the Input/Output Services Segment, the Platform-Specific Services Segment, Transport Services Segment, and the Portable Component Segment.

E. FVL PROGRAM

In October 2008, the Future Vertical Lift program (FVL) was announced; covering a number of individual development efforts aimed at bringing the next generation of military helicopters (or helicopter-like aircraft) into existence. This

initiative is a result of the belated realization that the DOD's current fleet of vertical lift aircraft has been historically under-developed compared to fixed-wing counterparts, and will not meet the performance, payload, availability and survivability metrics required for sustained world-wide Joint Forces operations. Ultimately, four different airframes of varying sizes (light, medium, heavy, and ultra-heavy) are envisioned, replacing some 4000 OH-58s, OH-6s, H-60s, AH-64s, CH-47s and H-53s in service with the U.S. Army, Navy, and Air Force. (Defense Industry Daily, 2013)

1. FVL ICD: Desired Attributes and Outcomes

A draft copy of the Initial Capabilities Document (ICD) for the FVL Family of Systems was released in December of 2011 and finalized seven months later in July 2012. Table 2, below, summarizes the desired performance parameters listed in the ICD, which represent an order-of-magnitude increase over what current DOD rotorcraft are capable of. Essentially, Future Vertical Lift aircraft will be expected to fly roughly *twice as fast, twice as far*, while carrying the same or greater payload. (Jeffrey, 2012)

Table 2. Threshold/objective performance requirements for FVL variants
(after USA, 2011)

	Speed (cruise)	Combat Radius	Payload (int/ext)	Passengers
JMR-Light	230-300 kts	265 nm*	2,000-4,500 lbs	4-6
JMR-Medium	230-300 kts	265 nm*	6,000-20,000 lbs	11-24
JMR-Heavy	230-300 kts	265 nm*	16,000-30,000 lbs	33-44
JMR-Ultra	230-300 kts	350 nm*	40,000-72,000 lbs	100-120
*Defined as "unrefueled distance w/2.0 hr loiter (full combat load at 6k/95° F)"				

This includes an emphasis on the ability to operate in hot/heavy/high conditions. The combat radius listed is based on 95° F day at 6000 ft pressure altitude, with a full combat load and a two-hour loiter time in the mission area. To extend that further, all variants are to be capable of aerial refueling, making strategic self-deployment a reality. Meanwhile, to ensure survivability, state-of-the-art countermeasures must be included in all airframes, and the design should incorporate lessons learned from combat losses in Iraq and Afghanistan.

Summarizing FVL requirements, The ICD lists the following as desired attributes and outcomes:

- **Range/Payload.** FVL FoS platforms must cover greatly expanded JFOR areas of operation in worldwide conditions with payloads responsive to mission requirements.
- **Flight Performance** ... platforms will have the ability to minimize transit time, solve mismatches in flight capabilities of vertical lift assets, enable time-critical MEDEVAC missions, conduct maneuvering flight to evade enemy fires and operate in complex terrain.
- **Deployability** ... conduct operational maneuver from strategic distances.
- **Shipboard Operation** ... USN, USMC, USCG and SOF FVL FoS platforms will be shipboard compatible ... USA and USAF FVL platforms will be shipboard capable ... Operational performance shall not be degraded by electromagnetic environmental (E3) effects.
- **Weapons** ... capable of integrating multiple Joint weapon types to rapidly configure for volume fire, precision and area effects weapon types and mixes.
- **Sensors** ... employ an array of multi-spectral, multi-function sensors ... fully integrated with targeting, navigation, and aircraft survivability equipment to effectively target and enable terrain flight during night and in Degraded Visual Environment (DVE).
- **Teaming.** Applicable FVL FoS platforms must control unmanned systems up to Level of Interoperability (LOI) 5. Unmanned or optionally-piloted versions of FVL variants must meet Joint interoperability profiles for Unmanned Aircraft System (UAS) Ground Control Stations (GCS).
- **Enhanced Situational Awareness** ... provide an integrated common air and ground picture to the pilots and crew, with automatic reporting ...

[internal and external] ... of threats, inclement weather, and other hazards encountered enroute.

- **Crew Station** ... provide a fully-integrated crew station enabling mission-focused operations [and] Joint mission planning systems compatibility, automation of critical battle tasks, cognitive aiding and decision making, fused sensor imagery, and interoperable communications/data systems ... minimizing crew workload. FOS platforms will also provide decreased cold start and airborne times.
- **NetCentric** ... comply with the provision of the Net Ready Key Performance Parameter (NR-KPP) per CJCSI 6216.01F. Sensor data ... will be fully compatible with the Future Mission Network (FMN) environment, Joint Service air/ground, allied, civilian (law enforcement-LE and maritime), mission command systems, to include the DOD Information Enterprise Architecture (IEA) and DODI 8320.02.” (U.S. Department of the Army [USA], 2011, p. 3)

Naturally, in keeping with today’s highly contentious budgetary climate, all of these enhanced capabilities are to be delivered along with reduced maintenance/operating costs, increased reliability, extended service-life and a high degree of component commonality between all FVL variants, including an open-systems, modular mission-systems suite.

2. Joint Multi-Role Technology Demonstrator

In an attempt to reduce the technological risk of developing an entire family of aircraft at once, the DOD has established a precursor program focusing on the medium lift platform. The Joint Multi-Role Technology Demonstrator, (JMR-TD) is a competitive development program, funded and administered by the Army PEO for Aviation. Several prototype middle-weight FVL contenders will be sourced from different manufacturers, and evaluated for performance potential and technological maturity. The winner (or winners) will then be awarded follow-on contracts to build aircraft for the Light, Medium, Heavy, and Ultra-Heavy classes within the FVL Family of Systems, using the technology explored in their middle-weight proof-of-concept.

At the time of this writing, the nine initial industry proposals have been down-selected to four. Boeing-Sikorsky’s concept builds upon the compound-helicopter architecture developed for their X-2 demonstrator vehicle; AVX’s proposal is a variation

on the same theme, with twin-ducted fans supplanting a single pusher tail rotor. Meanwhile, both Bell Helicopter and Karem Aircraft are developing advanced tilt-rotor platforms that they hope will be scalable and address some of the operational limitations or shortcomings of the similarly-configured V-22 Osprey. What all designs seem to have in common is multi-mode flight operation that will make fly-by-wire control a virtual requirement—a technology that is still novel among rotary-wing aircraft.

In the event it is determined that no single platform can successfully be scaled across all weight classes and still meet performance requirements, more than one concept may be accepted. Regardless of the aircraft layout however, all FVL aircraft are to feature *a common, avionics architecture*. Clearly, this will require a flexibility that would be difficult or impossible to achieve with a traditional federated systems model.

The requirement for a common avionics architecture is a reflection of supportability as a major emphasis area within the FVL program. Expected characteristics include “the ability to increase the service rate for aviation mission requests without expanding force structure, [...] open systems architecture [...] reduce fuel consumption and logistics footprint, share common training, education and equipment across the Joint VTOL fleet.” (U.S. Department of the Army [USA], 2011, p. 1)

Initial Operating Capacity (IOC) for the FVL-medium lift variant is conservatively set at 2035, allowing apparently ample time for cutting-edge technology to develop and mature. FVL contenders are expected to be flying prototype JMR airframes by mid-2017.

After the initial phase of competition, which will be focused on aircraft performance deliverables concludes, Phase II will pick up, with evaluation of aircraft avionics and mission systems. This portion is considered a semi-independent development effort, complete with its own program name: The Joint Common Architecture. A Broad Area Announcement (BAA) was issued for the JCA in March of 2014. In June of the same year, development contracts were awarded to Boeing and

Honeywell to build demonstrator modules to prove the feasibility of open-systems software architecture in an IMA environment.

Given that nearly all of the major industry players involved in the FVL and JCA programs also happen to be members of the FACE consortium, FACE standards are likely to figure prominently in the architecture that eventually emerges.

F. BOEING JOINT COMMON ARCHITECTURE STUDY

Within the Sikorsky-Boeing FVL team, Boeing will likely take the lead role in avionics, mission-system and VMS development. The Seattle-based company's experience with the highly integrated architecture of the 787 airliner, lends credibility to their efforts and suggests that some sort of advanced IMA architecture will find its way into their FVL design. The author of this study conducted an interview in September 2014 with Tom Dubois, JMR/FVL chief systems architect at Boeing's military aircraft division, and gained some detailed insights on the program. Most relevant perhaps to this thesis is the fact that no firm decision has been made on the customer side about the extent to which current IMA trends toward virtualization, centralized processing, and distributed real-time embedded systems will be incorporated into the Joint Common Architecture. The ICD and other government documents only describe the capabilities sought, not the means by which they should be achieved. The challenge for Boeing and other contractors is to strike a balance between accomplishing the DOD's ambitious objectives on one hand, and yet not going further with novel technology than their customer is comfortable with.

Du Bois was able to confirm that Boeing is indeed pursuing an approach that will blur the line between electronics and the air vehicle itself. In their concept, the JCA will definitively cross over into domains traditionally considered vehicle management, IE: "Things that touch the flight controls." Beyond addressing size-weight-and-power concerns, achieving this level of integration, Du Bois believes, will help facilitate the desired level of interoperability and interchangeability between manned and unmanned FVL variants. (T. Du Bois, personal communication, September 25, 2014). He also expressed confidence that advances in technology will allow the data-rates, processing

and through-put necessary for highly-centralized processing. “For the foreseeable future,” he explains, “there is still going to be a need for some form of data concentration” – IE: Remote Data Concentrators, to perform translation and network gateway functions for devices on the periphery of the network that may not be directly compatible.

1. What Is the Joint Common Architecture?

It is easy to misunderstand exactly what Boeing-Sikorsky and competitors at Bell and Honeywell are trying to create in response to the JCA BAA. “No one is going to build a JCA for the FVL,” explained Dubois (T. Du Bois, interview, September 25, 2014). That is because the JCA is not intended to be a specific set of hardware. Rather, the intent is to prove that an open-systems architecture, based perhaps on FACE technical standards, can enable a cost-efficient, modular approach to developing and fielding hardware and software. According to the Boeing system’s architect:

- The JCA is functional decomposition
- The JCA is referential, conceptual
- The JCA applies “IMA at its very highest levels”
- JCA is more guidance than blue-prints
- JCA encompasses system-developer tools
- JCA utilizes FACE open technical standards
- JCA is to be nominally owned by the Gov’t, while FACE belongs to the industry

If the JCA achieves its goals, the software developed to run on-board systems will be completely agnostic from the underlying hardware and platform. This offers several potential benefits from the perspective of aircraft life-cycle costs.

- Software re-use across different aircraft types could streamline capability acquisition while ensuring seamless inter-operability.
- Hardware re-purposed throughout a single aircraft or across multiple aircraft reduces development costs and shrinks logistical footprint required to maintain deployed aircraft.

- Software development independent of vendors access to the actual system hardware, promotes a competitive design environment, potentially lowering costs and accelerating new capability development.

G. SUMMARY

The technological landscape of aircraft avionics has progressed to a state probably unimaginable to early pioneer aviators. As complexity and costs have increased, several successive strategies have been implemented to improve efficiency. The latest, Integrated Modular Avionics, seems poised to progress to a new, second-generation standard (IMA2G) which will incorporate unprecedented levels of resource-sharing and systems integration, while simultaneously permitting tailored physical distribution of computing assets as dictated by form-factor and survivability. In this chapter, we have explored the evolution of this technology, identified the remaining technical challenges to implementation, and introduced the context within which the rest of this study will proceed: the application of advanced IMA to the Future Vertical Lift Family of Systems.

III. METHODS

A. COMPARATIVE ANALYSIS

The impact of pursuing highly integrated, software-defined avionics architecture for the Future Vertical Lift Family of Systems is certain to be as multi-faceted and complex as the proposed system itself. In order to begin this assessment, a divide-and-conquer approach will be applied, conducted on two separate levels: technological maturity, and suitability/alignment.

1. Technology Maturity Assessment

We will model this portion of the study on the framework provided by the latest (2011) version of the DOD's Technology Readiness Assessment (TRA) Deskbook, as prepared by the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) Table 3. is derived from paragraph 2.4.1 of that document, and provides a template.

Table 3. Skeletal Template for TRA (from Assistant Secretary of Defense for Research and Engineering [(ASD(R&E))], 2011, para. 2.4.1)

1.0	Purpose of This Document
2.0	Executive Summary
3.0	Program Overview
3.1	Program Objective
3.2	Program Description
3.3	System Description
4.0	Program Technology Risks Summary and Readiness Assessment
4.1	Process Description
4.2	Identification of Technologies Assessed
4.3	PM's and SME Team's Assessments of Technology Risk and Technology Demonstration in a Relevant Environment
4.3.1	First Technology
4.3.2	Next Technology
5.0	Summary

Referencing previous chapters of this thesis, the reader should be satisfied that the intended purposes of sections 1.0 through 3.3 of the TRA Deskbook template have been adequately accomplished. The present chapter, likewise, will accomplish the work of section 4.1, “Process Description,” and 4.2, “Identification of Technologies Assessed.” Given that advanced IMA is a broad field with many dependencies, our TRA will be broken down into the major challenge areas previously listed in Chapter II of this study:

- High-speed networking
- Multi-Core processing
- Secure virtualization
- Open standards software integration
- Model-based development, verification and certification

Within each subject area, we describe the need, list the primary issues or difficulties involved, and survey recent or on-going developments. To fulfill the role of Subject Matter Experts (SME)—as called for the TRA methodology—several JCA-program insiders have been interviewed and polled for their technical opinions. In addition, a variety of published sources have been considered, including both peer-reviewed journal entries, and vendor press-releases, were appropriate.

The assessed maturity level of each identified component of IMA2G will be expressed as integer on the standard Technology Readiness Level (TRL) scale, (see Table 4.). A more complete chart (After ASD(R&E), 2011, para. 2.5) with descriptions and supporting details for each TRL is included in Appendix B.

Table 4. TRL Definitions (after ASD(R&E), 2011, para. 2.5)

TRL	Definition
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Component and/or breadboard validation in a laboratory environment.
5	Component and/or breadboard validation in a relevant environment.
6	System/subsystem model or prototype demonstration in a relevant environment.
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations.

2. IMA2G and FVL: Suitability and Alignment

We will first apply a comparative analysis of documented IMA outcomes and desired FVL attributes. Referencing the previously sighted study on SWAP reductions, along with other sources (including interviews with FVL/JCA insiders), against the approved program Initial Capabilities Document (ICD), this portion will focus on the following areas:

- Aircraft Performance/Payload
- Mission Capability/Flexibility
- Manpower/Training
- Development Timeline
- Total Life-Cycle Costs
- Safety and Survivability
- Interoperability with UAS

For each area, we will determine to what extent, if any, an advanced IMA architecture would support achieving the desired metrics. Rather than attempt to extrapolate predicted values, only the basic *character* of the impact will be assessed, using as a baseline the likelihood of a federated systems approach achieving those same results. Ratings will then be expressed on the following five-point scale: *strongly negative*, *negative*, *neutral/indeterminate*, *positive*, and *strongly positive*. Owing to the current lack of a definitive IMA2G architecture installation aboard an operational military rotorcraft, specific predictions would be excessively speculative and of little value. The scope of this part of our inquiry must of necessity be limited to a single, qualitative assessment: how much does the DOD stand to gain by incorporating IMA2G-principles into its next-generation vertical-lift aircraft?

B. SYNTHESIS AND PROJECTION

With the maturity level of IMA2G technology assessed, and the alignment/suitability determined, we will find ourselves in position to develop a meaningful synthesis. The amalgamation of our study findings will be expressed in two forms: first, a risk-versus-reward summary of applying open-architecture, software-defined, highly-integrated avionics into the Joint Common Architecture for FVL; and second, a projected operational vignette depicting how a cyber-physical system of this kind might operate in a plausible future combat scenario.

After completing this synthesis and projection, we will offer our final conclusion. This conclusion will include recommendations on the technical architecture the DOD should pursue for next-generation rotorcraft, controls that can be implemented to reduce the inherent risks of that architecture, and finally, further research that should be done to build on, or validate the recommended approach.

IV. FINDINGS

A. CURRENT CHALLENGES TO IMA2G IMPLEMENTATION

While first-generation IMA architectures represent the current state-of-the-art in aviation today, momentum is building for the emergence of true IMA2G systems. Though clear obstacles remain, recent developments represent significant inroads.

1. Limited Data-Rates and Network Throughput

From a technical feasibility standpoint, the arch-nemesis of centralized processing on large and complex aircraft has traditionally been the rate at which data can be traverse from the boundaries of the system (near sensors and flight controls) to the shared computing resources and back. While critical flight control functions generally consume only modest volume of network traffic, their low tolerance for jitter and time-latency require careful handling. Although digital data bus standards have evolved to supply the requisite quality of service, that task is increasingly complicated by the trend toward ever-greater network traffic. The advanced sensors, external data links, graphical cockpit displays, etc., expected in operational aircraft today are a significant challenge to legacy systems, especially copper-based standards like MIL-STD-1553B. Advanced IMA2G systems will have to realize much higher effective throughput to ensure continued performance over their intended life-cycle.

One promising technology that may contribute is Time-Triggered Ethernet (TTEthernet). This standard, first described in 2005, unifies “realtime and non-real-time traffic into a single coherent communication architecture” (Kopetz, Ademaj, & Grillinger, 2005, p. 1). TTEthernet is essentially three protocols in one, with differing levels of service based on message-type: Deterministic Time-Triggered (TT) traffic, Event-driven or rate-constrained (RC) traffic, and Best-effort (BE) standard Ethernet traffic. TT service maintains the clock synchronization for all devices attached to the network, providing for a “global time [that] forms the basis for time-triggered network properties such as temporal partitioning, efficient resource utilization, parallel processing and precise diagnostics” (Bisson, 2011, p. 5).

Essentially, a standard Ethernet service provides for the bulk of high-volume traffic using standard message formatting. Event-driven messages take advantage of priority handling, (similar in principle to AFDX) while a separate, time-triggered function periodically takes control and ensures the unfettered transmission of sensitive real-time data. The technology was originally introduced by Austrian vendor TTTech, which promised fault-tolerant deterministic transmission of up to 100 mpbs. Subsequently, it has been codified as SAE standard AS6802. Now multiple vendors can be found offering PCI form-factor network end-nodes and switches. Total advertised throughput (for TT, RC and BE) is up to 1000 Mbps.

The apparent advantage of TTEthernet over other “deterministic” Ethernet protocols (such as AXDX/ ARINC 664) is the provision for a baseline of standard 802.3-compatible service. Whereas older deterministic solutions like the ones used in the Airbus A380/250, Boeing 787 and Lockheed F-22 are essentially proprietary network standards that must rely on network gateway devices for data-mapping with regular Ethernet, TTEthernet should allow seamless connectivity for devices not requiring real-time service.

Given the combined attributes of high bandwidth, sub millisecond jitter-rate, and IEEE 802.3 compatibility, TTEthernet/AS6802, seems to offer a workable network backbone on which a distributed real-time avionics environment could be built. Temporal synchronization across the network would allow for parallel processing to occur across physically separated clusters of avionics computers – making an aircraft so-equipped more resilient to battle-damage. So-called “temporal firewalls” (Bisson, 2011, p. 5) could be automatically instituted at the switch or bus-control level in the event of a failure in one or more processing nodes. Basically, the network would go “deaf” during the time-partition assigned to a faulty device.

Despite the promise of TTEthernet, our research has uncovered no present examples of operational military or civil aircraft utilizing the technology. It is however, being integrated into NASA’s Orion spacecraft, (TTTech.com News & Events, 2014) which recently completed its first unmanned test-flights. Boeing JCA System Architect Dr. Tom Du Bois also confirmed that at least one major aircraft development program

that he is aware of is also incorporating the technology (T. Du Bois, personal communication, September 25, 2014). Citing confidentiality, he declined to identify the aircraft or the manufacturer. With regard to Boeing’s own efforts to develop avionics for the FVL, he went on record as saying that time-triggered-Ethernet “or something like it” was a likely candidate—but no decision has yet been made.

It should be noted that outside of aviation, Time-Trigger Ethernet *has* begun to appear in production hardware. The automobile industry, which has been quietly and effectively developing IMA-like architectures in cars since the early 2000s, is a significant investor. German auto-giant Volkswagen has partnered with the originator of TTEthernet (TTTech) through its Audi subsidiary (Plankensteiner, 2012, p. 9). The current Audi A8 sedan incorporates this advanced, deterministic Ethernet backbone in order to facilitate what the company describes as “piloted driving” and “piloted parking,” which is to say, autonomous operation guided by a distributed network of integrated sensors and actuators (Lehner, 2014).

The level of sophistication and safety-critical reliability required of cutting-edge automotive systems should not be underestimated. Rapid product-development cycles and intense competition have led to massive advancements and highly-ambitious goals. With increasingly stringent government and consumer expectations for fuel economy, automotive designers have found themselves battling much of the same SWAP concerns as lead aerospace engineers to pursue wide-spread integration. It is not inconceivable that the industry move to increasingly connected, increasingly autonomous automobiles will make it a larger driver of cutting-edge networking and processing technology than the traditional aerospace/defense sectors within the next decade.

a. TRL Assessment for TTEthernet

Based on the findings of this study, TTEthernet, (AS6802) should be considered a rapidly-maturing technology with the ability to support a highly-integrated, distributed IMA2G architecture. In accordance with the DOD’s Technology Readiness Assessment (TRA) criteria (outlined in Chapter III), it would be appropriate to say it has achieved a TRL rating of 6, or “System/subsystem model or prototype demonstration in a relevant

environment” (ASD(R&E), 2011, para. 2.5). The *system prototype* in question being the Orion space-vehicle. Given the extreme operating conditions inherent to orbital space-flight, and the successful characterization of the flight test, it must be taken that TTEthernet has demonstrated some ability to function in a harsh environment. Naturally, the FVL’s intended environment is nothing like that of a space craft and may introduce other variables (in the form of dust, moisture, or battlefield RF), so this TRL rating must be considered tentative as far as application to the Joint Common Architecture is concerned.

2. Determinism in Multi-Core CPUs

Much of the advances that have been made so far in digital avionics architectures have been enabled by the exponential growth in processing power available from commodity chip-sets. In the last decade, most of that growth has stemmed from the development of multi-core processors, yet current-generation avionics have yet to fully-embrace this technology. There has been debate over how to best harness the performance advantages of multi-processing, while still ensuring strict determinism for high-criticality safety-of-flight functions. As a result, even the most advanced IMA1G architectures have remained reliant upon single-core CPUs, which are rapidly becoming obsolete as a commercial technology. Even though it may be possible to implement IMA2G without the support of multi-core hardware, as a minor consumer in the world-wide marketplace for processors, the aircraft avionics industry can ill-afford to ignore the market trend (Huyck, 2012). Further, there is no doubt that the performance from multi-core processors (MCPs) would greatly facilitate virtualization of resource-intensive applications.

There are two basic ways in which multi-core CPUs could be utilized: Symmetric Multi-processing (SMP) and Asymmetric Multi-processing (AMP). In SMP, each core within the CPU works concurrently on a different process residing within a single partition. When the time allotted to that partition expires, the processes are interrupted and a new set of processes from the next scheduled partition are distributed to the independent CPU cores. In AMP, by contrast, each CPU core works on a process (or a

series of processes) from a different partition, until triggered to interrupt that work and take up a process within the next scheduled partition. As its name implies, *Asymmetric* multi-core CPUs may contain two or more different types of core, optimized for various types of calculations; whereas the individual cores within *symmetrical* multi-processors, are identical and inter-changeable.

Generally, SMP is used when the goal is over-all computational performance enhancement – true multi-thread processing (Walls, 2014). AMP is inherently less efficient, as it only performs concurrent work at the system process level; however, it allows designers to run an RTOS or latency-sensitive program within the same CPU that is simultaneously running a lower-criticality (but perhaps more resource-intensive) process. To further muddle the issue, some contend that real-world performance of AMP systems is actually the same or better than SMP when many cores are present and the scheduling kernel becomes the weak link (Hermeling, 2009). This is because process-scheduling within partitions is simplified in AMP vis-à-vis SMP; IE: only one process is handled at a time from a given partition.

For the moment, AMP appears easier to implement with the current version of ARINC 653 standard, as memory resources shared by the processing cores can be apportioned along partition lines, avoiding conflict over memory address locations (Huyck, 2012). ARINC 653 has no mechanisms to subdivide such resources within a partition according to the number of cores currently splitting the work, so SMP may result in concurrent processes competing for the same memory resources.

It should also be noted that some advanced multi-core designs may combine AMP and SMP to balance the capabilities and trade-offs of each (Walls, 2014). In such an application, a specialized multi-core *within* a multi-core, may be dedicated to AMP, while an array of identical cores on the same chip performs SMP. Such hybrid architecture seems likely to proliferate; thus it is imperative that methods of integrating SMP into ARINC 653 (or follow-on standards) be investigated.

In May of 2014, the Federal Aviation Administration (FAA) released a position paper outlining its concerns for industry adoption of multi-core processors for safety-

critical flight operations. The paper cites features typically built into such CPUs that allow: “shared access to cache or other memory areas, operating systems / supervisors / hypervisors ... and coherency fabrics / coherency modules / interconnects that control all the data transfers between the MCP cores ... via a shared bus.” These features are asserted to have resulted in observable interference between applications running simultaneously on different cores within a processor during testing. The report goes on to say that “If safety-critical applications are to successfully execute on MCPs [multi-core processors], the allowable data latency of each input parameter to an application may have to be analyzed so it is ensured that the applications can cope with the worst case variations in data access times, which should be measured. The overall execution times of applications may have to include allowances for such variations” (Federal Aviation Administration [FAA], 2014, p. 4).

Despite this and other noted concerns, the FAA paper finally provided what some in the industry were waiting for: a roadmap to certification for multi-core processor-based systems consisting of 24 quantifiable objectives in determinism, software and error-handling. Wind River Systems, a long-time leader in RTOS development has since announced that they are working on a successor to their successful VxWorks653 OS (utilized on the Boeing 787) that will be able to take advantage of dual-core silicon. (Wlad, 2014). If this new OS follows the pattern of the VxWorks 7Core product, an RTOS already certified for industrial applications, it could utilize an advanced form of SMP that gains new efficiency by allowing idle processes to be handled during residual, unused time apportioned to the active process. Wind River seems confident that they will be able to deliver this capability and still “ensure reliable, interference-free consolidation of multiple applications with different levels of safety criticality on one hardware platform” sufficient to satisfy government regulators (Wind River Systems, 2014).

Independent industry experts, such as David Arterburn, Director of Rotorcraft Systems Engineering and Simulation Center at the University of Alabama at Huntsville, are less-sanguine about the short-term prospects of multi-core processing, pointing to the difficulty of understanding and predicting complex interactions within quad-core chips, which are rapidly replacing dual-cores in consumer electronics. Charged with compiling

the studies of various. Army Aviation PEO-funded working groups researching JCA issues, Arterburn downplayed the significance of the CAST-32 paper, asserting that no multi-core chip installation has actually achieved official airworthiness. He was quick to point out however that the issue will soon come to a head. “Within five years” he predicted, “you won’t be able to buy a commodity single-core processor” (D. R. Arterburn, personal communication, January 22, 2015). Like it or not, industry and government will soon be forced to develop methods of designing and certifying MCP-based systems – and that event-horizon is sufficiently near-term that it will likely be well-sorted by the time any FVL variant is ready to fly in anything beyond experimental status.

In the meantime, the only work-around may be to install multi-core processors and then intentionally limit them to single-core utilization. This deals with the commercial availability aspect, but of course completely defeats the point of having an advanced processor to begin with. It also works against the very principles of IMA, requiring multiple physical LRMs to do the work that a single, fully-optimized module could do. It is also questionable whether simply de-powering all but a single processor on a chip would actually make it legally certifiable. A source consulted by this author, who declined to go on record, related that several recently introduced aircraft (including an army rotorcraft) are current flying with partially-disabled multi-core processors – without any real declaration or sanction.

a. TRL Assessment for Multi-Core CPU Employment in Avionics

Based on the finding of this survey, it is apparent that MCP-integration is a hot-topic in the aviation and avionics industry today. Multiple studies are underway, but both vendors and the government are remaining tight-lipped on the results. Given the lack of demonstrated success, we cannot, in good faith, assign a higher TRL than 4; “Component and/or breadboard validation in a laboratory environment” (ASD[R&E], 2011, para. 2.5). Given the urgency of establishing workable protocols and methods, we are confident however, that the next five years will see significant advances. Even if the Joint Common Architecture must be demonstrated in prototype form without the use of MCPs (or with

partially-disabled MCPs), it seems fairly likely that the FVL program will eventually be able to leverage them.

3. High-Assurance Virtualization

As previously noted, extensive virtualization is the defining characteristic of second-generation IMA; however, there is still debate on how exactly to best implement that hardware abstraction for high-criticality vehicle management functions. Currently, *full virtualization* is the approach with the broadest (non-aviation) commercial use. In this schema, one or more complete, unmodified “guest” operating systems run atop a hypervisor. The hypervisor itself may have direct access to the hardware (in a so-called “bare metal” installation), or may run atop another operating system as a client program. In either case, the virtualized OS has no idea that it does not actually have access to its own processor and memory. Application-level service requests from its processes are passed directly to the real hardware by the hypervisor (or through the underlying OS, if present), while privileged-level commands from the guest OS are intercepted and translated so that they do not exert unfettered control over the processor and memory resources that must be shared with other guests.

In *paravirtualization*, the guest operating systems are installed with modified kernels, making the OS “aware” that it does not have direct access to its own resources. Instead of issuing un-executable calls that must be trapped and translated by the hypervisor, the guest OS kernel issues *hypercalls* that reduce virtualization overhead. This efficiency has a positive effect on performance, but the downside is that the hosted OS’s must be intrusively altered for installation. Though this is easily and affordably accomplished when OS source-code and vendor support is available, it can be a major obstacle to integrating older or proprietary OS’s in the virtual environment. (Windows, for instance).

The corresponding downside for full-virtualization is that hardware requirements are very specific. The guest OS must otherwise be able to run atop the actual underlying hardware. Using such a schema in an IMA architecture would seem to limit the choice of processing hardware and embedded OS’s to those that were natively compatible with

each other. (Most-likely x86-series processors.) This runs completely counter to the idea of using IMA2G to affect cost-savings on system development and life-cycle update. It also does not provide compatibility with the system resource partitioning concept enforced by ARINC 653 (Fuchsen, 2009, p. 7.B.5-6).

The present trend in hardware design is greater built-in support for virtualization, and it is possible that this will eventually allow comparable performance increases to paravirtualization without the need to modify the hosted operating systems.

In the meantime, hardware abstraction in the current IMA architectures relies on paravirtualization. In the Airbus implementations, this is provided by the Virtual Machine Monitoring (VMM) services of the well-established Pike Operating System. Instances of an ARINC 653-standard RTOS run in the abstracted environment, alongside LINUX, POSIX and other supported open-source operating systems. Similar capabilities are also touted by the makers of the Lynx OS 178 RTOS. This particular product is claimed to meet FAA's DO-178B Level A certification standard for safety-critical avionics software "right out of the box" (Lynx Software Technologies, 2015). However, it should be noted that since the introduction of this RTOS, the FAA has introduced an updated standard – DO-178C – which adds five additional parameters to the 66 listed in -178B for "Level A" certification. There is no indication on the maker's website that Lynx OS 178 RTOS has met these revised standards.

a. TRL Assessment for High-Assurance Virtualization

High assurance *paravirtualization* has been used in aircraft avionics, in varying levels of criticality, for at least ten years now, and must be considered a mature technology, or TRL 9. Some SCARLET consortium researchers (Jakovljevic & Ademaj) have asserted that PIKE OS 's Virtual Machine Manager is an adequate solution to the challenge of advanced IMA2G architectures, while others (Kleidermacher & Wolf, 2008) contend that hardware-assisted full-virtualization will likely be needed to deliver fully on the promise of software cost-savings and streamlined re-development. This field however is far less mature, with a TRL level as low as 3: "Analytical and experimental

critical function and/or proof of concept.” Adhering to the most conservative viewpoint, we will accept this latter assessment.

4. High Robustness virtualization

The threat of malicious cyber-attack on the avionics of commercial aircraft must be considered a legitimate concern. Indeed, when the Boeing 787’s IMA architecture was announced to the general public at launch, some observers wondered openly at the wisdom of providing passenger Internet via the same physical computers that hosted the aircraft system controls. Was this not introducing a blatant attack vector into the system? While fears that a determined passenger might somehow take control of an airliner with their laptop computer are completely overblown given the actual architecture of the system, the basic premise is not without merit – especially when one considers the further integration of VMS functions in proposed IMA2G aircraft. For military aircraft, whose mission-systems will host applications of differing classification levels, achieving strong security compartmentalization between hosted OSs in an on-board virtual environment is critical.

Though virtualization has often been touted as a security measure in itself, in reality it is just part of a layered defense system – and one that has the potential to introduce its own security vulnerabilities. While hosted OS’s might indeed be isolated from each other and have restricted access to system resources, they do interface with the hypervisor. If the hypervisor contains exploitable security flaws, (let alone the underlying OS in a paravirtualized scheme), so-called *guest-breakout* is possible. Malicious code could easily spread from one guest system to another, or take over the entire host computer (Kleidermacher & Wolf, 2008, p. 1.C.3-5).

The most often-proposed remedy for achieving what the Nation Security Agency (NSA) describes as “High Robustness” in a multi-level secure architecture is the Multiple Independent Levels of Security (MILS) concept, first described in 1984 by noted computer scientist John Rushby (Parkinson & Baker, 2011). A MILS-type architecture is based on two high-credibility assertions: 1.) A software component is only as secure as the layer beneath it. For virtual computing, that means that if the VMM or hypervisor is

not secure, than none of the hosted VMs are secure. 2.) The smaller and simpler a software component is, the fewer vulnerabilities it will contain, and the easier it will be for developers to find and correct those vulnerabilities prior to release.

MILS-based virtual computing environment would thus employ a very simple “micro” separation kernel, functioning as a bare-metal hypervisor. For application to an aircraft’s avionics, this hypervisor would also have to be optimized to support deterministic real-time processes in the hosted VMs. (Small kernel size and real-time capability are not mutually exclusive in any way; if anything, they tend to go hand-in-hand.) This underlying layer would contain no device driver’s specific to the VM’s above it, keeping it simple and easier to certify. It would be designed to enforce the following security policies to assure that system events (or intrusion) in one hosted OS could not spread laterally or upstream:

- Data isolation, which ensures that a partition cannot access resources in other partitions
- Periods processing, which ensures that applications within partitions execute for the specified duration in the system schedule
- Information flow, which defines the permitted information flow between partitions
- Fault isolation, which means that a failure in one partition does not impact any other partition within the system (Parkinson & Baker, 2011)

With that in mind, paravirtualization architecture with a large and complex hypervisor atop an ARINC 653 operating system (such as PIKE OS in the Airbus A380/A350) would probably not be an appropriate choice where certified “high robustness” was a requirement. Firstly, the large size of the kernel would make it difficult and expensive to certify. Furthermore, the inter-partition communications permitted under ARINC 653 standard may create violations of the MILS information flow policies that protect hosted domains of differing security classifications. (Kleidermacher & Wolf, 2008, p. 1.C.3-5). Pike OS’s inclusion of complex device drivers in the virtualization-layer for support of various host-OSs also would introduce increased certification

overhead; each would have to be evaluated to the same standard applied to the most secure hosted application on the system.

Various alternate solutions have been proposed; prominent among these is Green Hills Software's Integrity DO-178 RTOS, a micro-kernel-based hypervisor that supports time/space/memory partitioning (with no dynamic memory allocation) for safety-critical functions AND cross-domain security in a common platform. FAA-certified more than a decade ago (IAW the older DO-178B standard) for use aboard the Sikorsky S-92 helicopter, the maker asserts that the current version of the software has since achieved the official blessing of the NSA's NIAP lab as a "High Robustness" platform.

Hardware support of virtualization also interacts with achieving a balance between robust security and high system performance. As previously described, full virtualization typically offers lower performance than paravirtualization due to increased virtualization overhead; but full-virtualization is inherently easier to make secure according to the MILS paradigm. The consensus view seems to be that increasing built-in support for virtualization at the hardware level will help close (or even reverse) this performance gap. Furthermore, Asymmetric Multiprocessing on MCPs inherently offers an additional avenue by which the separation kernel could maintain the integrity of partitions. Threads from VMs of differing classifications could be routed to different cores, in addition to the separate physical memory blocks, with little or no performance penalty. Integrity-series software by Green Hills Software provides this ability when installed on MCP devices. The advanced SMP performance scheme utilized by Wind River Systems in their VXworks Core 7 product, on the other hand, intermingles threads from different partitions during cycle slack-time. This inter-partition resource sharing would have to come under close control and scrutiny to assure that only processes from the same security-domain level would share a core during a given cycle.

a. TRL Assessment for High-Robustness Virtualization

The most extensively flown RTOS VMM (Pike OS) may provide adequate security robustness for present-day civil applications, but in a world of increasingly sophisticated cyber-aggression that may not always be the case in the future. Certainly,

for the cross-domain needs of a sophisticated war-fighting platform, it is not appropriate. Fortunately, a MILS-architecture compliant, NSA-certified micro-kernel alternative has already achieved operational status with several aircraft, including the afore-mentioned S-92 helicopter and upgrades to the B-2 and F-16. The Green Hills Software product is also being incorporated into the F-35 JSF, where its virtualization capabilities are being extensively utilized. This fact might lead one to assign a very high TRL level to the technology; but our conservative approach dictates a bit more caution. The F-35, as advanced as it is, does not achieve full IMA2G-levels of integration, virtualization and distribution. Although Integrity DO-178B is likely capable of supporting that type or architecture, we have uncovered no evidence that this has been validated outside the laboratory environment. As such, we will restrict our rating to Technology Readiness Level 4.

5. Open Standards for Avionics-Grade Military Software

The goal of Integrated Modular Avionics is to dismantle the functional stove-pipes that have historically divided the complex collection of avionics systems in modern aircraft. The mismatch of software interfaces involved though makes that task immensely more difficult. Besides impeding integration and interoperability, the reliance on single-platform, proprietary software is considered a major cost-driver within military aviation; and there is no reason to suspect that developing, certifying and supporting unique imbedded software will ever get significantly less expensive. If anything, increasing levels of complexity make the opposite effect more likely. (Reference the NASA study, cited in Chapter I). The most widely prescribed solution—supported by both the FACE and SCARLETT consortiums—is the development a common, open-architecture for aircraft avionics. Such a system would allow “components conforming to agreed-upon standards to be added, upgraded, and swapped” and “independent parties to design and develop interoperable components that work together under the specified standards” (Hagen, Hurt, & Sorenson, 2013, p. 28). It would, in other words, be an application of “form, fit, function” on a logical, as well as physical level.

The idea is not new. According to Tom Dubois of Boeing, both the F-22 and the ill-fated Comanche helicopter programs initially hoped to leverage some sort of open-standard, by which different vendors could write software compatible with the system and drive down costs through competition. In the time frame during which those two projects commenced however, there was no existing framework that would offer the data-exchange and resiliency capabilities needed. A ground-up standard was developed – with hopes that it would become broadly accepted. Market factors and security concerns conspired to defeat that hope however, and both aircraft ended up with stove-pipes of their own making (T. Du Bois, personal communication, September 25, 2014). For the Comanche, the cost of that outcome may have contributed to the program’s demise. In some ways, the difficulty of establishing a successful open-standard is a variation of “the chicken or the egg” problem; a new product may not be successful unless it is compatible with broadly-accepted standards, but a new standard cannot find broad acceptance unless multiple products are built upon it. Which must come into being first? The product (the “chicken”) or the standard (the “egg”)?

The lessons of previously-unsuccessful open-architecture models have apparently not been lost on the FVL program. The Joint Common Architecture initiative is an attempt to create an *open-architecture egg*, while simultaneously developing an entire flock of new *open-architecture chickens* to hatch out of it. Just as the aircraft’s physical architecture is supported by a lobbying consortium of government, industry, and academics (The FVL Consortium), its avionics development has a symbiotic relationship with the Future Airborne Capabilities Environment (FACE) group.

In November 2014, FACE-members and JMR-TD partners Boeing and Sikorsky concluded a four month feasibility study that was essentially a proof-of-concept for the FACE technical standard. A sensor-fusion software component developed for the Navy’s P-8 Poseidon (a maritime patrol aircraft based on the Boeing 737) was minimally modified and then successfully run on different hardware in three other platforms: a Boeing AH-64 Apache helicopter, the Sikorsky S-99 Raider technology demonstrator, and a prototype Boeing computer known as Phantom Fusion (Freeburg, 2014). Honeywell conducted a similar study, also according to FACE standards. In both cases,

the successful result points optimistically to the development of a workable open-standard for high-assurance military systems.

By themselves however two successful, independent laboratory tests do not prove that a FACE-based model can provide adequate real-world performance given the limitations of currently available hardware. “Any time you introduce an open system,” laments Boeing’s Dubois, “you are introducing extra layers of processing” (T. Du Bois, personal communication, September 25, 2014). This is of particular concern with a highly-integrated architecture that fuses traditional Mission Systems and VMS functions, where performance is critical. An overburdened capacity for real-time processing could set limits on the scope of virtualization, especially in the near-term, without the added support of multi-core processors.

a. TRL Assessment for Open Standard Military Avionics

The FACE consortium has managed to build apparent momentum behind the adoption of an accepted open-standard model for military software systems. Given the revolutionary effect that successful open-standards in telecommunications, computer networking, and portable-device operating systems have had over the past few decades, the development of such a system would be both highly-welcome and long-overdue. Thus, far however, the FACE standard consists of little more than some documentation and a few proof-of-concept experiments. Based on the findings of our research we will assign it a current TRL rating of 4: “Component and/or breadboard validation in a laboratory environment” ([ASD[R&E], 2011, para. 2.5).

6. Model-Based Systems Engineering, Development, and Certification

The complex requirements being written into proposals for future aircraft (such as FVL) are increasing difficult to comprehend intuitively. Elaborate, document-driven frameworks such as DODAF (Department of Defense Architecture Framework, presently in its version 2.01 incarnation) have been adopted to help manage this growing problem – but there is a growing sense that they are falling short of the task. The need for a *model-based approach* was a consistent thread found in *every* scholarly article and conference

proceeding on IMA consulted for this study, and was also universally endorsed by the subject-matter experts interviewed.

In a June 2013 address to members of the INCOSE (International Council on Systems Engineering), Stephen Welby, Deputy Assistant Secretary of Defense for Systems Engineering expressed his view that, “we will begin to see simulation become a more integrated part of the design process rather than something that is engaged separately. I believe we will see the ability to affordably explore much more complex design spaces, with the opportunity to better understand how the implication of design changes downstream ripples back across an entire product design” (Zimmerman, 2014, p. 3).

Proponents of model-based systems engineering (MBSE) claim that it reduces the chance for errors and ambiguities to develop as a project passes through the many stages required to translate a broadly-written requirements outline into actual working software code. Multiple methodologies of MBSE currently exist, and are defined by variances within their processes, methods, tools, and environment (Estefan, 2008, para. 2.1). The approach that the FACE consortium is attempting to develop for use on the JCA and other embedded software-intensive DOD projects is called the Modular Open Systems (MOSA) Data Model. It has been demonstrated in principal but should not be considered fully mature. In a November 2014 press-conference, Michael May, the associate director for software and embedded systems in the office of the Assistant Secretary of Defense for Research and Engineering, cited the pressing need to reinvent the way complex aerospace and weapon systems are developed, but confessed that “Some of our methods don’t scale well.” (IE: from individual software programs to entire systems). They also rely upon programming and formal methods of analysis that are still not the norm in the current work force. “The formal-methods guys tend to be PhDs,” May clarified (Freeburg, 2014). Left unsaid, but presumably a limiting factor as well is the culture and environment of the DOD acquisition ecosystem. It remains to be seen if the good intentions of the FACE consortium will actually succeed in bringing about any meaningful paradigm shift on the equally important government side of the defense technology industry.

Testing and certification are also areas where model-based approaches may hold promise. The current impasse on airworthiness of multi-core processors may be a sign that a tipping point has been reached in our ability to adequately test and validate complex cyber-physical systems. It has even been alleged that Boeing purposefully held back on integration and virtualization in the 787 airliner because they feared certification of such an advanced architecture would unduly delay sales (D. R. Arterburn, personal communication, January 22, 2015). In order to continue the upward trend of system complexity and capability, the pressure is on to reinvent the way we design, test, and certify aircraft.

Formal recognition of MBSE as a valid approach for demonstrating compliance with applicable airworthiness regulations may finally be on its way; 2013 saw the FAA release a circular (AC 20-115C) affirming that the current DO-178C standard could be supported via model-based testing. Given the complexity of highly-integrated future architectures-- especially those with extensive cognitive-decision aiding, or optionally-manned control schemes (as planned for the FVL) – there is still a long way to go. Current standards are still based on *deterministic* airworthiness; implying that all possible system states and interactions can be known and adequately tested. It is predicted that the F-35 will reach operational service with some 24 million lines of code (Charrette, 2012); the FVL is likely to be just as complex. Without resorting to some sort of *probabilistic* airworthiness or extensive dependence on computer-based simulation, it is difficult to fathom how we will be able to certify such systems in a time and cost-effective manner.

The barriers here are likely more cultural than technical. “The flight test guys sometimes think we’re trying to put them out of business,” explains David R. Arterburn. (personal communication, January 22, 2015). A more accurate assessment is that the task of flight test will be next-to-impossible in the near future *without* heavily leveraging model-based simulation, but live testing will always be required to validate parameters for the model. With assurance that the input is valid, developers can then rely upon their model environment to run an astronomical set of scenarios in a wholly reasonable time. Not only will this simplify certification, it will facilitate the early discovery (and

correction) of flaws in a design that might otherwise be accepted because they were found too late in the testing process to economically fix.

It is important to emphasize that the U.S. government and defense industry is not operating in a vacuum with regard to the modeling and simulation issue. SCARLETT researchers at the University of Bremen, Germany in 2010, published detailed descriptions of model-based testing protocols for advanced IMA systems, claiming that “Compared to the manual implementation of tests ... this approach promises to reduce the effort needed for test development by at least 30% and to avoid errors made during the manual implementation of test cases” (Efkemann & Peleska, 2010, para. 3). FVL consultant Arterburn confirms that SCARLET may be well-ahead of US-industry in this area. “They [European Governments] are investing heavily in this stuff” (D. R. Arterburn, personal communication, January 22, 2015).

a. TRL Assessment for Model-Based Development

Our findings indicate the model-based systems development is a rapidly advancing field, and one that—by weight of necessity—is likely to become the dominant paradigm for aerospace systems design in the coming decade. As evidenced by top-level comments from the civilian leadership within the department of defense (Zimmerman, 2014; Freeberg 2014), change is coming, because it is needed. No matter what architecture choice is arrived at for the FVL, the program will benefit on some level; but in order to facilitate development of an advanced, common IMA2G avionics suite for these aircraft, timely adoption is of pivotal importance.

Rating the TRL for model-based development strictly in the context of FACE’s MOSA-data model—the system most likely to be applied to the FVL—we find level 7 is an appropriate reflection of the current status. “System Prototype demonstration in an operational environment.” Though not strictly speaking a part of the technology of highly integrated software-defined systems, the relative maturity of this needed faculty lends some needed optimism to the other challenge areas described previously.

B. IMA2G: MATURITY ASSESSMENT

The findings of Technology Readiness Assessment are summarized in Table 5.

Table 5. TRL Summary for IMA2G Critical Path Areas

Technology	TRL	DOD Definition	Study Findings
High-speed networking	6	System/subsystem model or prototype demonstration in a relevant environment.	TTEthernet has demonstrated characteristics needed to support IMA2G[1],[2]
			Has not been integrated beyond prototype applications in an air vehicle.
			The Automobile industry is investing in this technology[3].
Deterministic MCP	4	Component and/or breadboard validation in a laboratory environment.	No current MCPs are certified airworthy [4]
			Disabled MCPs are flying without clear airworthiness [5]
			Vender Wind River Systems recently promised a compliant RTOS that can leverage dual-core silicon, but has not yet delivered[6].
			Single-core processors may be obsolete in 5 years[4],[7]
High-Assurance Virtualization	3	Analytical and experimental critical function and/or proof of concept	Paravirtualization is a mature technology, but may not be suitable to military IMA2G[8],[9]
			Hardware-assisted, full-virtualization is tied with chip-design, and such products are not yet available to assess.
High-Robustness Virtualization	4	Component and/or breadboard validation in a laboratory environment.	Integrity DO-178 RTOS offers a MILS compliant secure VMM, already certified and in use aboard operational military aircraft [9]
			Current Integrity applications do not stress the system to the extent that an IMA2G architecture might.
Open Standards Integration	4	Component and/or breadboard validation in a laboratory environment.	FACE consortium technical standard continues to evolve and has broad industry support[7],[10]
			Independent JCA experiments have demonstrated that the proposed open architecture is feasible. [11]
Model-based, design, test & certification	7	System Prototype demonstration in an operational environment	Multiple demonstrations of need/capability/intent from both industry and government.[11][12]
			Cultural factors may retard full adoption [7][10]
1. Kopetz, Ademaj, & Grillinger, 2005 2. Bisson, 2011 3. Plankensteiner, 2012 4. Huyck, 2012 5. Reported in confidential personal communication 6. Wlad, 2014			7. D.R. Arterbum, personal communication, January 22, 2015 8. Fuchsen, 2009 9. Kleidermacher & Wolf, 2008 10. T. Du Bois, personal communication, September 25, 2014 11. Freeburg, 2014 12. Zimmerman, 2014

Overall, it may seem that the low ratings (averaging only 4.7 on a scale of 1–9) paint of bleak picture for the short-term prospects of second-generation IMA. It should be kept in mind however that the technology areas listed in this portion of the study represent *critical path* items in the development of such a system. It is not inclusive of the many mature or nearly-mature technologies that would also be leveraged in a notional IMA2G design. Had we listed our identified challenge-areas alongside all these other low-risk items, the outlook naturally appear much more optimistic. Since a developmental system can easily be derailed by its weakest link however, we feel the picture as described in the following table is the better one from which to formulate a recommendation.

C. IMA2G IMPACT ON FVL ATTRIBUTES

As outlined in chapter II of this study, the Future Vertical Lift program ICD sets out a broad set of highly ambitious requirements. In this section, we will assess the potential impact of a fully-realized IMA2G architecture on individual aspects of those requirements, as well as the relative potential for a less-integrated system to achieve those same thresholds.

1. Aircraft Performance/Payload/Range

Table 6 lays out a stark comparison between the performance threshold expected of the medium-weight FVL variant and one of the more avionics-weight-challenged challenged aircraft it would one day fulfill the role of, the U.S. Navy’s Sikorsky SH-60B.

Table 6. FVL-medium and SH-60B performance compared

	Speed (cruise)	Combat Radius	Payload (int/ext)	Passengers
SH-60B	120 (max range)	80 nm*	600-3000 lbs	1-2
FVL-M	230-300 kts	265 nm*	6,000-20,000 lbs	11-24
* Defined as unrefueled distance w/2.0 hr loiter (full combat load at 6k/95°)				

Though the size, weight, and power-consumption (SWAP) benefits of a more efficient, integrated avionics package are not enough to deliver the required improvements on their own, they could make a significant contribution – both on their own, and synergistically.

- **Reduced Avionics Size:** increases the volume of internal fuel that can be carried, increasing range, and on-station endurance. If those benefits are sufficient to eliminate the need for external fuel for certain missions, the increased speed may be realized through reduction in drag, or increased armament/payload can be carried.
- **Reduced Avionics Weight:** Improves rate of climb, top-speed, and range. In Helicopters, contributes to better hover performance and controllability under hot/heavy/high conditions. Also, more fuel can be carried, (internal or external) increasing range. Payload (external/internal) and armament also can be increased.
- **Reduced Power Consumption:** Reduces size/weight of generators/power-supply busses, wiring, and cooling systems required, contributing to range/speed/payload/armament improvements. Reduction in parasitic drag on engines to run generators may also contribute slightly to performance. Alternately, these small benefits could be traded in for greatly increased excess power-capacity for high-draw weapons and sensors.
- **Synergistically:** reduction in all three aspects of size, weight and power in on-board avionics have a ripple-effect across the entire airframe, allowing for more efficient packaging, and reduced design-penalties for the delivered capabilities.

The ability for first-generation IMA to deliver size, weight and power savings has already been discussed in this work. The 2014 report by Mairaj and Tahir demonstrate that size reductions on the order of 28% to 50%, weight reductions of 25% to 50%, and power-consumption reductions of 38% to 60% are possible when transitioning to from a federated-systems model to an IMA-based model. There is abundant cause to speculate that a second-generation IMA avionics suite would improve significantly on those already-impressive figures. However, since there is no flying example of true IMA2G architecture at this time, no equivalent data exists to validate that hypothesis, much less quantify it statistically. For the purposes of this study we will adhere to a conservative estimation, assuming that the adoption of fully-developed IMA2G avionics and mission-systems will realize SWAP improvements in the FVL no

greater than the upper-bounds already reported in the Mairaj and Tahir paper: *50% size, 50% weight, and 60% power consumption.*

Just how much of a real-world performance improvement would those figures translate to for an FVL rotorcraft? As discussed previously, that will depend largely upon the ratio of avionics weight to aircraft empty weight. In an attempt to estimate what that ratio might be for an FVL-medium variant (which will probably be the most numerous derivative), we have compiled data from a 1981 Rand Corporation study that included a breakdown of avionics weight for various then-current U.S. combat aircraft. Added to the list is corresponding empty weight and avionics weight for the SH-60B Seahawk helicopter, which was introduced to service around the same time as the Rand study was conducted. Columns B through D in Table 7 represent the as-is state for complex, federated-systems military aircraft of varying sizes. Note that the percentage of total empty weight represented by on-board avionics is highest in the SH-60B, at 14.6%. With a 50% reduction in weight accomplished through advanced IMA (remember, a conservative figure) that percentage would decline to 7.9% (Column F), reducing the overall aircraft empty-weight by a very significant 7.3%.

If 100% of the weight shed (nearly a thousand pounds) were to be translated directly into a corresponding quantity of extra onboard fuel, the increase in range would be significant. According to type-model NATOPS manual, the SH-60B normally carries approximately 3000 lbs of fuel; enough to support 3.5 hours of total endurance, or a 80 mile transit, with a 2 hour on-station time, and 80 mile return. Adding 996 lbs of internal fuel would allow for a 140 mile two-way transit with the same 2 hour on-station time. In other words, notwithstanding any aerodynamic gains made through the FVL's proposed compound-helicopter or tilt-rotor layout, just building the aircraft around a IMA mission-systems suite could improve combat radius by 75%!

Table 7. Avionics as percent of empty weight: Federated vs. IMA

A	B	C	D	E	F	G	H
As-is			IMA2G (with 50% weight-reduction in avionics)				
	Empty Weight	Avionics Weight	% of empty weight	Avionics Weight	% of empty weight	Empty Weight	Weight reduction%
F-14A [1]	38,900	2,199	5.7%	1,099	2.9%	37,801	2.8%
F-15A [1]	25,800	1,580	6.1%	790	3.2%	25,010	3.1%
F-111D [1]	46,800	2,354	5.0%	1,177	2.6%	45,623	2.5%
A-4M [1]	10,800	840	7.8%	420	4.0%	10,380	3.9%
SH-60B [2][3]	13648*	1,997*	14.6%	996	7.9%	12,652	7.3%
1 Dryden, Britt, & Binnings-Depriester, 1981, p. 29 2 Polmar, 2001, p. 389 3 NAVAIR, SH-60B NATOPS manual * Does not include weight of FLIR/Hellfire package (add 700+lbs)							

If the FVL airframe turns out to be capable of delivering the required range improvements without carrying extra onboard fuel, that weight and space saving could be traded toward other performance enhancements, including speed, maneuverability, hot/heavy/high hover ability, and cargo/weapons payload.

a. Impact Assessment for Performance/Range/Payload

Given the high percentage of aircraft empty weight likely to be devoted to avionics in a complex multi-mission platform like the FVL-medium, the projected SWAP gains of IMA2G (upwards of 50% for size, 50% for weight, and 60% for power-consumption) are likely to be highly significant to aircraft performance. Likewise, the consequence of attempting to achieve the desired multi-mission capability *without* resorting to a highly-integrated avionics architecture is likely to be highly detrimental. In other words, communications, sensors or weapons, would have to be traded for speed and range, or vice versa. With fully-realized IMA2G, the trade-off would be greatly reduced.

In accordance with this study's findings, we rate the impact of advanced IMA on achieving the desired performance characteristics of the FVL program as *strongly positive*.

2. Mission Capability/Flexibility

FVL program attributes and outcomes associated with Joint Forces (JFOR) Mission Capability/ Flexibility include the following:

- The ability to integrate and rapidly configure a mixture of “multiple Joint weapon types”
- Advanced Sensors that combine “multi-spectral, multi-function ... targeting, navigation, and aircraft survivability equipment” and the ability to operate at night and in degraded visibility.
- Enhance Situational Awareness through various data-links that automatically send/receive information and help build a common operating picture, including “threats, inclement weather, and other hazards encountered enroute.”
- Fully integrated crew station to enable “mission focused operation” while providing for “automation of critical battle tasks, cognitive decision aiding, and decision making, [and] fused sensor imagery.”

(US Department of the Army [USA], 2011, p. 3)

The total picture that emerges when looking at the above requirements is of an extremely complex aircraft with numerous sensors, communication systems, weapon systems, and a centralized management capacity for the interpretation and presentation of information. What would happen if an attempt was made to integrate such advanced capabilities into an existing airframe *without* resorting to an advanced IMA architecture ? (Assuming it is even possible to design a system like this under the federated model.) As it turns out, we have a perfect experimental case to answer that very question: the MH-60R – which is now replacing the SH-60B in service with the U.S. Navy. While the “Romeo” certainly succeeds in upgrading the weapon suite, sensor reach, data-link capability, and cockpit presentation of the legacy platform is has supplanted, the corresponding increase in empty weight is illustrative.

Table 8. Avionics complexity and aircraft weight; SH-60B to MH-60R

	SH-60B	MH-60R
Empty Weight	13,648* [1]	15,200 [2]
Gross T/O weight	21,700 lbs [1]	23,500 lbs [2]
1 NAVAIR SH-60B NATOPS manual 2 NAVAIR MH-60R NATOPS manual * Does not include weight of FLIR/Hellfire package (add 700+lbs)		

Essentially, the MH-60R features the same airframe as the SH-60B. Indeed the first LRIP (Low-Rate Initial Production) batch of “Romeos” were built from existing 60B, 60F and 60H airframes. The weight growth shown in Table 8, is almost all attributable to either 1.) avionics systems growth, or 2.) airframe reinforcement and auxiliary support systems designed to accommodate that avionics growth.

As capable as the MH-60R is with regard to multi-mission flexibility, weapon employment, and sensor-fusion, it represents only the *current* state-of-the-art, and falls well-short of the corresponding characteristics described in the FVL ICD. By 2035, the FVL’s intended IOC, the “Romeo” will be as moribund and obsolete as the SH-60B is today. To add the capabilities called for in the FVL FOS ICD *without* an advanced IMA architecture would add even more weight to an aircraft that is already reaching the upper bounds of what the airframe and powerplants can support.

That argument may be academic however, as the type of automation, information-sharing, and in-flight reconfiguration called for in FVL documents may be all but unachievable *without* a software-defined approach to system integration.

a. Impact Assessment for Mission Capability/Flexibility

Not surprisingly, our findings indicate that successful development of an advanced IMA2G architecture for the FVL Family of Systems would have a *strongly positive* impact on achieving program thresholds for mission capability and flexibility. Any attempt to achieve greater sensor-fusion, weapon integration, or battle-space

awareness over the current MH-60R multi-mission maritime helicopter would likely result in severe SWAP consequences.

3. Manpower/Training

The optimal manning required to maintain a military aircraft at the desired level of operational availability varies with the characteristics of the aircraft in question. Airframe size and complexity play a key role, but the electronic and avionics architecture is also highly influential, particularly when FMC (Full-Mission-Capable) rates are considered. Although the concept of the LRU was supposed to simplify field maintenance, in reality, a complex federated architecture requires a large footprint of maintenance manpower.

- Large number of individual physical components and connections between them create numerous potential points of failure.
- Software and hardware are tightly coupled, making it difficult to isolate whether a fault is in one or the other.
- Built-In-Testing (BIT) on LRUs does not span system wide, resulting in ambiguous results and unnecessary replacement is order to chase faults.
- Depot-level maintenance requires numerous specialists to effect repairs on unique LRU components.
- Lack of commonality between federated platforms favors specialization over generalization, resulting in a larger maintenance manning footprint.

The first commercial developments of IMA meanwhile were sold as much on the basis of reducing that heavy maintenance footprint as they were on SWAP considerations. IMA in general, and advanced IMA in particular, directly addresses all the previously described causal factors that inflate the maintenance-manning requirements of a federated-systems fleet. The mechanisms for that enhanced efficiency are as follows:

- Reduced number of unique hardware components and fewer connections and junctions in-between, resulting in limited physical points of failure.
- Software and hardware faults are inherently easier to separate in an IMA scheme.

- Advanced, autonomous, system-wide conditional-monitoring can isolate and announce faults before they even become apparent to operators.
- Fewer physical components in the avionics system means fewer specialists required at the depot-level.
- System commonality across platforms allows a single qualified maintainer to work on multiple airframes with equal competence.

This last characteristic is particularly germane to the FVL program. A forward-deployed force pays a logistical premium for maintenance manpower; and vertical lift aircraft are often deployed to austere locations where security, supplies, and even shelter are limited. When two avionics technicians at a small FOB (Forward Operating Base) can do the job of three or four, or when one technician can work on multiple FVL types, the benefits are particularly manifest. In operational terms, a manpower reduction of this order – with no corresponding downgrade to capability – means that the FOB has a lighter logistical footprint to support and can thus hold out longer between resupply missions.

Advanced IMA architectures would also be likely to use more commercial, open-source software to deliver common, non-tactical functionality – as opposed to proprietary military programs. Greater convergence between skill sets utilized in the military and civilian spheres broadens the pool of experienced technicians, and can be leveraged to motivate both recruitment and (to an extent) retention of military technicians. This may be mitigated perhaps by the higher level of knowledge and education required, but in the long term, such an effect would be in-line with the apparent U.S. societal trend toward increased educational requirements for employment. Without doubt, young people entering the work force today are more comfortable and conversant with software-driven systems than any previous generation—to say nothing of those entering the work force in 2035! (Of course it remains to be seen however whether that high-level familiarity actually translates into functional *understanding*.)

Operator training and manning meanwhile, may also benefit from adoption of a common IMA architecture across the FVL Family of Systems. Shared cockpit interfaces enable easier cross-platform type rating. Optionally-manned capabilities (which would be

far easier to implement in an IMA2G architecture) could reduce the number of human pilots and aircrewmen required – at the very least be taking on routine maintenance or ferry flights. The ability to operate instances of mission software fully abstracted from hardware and linked by a common virtual environment opens the possibility of using an FVL aircraft as a full-function tactical simulator for deployed forces. A crew could practice for an upcoming mission, participate in a battle-group war-game, or even catch up on their yearly instrument approach minimums without ever leaving the ground. Limited aircraft maintenance (daily and turn-around servicing for instance) could even be conducted at the same time on a non-interfering basis. Later, after the mission was actually flown, data collected and fused from the on-board network of embedded systems could be used to re-construct events, aircraft performance and crew actions in rich detail.

a. *Impact Assessment for Manpower/Training*

As a result of the reduced physical complexity, but increased *logical* complexity of IMA systems, fewer maintenance personnel will be needed, but for those that are retained, a higher (more software-focused) level of expertise will be called for. This may have both positive and negative repercussions for military technician recruitment and competition against private-sector employers, but overall, the balance is likely to be in favor of IMA.

On the operational training aspect, advanced integrated systems offer many possibilities to make more effective use of pilot/aircrew time and enhance training/readiness. As a result, we assess that IMA2G is likely to have an overall *positive effect* on manpower considerations for the FVL program.

4. *Development Timeline*

Application of any novel technology (or in the case of IMA2G, *several* novel technologies) carries inherent schedule risk. Earlier in this chapter, we assessed the overall Technology Readiness Level for advanced IMA architectures as approximately 4.7 on a scale of 1–9. This limited state of maturity of increased the probability of unknown-unknowns emerging during the course of system development.

Given novel airframe architecture(s) proposed for the FVLFOs however, it cannot be taken for granted that delays with avionics will be the critical path that causes overall schedule slippage. An instructive parallel might be Boeing's development of the 787 Dreamliner. Company executives launched the program in January of 2003, with intent for first deliveries by the end of 2008 – assuming it would take just six years to design, build, test and certify the new machine. This aircraft's fully-fledged First-Generation IMA architecture represented a very large advance over the previous transitional IMA applied to the company's 777 airliner; but the aircraft also employed extensive use of composite construction that was without precedent for an aircraft of its class. The confluence of these two factors make it difficult to sort out which one (avionics or airframe) was predominantly responsible for the three-year schedule slip in actual customer deliveries.

IOC for the FVL-Medium variant (the first to be fielded) is 2035. Given that Joint Multi Role Technology Demonstrator (JRM-TD) prototypes should have completed their fly-off competition by the end of 2018, the projected timeline allows for twelve years of further development. Compared to almost any other similar program (with the possible exception of the notoriously tardy V-22 Osprey) this seems like a generous schedule.

Moreover, the extremely high-level of complexity inherent to an advanced IMA2G architecture in a multi-mission tactical aircraft makes model-based design and testing a virtually inescapable necessity. All subject matter experts contacted for this study agree firmly on that point. This forced transition is likely to make progress more difficult at first, but if advocates of MBSE are right, it will pay significant dividends in the long-term, greatly streamlining the development process. Given the long-term scope of the FVL, the program is likely to benefit from that effect eventually – perhaps even enough to make up for initial delays.

Another factor to be considered is the ease with which open-source, COTS, or legacy software components could be integrated into an advanced IMA2G system. This characteristic is one of the most heralded advantages of IMA2G, and has the potential to radically streamline avionics capability development. As noted previously in this chapter, experiments with the FACE consortium's technical standard for Modular Open Systems

Architecture (MOSA), have already demonstrated the feasibility of cross-platform software re-use.

a. Impact Assessment for Development Timeline

On the whole, it is difficult to predict the impact of IMA2G architecture on the FVL program. Due to the novel (and as-yet undetermined) airframe construction, the immature, but rapidly-developing state of required technology, and an on-going paradigm shift within Government and Industry, any projection would be highly speculative. The relative speed and success of the transition to model-based development, and MOSA will strongly impact the schedule of the FVL program; but investing in a heavily-integrated IMA architecture is more likely to force these issues.

Since equal potential exists for IMA2G adoption to delay or enhance the FVL's acquisitions schedule, we assess the impact as *neutral/indeterminate* for the purposes of this study.

5. Total Life-Cycle Costs

Many of the same characteristics of IMA that would positively impact maintenance manning would be reflected in reduced life-cycle expenditures. It stands to reason that a system with fewer physical parts, fewer redundant, duplicated capacities, and greatly reduced wire count would also be less expensive to maintain and repair. Each LRU in a federated-systems model (and a single function require *many* LRUs) represents an tightly-coupled integration of hardware and software, and testing program to validated it. It is not unreasonable to expect that a system with 90% fewer LRU's would be significantly reduce maintenance and upgrade costs.

Achieving enhanced efficiency in software development and integration is of course, one of the major factors driving IMA and advanced second-generation IMA. Avionics contractor Honeywell, for instance, claims to have reduced software costs 20% for the avionics suite onboard the Boeing 777 ER (<http://www51.honeywell.com/>). In particular, the high degree of software re-use possible with a heavily virtualized avionics computing environment would seem to open the gate to very impressive savings. In

general, it costs the same to develop a particular software package irrespective of how many aircraft that software ends up installed in. Clearly, if a single software capability can be re-used across multiple different aircraft, entire development programs can be reduced to mere integration efforts. That integration itself becomes immensely easier the more abstracted the software runtime environment is from the underlying hardware. Much of integration testing, after all, involves the quest to discover and eliminate adverse interactions between component and another (hardware or software). The isolation of a “guest” operating system within a virtual environment can help contain those interactions.

Furthermore, an FVL aircraft equipped with IMA2G avionics might well be able to integrate obsolete legacy programs supporting sensors, communications or weapon systems introduced decades earlier; just as one might run an obsolete version of Windows in a virtual machine on one’s personal computer to allow a superseded application to run. This could take what might have otherwise been a long and costly integration program and greatly reduce the time and expense.

Of course, public funds expended in developing software for military aircraft are merely the tip of the proverbial iceberg. According to a recent U.S. Air Force study, “software sustainment activities (i.e., O&M plus upgrades) can account for 60–90% of the total life cycle software costs”(USAF Science and Advisory Board [SAB], 2011, p. 75) and those costs are trending strongly upwards. The same report found that expenditures on software maintenance “nearly doubled over the past decade (an increase from \$483M in 2002 to \$841M in 2011)” (SAB, 2011, p. 74). and predicted they would continue to climb over the next two decades as highly software-dependent aircraft like the F-22 and F-35 enter the sustainment phases of their life-cycle.

Again, there is little difference in the costs to maintain a particular software configuration item whether it is used in one aircraft or many. Any reduction in the number of unique software programs used across the FVL fleet would help contain sustainment costs. If extensive virtualization means that software and hardware can be upgraded *separately* and independently, the ease of upgrading FVL variants during their life-cycle would also be enhanced. It might also lead to more competitive market

conditions among vendors and bring down prices. Contrast this to the current circumstance where the DOD typically finds itself held hostage to a single supplier of an obsolete processor or software item. Often times, the vendor may be forced by economic factors to discontinue the product, leaving that particular military system vulnerable to widespread service outage.

a. Impact Assessment for Total Life-Cycle Costs

Few matters in business or government are as contentious and often-exaggerated as the potential for long-term cost savings. Despite the preponderance of claims that advanced IMA architectures will be less expensive to upgrade and maintain over the life of an aircraft, there is little present evidence in the public domain to quantify that. Recall that even the initial generations of IMA architected aircraft have not yet reached the back half of their service lives, where maintenance and upgrade costs are likely to be highest. Furthermore, most of these planes are operated by profit-driven, publicly-traded corporations, who are understandable tight-lipped about the actual monetary figures involved. Thus, all we are left with is expansive sales pitches from manufacturers – who can hardly be expected to present a sober and restrained sales-pitch. Even if the massive cost-efficiencies promised by IMA vendors and advocates turn out to be achievable, the initial cost of entry into state-of-the-art technology cannot and should not be ignored.

That being said, our findings indicate little reason for outright pessimism. Viewed strictly in the long term, we find there is reason to expect that IMA2G *would* indeed carry a *positive impact* on life-cycle costs for the FVLFOs. This might be partially mitigated in the short and medium-term however by larger up-front costs, but the FVL program as a whole is large enough to support such costs, and long enough in scope to reap the rewards.

6. Enhanced Safety and Survivability

In the first six years of combat operations in Iraq and Afghanistan, 375 rotary wing aircraft were lost as a result of enemy fire, aircrew mishap, or mechanical failure (Couch & Lindell, 2010, p. 9). To what extent could adoption of software-defined avionics help enhance the flight safety and combat survivability of Future Vertical Lift

aircraft? As it turns out, there are multiple aspects where IMA2G could have a positive impact:

- *More armor/protection.* As previously shown IMA2G would save considerable weight. Every pound of avionics and wiring saved could be replaced with a pound of additional armor and countermeasures.
- *Greater performance margin.* Alternately, weight savings from IMA2G could mean a lighter, faster, more maneuverable FVL, better able to evade enemy fire, and more resilient to the hazards of mountain-flying.
- *Enhanced resiliency.* An IMA2G architecture could distribute critical avionics functionality across several decentralized servers, running parallel software instances. Battle damage or power failure to one server rack would result in seamless “failover” – or transfer of processing responsibility to the alternate server.
- *Enhanced awareness.* IMA2G supports the integration of numerous, advanced sensors (at reduced SWAP penalty) to detect threats, and present them to the pilots and aircrew in an intuitive, helpful manner.
- *Cognitive decision aiding/Assisted piloting.* Centralized fusion of data in IMA allows for the possibility of effective cognitive assistance for the pilot, reducing mental workload in challenging and stressful situations. Since an IMA2G FVL rotorcraft would have all the underlying characteristics of an optionally manned aircraft, (whether it was designated as such or not) the machine could take over vehicle management and respond dynamically if the pilot was incapacitated or not responding correctly to flight-envelope warnings.

Any one of these improvements would be welcome on their own; taken together, the synergistic effect may be even greater than the sum of the individual parts.

a. Impact Assessment for Safety and Survivability

It should be emphasized that despite all these potential advances, FVL aircraft will still be required by the nature of their missions to fly low, slow, and in close proximity to threats on the ground or the ocean surface – and often in the hours of darkness or in poor weather. In other words, even with the full suite of IMA2G-enabled survivability enhancements described above, flying a military helicopter will never be *safe*.

That being said, our findings indicate with a high degree of confidence that IMA2G would have a *strongly positive* effect on the relative safety and survivability of FVLFO aircraft.

7. UAS Interoperability

Interoperability has been a strong selling point for vendors of military equipment ever since the Goldwater-Nichols Reform Act of 1986 ushered in the modern era of “Jointness” for the U.S. armed forces. In recent years, the focus of interoperability has grown in scope to include the ability to work with autonomous or unmanned military platforms. This has led to a new, high-visibility concept: manned-unmanned teaming, or MUM-T. A U.S. Army-led initiative to develop a standard Joint MUM-T interface is (not-coincidentally) co-located with FVL program activities at the Redstone Arsenal in Huntsville, Alabama. Though the programs are not formally connected, there are clearly common threads of effort. The FVL ICD states that “applicable FVL FoS platforms must control unmanned systems up to a Level of Interoperability (LOI) 5” (US Department of the Army [USA], 2011, p. 3). According to the latest revision of MUM-T standards, LOI 5 entails “Full control of the UAS, including take-off and landings” (Baxter & Eschenbach, 2014).

The latest version of the Boeing’s Apache attack helicopter, the AH-64E Guardian has been extensively upgraded with IMA-style mission systems, and is now capable of supporting LOI 3 “Control of the camera and sensors on the UAS” and even limited LOI 4 “Control of the flight path and payloads” with several common tactical unmanned aerial vehicles. A full IMA2G implementation on the FVL may not be *necessary* to achieve the desired level of interoperability, but it will greatly facilitate it. There is, after all a large capability gap between limited in-flight control of a UAV, and full mission-teaming from take-off to landing. Software-defined avionics supports the information sharing, data-fusion, and cross-domain functionality required to make the most of such an arrangement. Additionally, the common virtual environment that would form the backbone of manned FVL variants would be identical to that found on unmanned or optionally-piloted variants; strengthening the connection.

Whether or not it is designated as such, any FVL aircraft built atop an advanced IMA architecture would have all the inherent characteristics of an optionally-piloted vehicle. The fact that all or nearly all mission-system, navigation and VMS controls would be part of an integrated, software defined (and thus software-controllable) system, places the pilot in the position of *decision executive* vice integrator-operator. Separation of physical I/O from avionics functions means that those executive-inputs could just as easily come from an external data-link, or from the aircraft's own autonomous central control authority as from switches and levers in the cockpit. Manned aircraft based on federated systems *can* be turned into drones – we have been doing so for decades with obsolete fighters used for missile tests – but not with level of sophistication needed to operate as an integrated combat or ISR asset. IMA2G would allow any FVL to turn into a UAS, in the field – or even in the air – as necessary. No physical modification of the airframe or avionics would be required; rather than mere *interoperability*, such an architecture would establish *interchangeability* between manned and unmanned systems.

a. Impact Assessment for UAS Interoperability

Our findings indicate unequivocally that there is a strong alignment between advanced IMA architectures and teaming/interoperability with unmanned platforms. For the purpose of this study we assess the impact as *strongly positive*.

8. FVL-IMA2G Impact Study Summary

Table 9 summarizes the alignment and impact comparison between FVL program goals and IMA2G attributes. In general, we find the potential benefits of IMA2G architecture to be supportive or strongly-supportive of nearly all FVL mission goals – even those that only tangentially involve aircraft avionics. The only area we examined that was not robustly and conclusively supported is timely development. Although several associated aspects of IMA2G (reduction of unique hardware, open-source standards for software, model-based systems engineering, etc.) may contribute in the *long term* to a more efficient acquisition path, the complex nature of the technical/organization/cultural barriers that must first be overcome precludes us from being overly optimistic in our assessment.

Table 9. Impact of IMA2G characteristics on FVL program goals

Desired Attribute:	IMA2G Impact	Findings/Justification
Performance/ Payload/Range	Strongly Positive	Supports aircraft empty weight reductions of 7% or more. Synergistic effects contribute to reductions in weight, and drag of the entire aircraft. SWAP gains in avionics can be traded for range, speed, hover performance, or weapons/cargo/passengers
Mission Capability/ Flexibility	Strongly Positive	Software-define avionics may be required to achieve advanced capabilities for sensor fusion, weapons integration, and partial automation specified in FVL program ICD. Attempts to achieve desired functionality without advanced IMA will be result in excessive SWAP for mission systems, and thus compromise performance goals.
Manpower/ Training	Positive	IMA2G should facilitate maintenance and reduce manpower footprint. Reduced maintenance manpower may be partially off-set by a requirement for more highly-skilled technicians.
Timely Development	Neutral/ Indeterminate	Remaining technical challenges will take time to overcome. Complex requirements will take time to validate and test Complexity factor partially or wholly mitigated by adoption of model-based systems design, testing and certification. Open source development of mission software may speed up design cycle.
Reduced Life-Cycle Costs	Positive	IMA systems easier and less-expensive to upgrade/maintain Open source development can increase competition between vendors or allow repurposing of existing or COTS program. IMA2G would likely reduce FVL's reliance on expensive proprietary systems
Safety and Survivability	Strongly Positive	IMA2G avionics allows resiliency and fault-tolerance greatly exceeding Federated Systems. IMA2G supports integration and sensor fusion for advanced counter measures, and cognitive decision aiding. IMA2G is easier to upgrade with new software/hardware, allowing the FVL FOS to keep up with development of anti-aircraft weapons.
UAS Teaming	Strongly Positive	The sharing of a common avionics systems architecture between manned and unmanned FVL variants would facilitate data-exchange and operational teaming.

V. SYNTHESIS

A. ASSESSMENT

Taken as a whole, the material presented in the Chapters II and IV of this study leads to several distinct conclusions. First, the prevalent trend within the avionics industry is Integrated Modular Avionics, with technology and competitive pressure favoring the emergence of advanced IMA2G-like architectures within the next 5 to 10 years. These architectures will be distinguished from current state-of-the-art systems by high degrees of virtualization and extremely limited hardware specialization. They will employ multi-core processors, high-speed deterministic Ethernet, and will be designed, tested, and certified using a data-model-driven paradigm. The convergence of functional domains in these second-generation IMA designs will reduce (or in some case, eliminate) the gap between manned and unmanned platforms.

From our alignment comparison in Chapter IV, it is clear that key attributes and outcomes of the Future Vertical Life program are strongly supported by the projected benefits of the IMA2G technology. As a consequence of this fact, as well as the marketplace trends described previously, system architects are already attempting to incorporate IMA2G-like technologies into the Joint Common (avionics) Architecture for the FVL.

So where do these intermediate conclusions leave us in our assessment? Is it already a foregone conclusion that the FVL will employ software-defined mission-systems with converged VMS? We have already established that the ambitious requirements written into the FVL ICD make IMA2G a natural fit, but is there anything *outside* those explicit requirements that might counter-indicate that choice? Have we considered, for instance, the sum-total attributes that a fleet of such aircraft would display in operational service? Are there any objectionable second or third-order effects that may result from these attributes? If so, how might these effects be countered or mitigated against? The remaining portion of this thesis will be dedicated to proposing speculative, but well-grounded answers to these questions, and stimulating further research.

1. Is IMA2G inevitable?

In the long-term, our findings indicate no reason to believe that the current trend toward increasingly software-defined avionics will abate or reverse. This forecast progression will eventually lead to flying IMA2G-like architectures in production civil and military aircraft. That being said, it is not certain yet to what extent the FVL program will participate in, or contribute to that trend. In our interview with Boeing JCA architect Tom Du Bois, he stressed that development efforts are purely experimental and conceptual at this point – meaning that a great deal could change. The Joint services could, for instance, decided to scale back some of the more technically ambitious wording in the FVL program documents, allowing room for a less-integrated, off-the-shelf solution to the identified capability gaps. To offer one example, scaling back the UAS interoperability requirement to Level 4, (limited in-flight and mission package control), is already achievable with partial IMA in refitted AH-64 Apaches. If the requirement to build unmanned and optionally manned variants with the same common avionics architecture is also relaxed or omitted, it would greatly reduce the amount of system-wide integration and abstraction required. Second-Generation IMA might not be necessary at all.

In light of the pervasive technology trend evident in the avionics industry (and elsewhere) toward converged, software-defined systems, it may not be *wise*, however, for the FVL program to bypass this emerging paradigm. The life-cycle of major military systems has grown steadily longer in past decades, in spite of the apparent acceleration of consumer technology advances. Where once the nation's defense relied upon the cutting-edge systems that were well-beyond anything available to the general public in terms of sophistication, the situation has utterly reversed itself now. The recent push for Commercial-Off-The-Shelf (COTS) technology adoption for DOD applications has as much (or more) to do with performance as it does with cost-savings.

An argument can be made that military technology must of necessity follow a more conservative path than consumer products, as the security, reliability, and survivability requirements for military applications are much, much more stringent. Allowing front-line aircraft to lag excessively behind the state-of-the-art in terms of

computing power and network technology could have severe consequences for the cost of support and service-life extensions though. It is not difficult to envision a scenario in which the first operational FVL variants reach squadron service in 2035 with basic IMA architectures comparable to what Boeing and Airbus were delivering to their customers *twenty-five years* earlier. In that case, the DOD might find itself as the sole remaining customer for outdated processors and network technology. Since foreign military sales will no-doubt be an important success-metric for the FVL program, one must ask how competitive such rotorcraft might be vis-à-vis, European or Asian-designed IMA2G aircraft? Indeed, opting for fully mature technology in the Joint Common Architecture seems sensible and conservative *now*, but by the mid-century mark, we could well regret that decision.

2. Operational Effects

In order to project meaningfully upon the operational impacts of advanced IMA in future rotary wing assets, it is necessary to embrace the totality of the picture and consider the characteristics of the end product: the aircraft itself. There will be some aspects of IMA2G technology itself that have direct consequences; but many others will simply be an effect of the capabilities that IMA2G allows. If the latter seems like an unwarranted digression in an otherwise technical analysis, it can be argued that decisions on military technology should always be made with knowledge and forethought of possible second-order effects. Doing otherwise risks opening new capability gaps even as we succeed in closing existing ones.

A wider systemic view is essential. An aircraft like the FVL (with or without IMA2G technology) must function as a component of other, larger systems. Upgrading and enhancing one component of a complex system often creates new points of strain or limitation elsewhere. There is no doubt that a Joint force fleet of IMA2G-equipped FVL rotorcraft would offer impressive capabilities and address many of the shortfalls and limitations of current (federated-systems) helicopters, but those enhanced capabilities are likely to shift points-of-failure elsewhere. If known in advance or anticipated, the ripple

effects of implementing new technology can be planned for and mitigated. Waiting for such effects to actually materialize before considering the impact, however, is ill advised.

As an outgrowth of our research on the technology of software-defined avionics and mission systems, we have developed several matrices of operational and tactical impacts, likely consequences or ripple-effects (both positive and negative), and proposed mitigation strategies where appropriate. The list is in no means exhaustive; yet exploring each item in detail would still be beyond the scope of this study. Our purpose in including them is purely to suggest further lines of research, and perhaps paint a more comprehensive view of how we see advanced IMA taking the DOD's rotary wing fleet in the future. Our speculations will be further refined in an operational vignette to follow.

a. Extended Aircraft Availability

In Table 10, we compare the obvious positive operational consequence of higher mission-availability rates, with the less-obvious (but no-less significant) second-order effects of that increased availability. The underlying assumption is that commanders will continue to utilize all, or nearly all, of the available rotary-wing services at their disposal – even as that notional capacity increases.

The primary concern here is that the human element (both aircrew and support) will be stretched dangerously thin. This hazard must be considered particularly probable in the context of pressure on the DOD to reduce its manpower footprint. Making a value-based decision on airborne services versus manpower costs is essential here: if the Joint services *benefit* from increased value-per-dollar expended on rotary wing aircraft (due to increased reliability/decreased maintenance), they must be prepared to *pay* for at least a portion of that added value by supplying sufficient human capital to sustain the desired op-tempo. If human costs are deemed prohibitive beyond a certain point, then the only sustainable long-term solution is to give up some of the potential benefit. IE: cut back flight hours to fit the new limiting factor: personnel.

Table 10. Operation impact: extended aircraft availability

IMPACT/CHANGE	Increased aircraft availability and FMC Rate
POSITIVE CONSEQUENCES	• Fewer aircraft required to meet mission, reduces total procurement cost and footprint of deployed force. • Operational planning less constrained by aircraft availability. • Enables reduced maintenance manning, and component replacement costs. • Aircraft are safer to operate, with fewer in-flight or on-deck aborts due to equipment failure.
ADVERSE CONSEQUENCES	• Increased availability puts aircrews at additional risk for fatigue if crew numbers are not increased proportionately. • Enhanced op-tempo puts additional strain on ancillary support services, such as tower and flight deck personnel.
MITIGATION STRATEGIES	• Be prepared to increase aircrew manning in near-proportion to the improvement in FMC rates. Deployed units already operate at or near safe margins for crew day/ crew rest. • Consider adjusting air-capable ship manning to enable sustained 24 - 7 flight support for rotary wing assets (manned and unmanned).

b. Enhanced Mission Capability

Table 11 projects that the combination of IMA2G-based mission systems agility, UAS interoperability, and the increased range, speed, and payload of the FVL platform is likely to generate new or expanded mission-sets for the rotary-wing fleet. Helicopters currently make up over 50% of the total aircraft in the Joint service inventory – compared to less than 20% for fixed-wing attack/strike aircraft. (“U.S. Military Strength,” 2015) It is reasonable to expect that FVL variants, especially the medium-lift platform, will also be built in large numbers. Assuming a reasonably successful development program, this should bringing FVL per-unit costs down relative to comparably advanced fixed-wing jet aircraft, which almost-surely be purchased in smaller quantities. This fact opens up the

possibility that certain force-application missions that have traditionally been associated with such assets may begin to migrate to newly-capable vertical-lift aircraft. Even if they are judged less-effective at those missions on a per-aircraft-sortie basis, their greater numerical availability, along with their capacity to work closely with tactical drones, and their reduced reliance on well-developed airfields or aircraft carriers will make them an attractive alternative in many cases.

Table 11. Operational impact: enhanced mission capability

IMPACT/CHANGE	Broadened mission-capability, flexibility, outreach
POSITIVE CONSEQUENCE	- Operational planners less constrained by available assets, since aircraft can be reconfigured via software for specialized mission support. - New sensor-fusion ISR and communication capabilities for Joint Forces resulting in higher SA for both aircrew and commanders near the tactical edge - Ability to rapid adopt new communications paths, sensors, or weapons as they become available
ADVERSE CONSEQUENCE	- Capacity for multi-mission flexibility may further erode specialty skills of aircrew. “Jack of all trades, master of none” scenario. - New mission sets may evolve for rotary-wing assets in competition with existing capabilities, leading to inter- and intra-service rivalry.
MITIGATION STRATEGY	- Consider longer duration initial fleet tours for aircrew to allow for extended experience with multiple mission-types. - Review and re-align as mission-sets for advanced rotary-wing platforms at appropriate to their newfound capabilities. - Leverage the mission-equipment-as-tactical-simulator concept enabled by IMA2G to assist in proficiency for deployed crews

On order to make best use of available aviation components, including the FVLFOs, we anticipate the need for a serious review and/or realignment of mission priorities for various platforms. It seems likely that a projected future of limited wars,

counter-insurgencies, and proliferated anti-access/area-denial (A2AD) weapons will favor the flexible capabilities of advanced rotary-wing aircraft, closely teamed with unmanned, or optionally manned platforms.

Of course, the inherent capability of a given aircraft to fly of a multitude of missions does not mean that the majority of its crews are competent to execute 100% of those missions 100% of the time. The reality of personnel rotation, work-up cycles, and fiscally constrained budgets for training virtually preclude this from being the case. In the largely-bygone era of single-mission military aircraft, pilots and crewmen could concentrate their training and experience on a particular, narrowly defined skill-set, usually achieving a high degree of competency as a result. Modern crews of multi-mission platforms do not have that luxury. Though they generally have assistance from on-board automation to help make up for their lack of specialist competency, they are still required to remain cognizant of a very broad spectrum of tactics, techniques and procedures. At a certain point, as mission-sets continue to expand and diversify, a tipping point could easily be reached. Again, the limiting factor becomes the human element.

Cognitive decision aiding and partial automation are proposed within the FVL ICD to help address this “weak link” in the cockpit. Both of these services are robustly supported by an advanced IMA2G system, but there is perhaps an additional way that software-defined avionics could help: by ensuring that aircrews are better prepared for their missions in the first place.

High-fidelity tactical simulators have already proven their worth as a training tool and are in many cases supplanting actual flight hours for maintaining readiness. Due to their cost and large logistic footprint however, they are generally in short supply, and never available in deployed environments. But what if every fleet aircraft could function as its own simulator? With access to the latest theatre intelligence, aircrews could rehearse real-world missions, experiment with different tactics, and then actually launch on the sortie and fly it. Afterwards, if deemed useful, the mission could be re-flown based on recorded data.

The highly-abstract nature of IMA2G makes this a very real possibility. Most avionics and mission-systems functions would exist as hosted virtual machines on the

server network, with their only connection to I/O and effectors provided through the services of the hypervisor. A special mode could be enacted in which the hypervisor re-routed the majority of those outbound messages to a hosted simulation program. Loaded with the scenario of choice, the program would define the virtual world that the other hosted aircraft systems would “see.” From the aircrew’s perspective, cockpit functionality would be identical to what they would experience in an actual flight. External visuals could be provided (optionally) by a kit of deployable projection screens, and multiple aircraft and UAV’s could be linked together to practice cooperative tactics. (See Appendix A for a notional depiction of this set-up.) Minor maintenance and servicing could even be accomplished concurrently with the simulator event, in order to assure the aircraft was ready to launch immediately afterwards. Alternately, airframes that are currently grounded for repairs might in some cases still be usable as simulators, providing value even while not available for flight ops.

c. Manned/Unmanned Aircraft Convergence and Teaming

Of course, any discussion of human pilots as a “weak link” in an otherwise highly-capable airborne system begs a further question: why put a warm body in the cockpit at all? Certainly, for some missions—especially those falling under the description of “dull, dirty, or dangerous”—unmanned systems are probably the best choice. In a fully-developed future battle-space however, the more likely scenario is close teaming and interaction between UAVs and manned aircraft. MUM-T, as previously described, is strongly supported by advanced IMA mission-systems architecture. In Table 12, we list some of the prominent advantages that might be gained by the convergence and teaming of manned and unmanned FVL variants, and the down-stream effects could possibly develop.

Contrary to the starry-eyed optimism envisioned in the DOD’s Unmanned System Integration Roadmap (2013), we do not feel that the increased utilization of UAVs to provide round-the-clock aerial services is a silver-bullet solution to the Joint services current manpower concerns. In the context of optionally piloted FVL variants, the cost-per-flight hour is likely to be exactly the same whether the craft is manned or not. The

decision of what mode to employ it in must be driven by factors other than cost-containment.

Employment of optionally-manned rotorcraft must also be considered in light of adversary perceptions. Opposing forces under surveillance by FVL aircraft will often have little way of knowing whether or not there is a human crew on board, and the assumption (one way or the other) could mean a radically different reaction. Shooting down a drone might be considered an acceptable escalation of current tensions, whereas attacking a manned aircraft would not; thus a drone might be protected by the perception that it *could* be manned. Conversely, a manned crew could be targeted based on the mistaken belief that their aircraft is “just a drone.”

Table 12. Operational impact: manned/unmanned convergence/teaming

IMPACT/CHANGE	UAS Teaming / Convergence of Manned/Unmanned Systems
POSITIVE CONSEQUENCE	• Powerful force multiplier. Enables extended air-mission coverage. • Enables new tactics that will reduce risk to manned aircrews while still extending high-quality support for CAS mission and OTH-T. • Human crews can be “saved” for missions that significantly benefit from their presence. Missions that are just-as-well conducted autonomously or remotely need not be manned. • Optionally-piloted aircraft provide a unified asset – with common maintenance support – for both manned and unmanned missions. • The manned or unmanned status of optionally-piloted FVL aircraft will be opaque to potential adversary forces. They may be more reluctant to engage the aircraft due to the perception of more severe consequences for destroying a manned aircraft.
ADVERSE CONSEQUENCE	• Additional round-the-clock strain on aircrews due to the need to supervise unmanned FVL mission in addition to manned sorties. • Reduced flight hours and actual “stick time” erodes basic aircrew competency and Esprit d’Corps. • Without aircrew-driven limits, commanders will

IMPACT/CHANGE	UAS Teaming / Convergence of Manned/Unmanned Systems
	demand 24-hour flight operations, straining support services like maintenance, ATC, and flight-deck crews. • Planners may be tempted to supplant qualified pilots with less-expensive, junior personnel for unmanned FVL missions; loss of experience may result in poorer mission performance. • A manned aircraft may be targeted on the assumption that it is “just a drone.”
MITIGATION STRATEGY	• Be prepared to increase aircrew and support-crew manning in order to support 24/7 flight ops. • Develop new TTP for UAS-manned aircraft teaming, established firm policy guidance on what mission-sets require on-board human crew for execution.

d. System Software Complexity

Software and overall system complexity is a fact of life for modern aircraft, and IMA2G architectures will be far more complex than anything flying today. The open question is whether the cleverness of the system’s open-architecture and MILS-compliant foundation will be enough to help mitigate (or even reverse) the adverse consequences of that logical complexity, or whether it will only make things worse. One way or another, robust security needs to be fundamental to the design of the FVL’s mission-systems; not merely assumed away or added on afterwards as a patch.

Table 13. Operational impact: system software complexity

IMPACT/CHANGE	Software Complexity, Functionality and Authority
POSITIVE CONSEQUENCE	• Software-driven functionality will be easier to upgrade during vehicle life-cycle, allowing rapid capability evolution • Aircraft will be capable of providing autonomous support to human crew, reducing workload in critical combat situations. • Every onboard function can be tracked and

IMPACT/CHANGE	Software Complexity, Functionality and Authority
	monitored; feeding into proactive condition-based maintenance, and maintenance-availability-based sortie planning. • Aircraft will be easier and safer to fly at the margins of performance, perhaps approaching the ideal of a “uncrashable” aircraft
ADVERSE CONSEQUENCE	• Need for advanced skill-set to troubleshoot problems with IMA2G aircraft avionics could make front-line Joint forces more reliant on expensive contractors for support. • In the event that an FVL aircraft is captured by a sophisticated adversary, the enormous quantity of data on board, much of it stored in open-source COTS applications may be a significant liability. • Near 100% of aircraft functionality, including flight and weapon systems will be potentially vulnerable to malicious code implanted by a sophisticated enemy. • A malfunctioning or enemy-corrupted full-authority IMA system could take control away from the human crew with tragic and devastating consequence.
MITIGATION STRATEGY	• Include a requirement for a hard-disconnect option in the JCA to restore manned control in the event of corrupted autonomous or external control. • Ensure capacity exists within the system to conclusively (and remotely) wipe all classified and mission data from on-board aircraft memory in the event of imminent capture by adversary forces.

B. OPERATIONAL VIGNETTE

The following is a hypothetical scenario in which the presumed characteristics of an FVL aircraft with software-defined mission systems is imagined in a potential operational environment. The FVL variant in question is an optionally-manned multi-mission maritime version in U.S. Navy service. The presumed time-frame of this scenario is the late 2030’s; several years the aircraft has reached IOC. The backdrop of events is a rapidly escalating territorial dispute in the Western Pacific over energy exploitation and fishing rights.

1. Scenario Background

Seeking an alternative method to realize territorial claims rejected by the rest of the international community, Country Orange has apparently resorted to arming and assisting separatist rebels on an island chain bordering disputed shoal waters. The Brown Islands are a recognized archipelago of Country Green, and most inhabitants of its major population center consider themselves loyal citizens of Country Green. Country Orange, however, claims ethnic and historical ties to an oppressed minority population in the southwestern third of the archipelago. Six months ago, the Brown Islands were struck by a severe typhoon, providing Country Orange the pretext to establish a humanitarian naval and air mission to the rebel-dominated portion of the archipelago. Since then, hostilities between the rebels and Country Green forces have escalated rapidly. Western intelligence sources suggest that Country Orange is providing military weapons and training to the otherwise isolated rebels, in addition to food and relief supplies. Country Green suspects this as well, and has openly accused Country Orange of fomenting revolution on the archipelago. Recently, a Green corvette near the Brown coast was destroyed by a suspected light-weight anti-ship cruise missile fired from a shore-based TEL (Transporter, Erector, Launcher). Rebels claimed responsibility, but all signs point to Country Orange as the supplier of the missile system.

In order to help arrest further hostilities and deter Country Orange from undertaking overt military action in support of the Brown Island Rebels, the U.S. Pacific Command has dispatched a combined joint task force to the region. As part of that task force, the guided-missile destroyer USS Chris Kyle, DDG-123, is currently sailing off the western edge of the brown Archipelago. Embarked aboard the *Kyle* is a two-plane detachment from Vertical-Lift Maritime Strike Squadron Five-One (VMS-51) – the “Warlords” – out of Iwakuni, Japan.

2. Phase I: Ops Normal

Date: March 29, 2039

Time: 1645L (0845Z)

Location: 70 NM WSW of Goat Island in the Brown Archipelago.

Threat Warning Condition: Yellow

Weapon Control Status: Tight

Warlord 710 flew a rock-steady approach to the back of the *USS Chris Kyle*, touching down and dropping its landing probe dead-center in the Recovery & Securing Device (RSD) “trap.” It was just the sort of landing one would expect from a well-seasoned crew on the back-end of a long deployment. Except for one small detail... The cockpit and cabin of Warlord 710 was presently *unoccupied*.

Detachment Four Officer-in-Charge (OIC) “JD” watched the recovery from the right seat of the Det’s other aircraft, Warlord 704, orbiting a quarter-mile off. *Tough act to follow*, he thought to himself. The only way of really competing with the smoothness of an automated FVL approach was to add a little style; come in fast, flare at the last minute – and hope you didn’t “goon it up” and make a fool of yourself. Most of the time he managed to pull that off pretty convincingly, but then again, his first fleet tour had been spent wrestling overweight, nervous-handling conventional helicopters onto small decks like this—without the benefit of fly-by-wire controls or the safety-net of an automatic approach mode.

Those old MH-60Rs couldn’t fly their own functional check-flights (FCFs) either, come to think of it—which was exactly what Warlord 710 had just done. After a few minutes of spinning on deck, the unmanned aircraft shut down and began folding its rotors. JD’s aircrewman aboard 704, AW2 Stout, who had been monitoring the other aircraft’s flight via secure data-link, keyed the ICS. “Looks like 710’s up FMC Boss. All Vibe runs and final grounds are within limits.”

“Roger,” JD replied, nodding. “I guess we’re going to have an alert aircraft tonight after all.”

“Sir, I was kind of hoping we wouldn’t,” Stout replied with his usual excessive candor.

“Me too.” JD agreed. Things had been certainly been heating up lately in this AOR. Back in November, the *Kyle* and Det Four had been sent down here to support humanitarian assistance and disaster relief (HADR) operations in the Brown Archipelago.

They had no idea at the time that they would be back just a few months later, getting shot at.

Well strictly speaking, JD clarified to himself, *we didn't get shot at*, Warlord 710 *got shot at*.

Two nights ago, while flying an autonomous ISR flight in the vicinity of Goat Island, 710 had taken small-arms fire from a rebel gunboat. Reacting as quickly to the threat as any human pilot could have, the self-flying rotorcraft had managed to get away safely, but returned to the ship with a gaping hole from a 12.7 mm machine gun in one of its rotor-blades. Replacing that blade had driven the FCF today; and now, after two unmanned vibration runs, the machine was back up and available for tasking.

The same could not be said, unfortunately, for the Detachment Maintenance Officer. “Squirrel” was currently laid up with fractured a bone in her left hand. She had fallen down a ladder well on the ship while rushing to inform her OIC that 710 had been fired upon. That left JD as the only qualified AC (Aircraft Commander) on the four-pilot det.

Given the recent spate of hostilities, the captain of the *Chris Kyle* had insisted that the Detachment fly an armed overwatch mission to cover 710 during its FCF runs—which was the only reason why JD was airborne at the moment. The majority of action around Goat Island, including the covert intrusion of Country-Orange vessels into Green territorial waters to supply arms to the rebels, happened only under the cover of darkness.

JD glanced over at the empty seat to his left. Taking advantage of 704's single-pilot mode, with its “virtual co-pilot” service, he had been able to spare his two nugget pilots the boredom of a daytime drone-escort mission; that way, they would be fresh for tonight's alert, and could remain on the nocturnal schedule they had already adapted to. As for himself and AW2 Stout, his goal was to be on deck as soon as 710 was folded and stuffed inside the port hangar.

“Green deck,” JD announced over the ICS. Up ahead in the distance, he could make out the green deck status light on the *Kyle*; but he needn't have looked up from his instrument console to know that he had been cleared to land. The four MFD's (Multi-

Function Displays) in front of him currently showed everything he needed to know, including the deck-status. Courtesy of the KU-band data-link with the destroyer and the attentive services of his virtual co-pilot, he had the ships BRC (base recovery course) dialed in, as well as a continuously updated read-out on such factors as closure-rate, winds-over-the-deck, and pitch and roll.

“Hal-704,” JD annunciated into the mike, summoning his voice-activated virtual co-pilot by its programmed sobriquet. “Landing Checklist: shipboard recovery.”

At once, the NATOP checklist for landing operations appeared on one of JD’s MFDs, and a faultlessly calm, computerized voice began methodically reading checklist items. On cue, JD either performed the listed step, or issued a verbal reply, prompting “Hal” to do it himself. At the end of the checklist, the computerized co-pilot confirmed that winds over the deck were within limits and landing gear was down and locked.

Approximately ninety seconds later, Warlord 704 crossed the deck-edge and alighted securely with its probe in the RSD.

“Try to beat that one, Hal” JD mumbled to himself.

“Please repeat your last,” replied the automated voice, apologetically. “I did not understand your request.”

“Disregard Hal 704,” JD instructed. “Initiate autonomous hand-over checklist.”

As the Det Four OIC and AW2 Stout unstrapped, Warlord 704 began preparing itself for its next mission. Tonight, a SEAL platoon was going ashore via submersible delivery vehicle to scout for (and hopefully neutralize) the Orange-supplied mobile ASCM launchers with which the rebels had been attacking Country Green shipping. 704 would provide armed overwatch and continuous surveillance throughout the night. If all went well, the SEALs would hit their target and egress the same way they had come before sunrise. Until then though, Warlord 710—and a human crew—would be on 30-minute alert for an airborne extraction.

3. Phase II: Mission Preparation

Time: 1830L (1030Z)

After dinner in the wardroom, JD rounded up his two nugget pilots and the aircrewmembers that would be sharing the night's alert mission with him. After checking in with the ship's Tactical Action Officer (TAO) in the Combat Information Center (CIC), and watching a few minutes of live sensor feed from Warlord 704, they conducted their own mission brief and headed to the hangar. Per JD's instructions, Warlord 710 was already set up with the Det's DIVTAC (deployable integrated virtual tactical simulator) kit, and a simulated mission emulating an opposed SEAL extraction from Goat Island was loaded and ready to go.

A wealth of recent all-source intelligence and fused sensor data from the Navy's "Big-Data" tactical cloud ensured a high degree of fidelity in the simulation model. JD flew two ingress and egress runs apiece with each of his nuggets in the space of just 40 minutes, experimenting with various routes to and from the LZ (Landing Zone). Based on the simulation results, he concluded that his odds of getting feet-dry for the pick-up without being detected were better than 50–50. Getting back out again however, was going to be a bit tricky. By the end of the last run, there were tracers arcing all over the computer-generated night sky, and JD's co-pilot, Flo, was working hard to evade.

"You think there's really going to be that many of them shooting at us," she asked.

"This is just a worst-case scenario," JD dismissed calmly. "Don't worry about it...Too much."

Satisfied that that his crew was ready, the Det Four OIC called an end to the simulator session. "Get some rest everybody. There's going to be a whole lot of hurry-up-and-wait before dawn."

4. Phase III: Alert Upgrade

Time: 2330L (1530Z)

The first four hours of this alert period went by as expected: quietly. It was not the first time Det Four had been tasked with such "hurry up and wait" tasking in support of SOF forces in the Brown Archipelago; and they usually ended up sitting on the bench

while army rotorcraft from the 160th SOAR (Special Operations Aviation Regiment) got the actual sortie. JD had no inkling yet that tonight would be any different, so after Warlord 704 returned for fuel and re-launched autonomously, he grabbed a workout mat, stretched out on the flight deck, and fell asleep under the stars.

Not long before midnight, Flo suddenly shook him awake. “JD!, JD! Sir!” the lieutenant junior-grade spoke in a frenzy. “We just got upgraded to a ready-five!”

Jarred instantly from his stupor by the announcement, JD leapt to his feet and snatched up his yoga mat. A moment later, the port hangar door began to open, and the clamor of busy sailors spilled out onto the flight deck.

“Gear up,” he instructed Flo. “I’ll be back in a minute.”

As JD rushed past Warlord 704, still folded and stuffed in the hangar, he noticed that the DIVTACS kit was still installed and activated. Now though, instead of acting a simulator, it was linked to the Warlord 710, and the images projected on the deployable view screens were live feed from the other aircraft’s onboard cameras. In theory, 710 could be remotely piloted from the cockpit of her sister-aircraft, through the medium of the *Kyle*’s data link, but right now, it was only functioning as a secondary monitoring station. The primary mission-control station was in the Combat Information Center (CIC) – and that was where JD has headed now, grabbing his helmet and vest as he went.

“Looks like the SEALs are having trouble making it back to their sub rendezvous,” explained Squirrel as JD and the ship’s TAO leaned over her shoulder in CIC. “Too much heat.”

“I can see that,” agreed JD. The sensor feed from Warlord 710 was up on Squirrel’s console. There was clearly a firefight in progress on the coast of Goat Island. Glowing arcs of tracers were crisscrossing over the tropical beach.

“Captain in Combat,” someone announced. A moment later, the CO of the *Chris Kyle* joined JD, Squirrel and the TAO. The commander’s first question was about the TELs; he wanted to know if the SEALs had managed to take them out.

“Negative Sir,” answered the TAO. “They found them, but they can’t get there right now.”

“What about 704?” asked the captain. “It’s armed. Can we use it to hit the launchers?”

Squirrel field that question: “Out of range Sir. 704 had to stand back when she started taking AAA and MANPAD fire.”

“How far out are we?” asked JD.

“32 nautical miles from the beach,” said the TAO. “Just outside the range of those cruise missiles.”

“Until those TELS are down, that’s as close as you’re getting,” stated the captain with a glance toward JD.

“I’ve got missiles on the rail on 710, ready to go,” JD replied. “All I need is the word.”

“Unfortunately, that’ll have to come from the Admiral,” shrugged the captain.

JD wasted no further time in CIC. Squirrel was already busy uploading the additional intel and mission information onto Warlord 710’s avionics servers. By the time the Det Four OIC was strapped in, the aircraft was configured for dual-piloted flight, and waypoints determined on the basis of the earlier simulation run were up on the navigation screen. The old saw “Fight like you train” had rarely found more literal expression.

JD’s copilot tonight—aside from the omnipresent virtual one imbedded in the avionics server—was the det’s most junior aviator, Flo; but the OIC didn’t consider that fact a liability. A fresh set of eyes in the cockpit could sometimes be a vital asset, especially when backed up by some experience in the right seat, and the unblinking eye of technology imbedded in the aircraft’s smart systems.

Stuck in CIC with her broken hand meanwhile, Squirrel couldn’t pass up the chance to tease her fellow JO (Junior Officer) over the data-link.

“Ready to be a hero, Flo-Baby?”

Flo got her right back without missing a beat. “Maybe if you weren’t such a klutz, you’d be sitting here instead of me tonight. But anyway, I’m sure Hal’s got my back.”

5. Phase IV: Launch the Alert!

Time: 0012L (1612Z)

With the aircraft spotted and spread on the deck, and the alert checklist complete, things got quiet for a few minutes aboard Warlord 710. Thanks to the live feed of video and data from Warlord 704, JD and his crew already had a remarkably clear and detailed tactical picture of the operating area on their MFDs, complete with blue-force position indicators for the SEAL platoon, and tracks for the cruise missile TELS.

“Look – the TELS are on the move,” Flo pointed out. “They’re buggin’ out.”

JD nodded, watching the vehicles line up in a convoy and start to drive slowly westward. It was exactly the scenario he had programmed into his simulation earlier. He knew already that if the launchers managed to reach the jungle-covered highlands seven miles up the road, they would be very difficult to root out; but if he could launch right *now*, there was still time to engage those TELS *and* meet the SEALs at their back-up extraction point. They had just practiced it in the DICTACS.

As if on cue, a new message popped up in the secure command chat that JD was monitoring on one of his ancillary screens: “CJTF says: Launch Warlord 710,” it read. A few seconds later, the tactical controller echoed the command over the data-link voice channel. By then the crew was already working their checklists through Hal to start the engines and prepare for take-off. While they were waiting for the ship to turn into the wind and pass green deck, JD noticed another, follow-on message from the CJTF Battle Watch. “Sniper helos directed to neutralize TELs on Goat Island prior to SEAL extraction. 160 SOAR is avail for p/u of team in 40 min if required.” *Sniper*, was the local callsign for the *USS Chris Kyle*, of course. JD grinned to himself as the deck status light turned green. It looked like he was going to get the opportunity to translate his simulator run into reality after all. *Let’s try not to goon this was up so bad*, he thought to himself silently.

“Gauges green, ready to lift,” he announced calmly. Second later, Warlord 710 was airborne and headed East.

6. Phase V: Flexible, Lethal, Survivable.

Time: 0018L (1618Z)

Warlord 710 skimmed the moonlit waves at just 25 feet AGL (above ground level) and over 300 knots—a performance enabled as much by the aircraft’s advanced automated terrain/collision avoidance system as by its agile airframe. Shortly after take-off from the *Kyle*. JD’s crew had managed to establish direct link with Warlord 704, currently in a 6,000 ft orbit off the coast of Goat Island. Now the two aircraft re-synchronized their tactical data and began automatically pooling their sensor information to create a fused tactical plot. Using cross-fixed ES (electronic support) bearing-lines from each aircraft’s receivers, anti-aircraft and coastal warning radar installations on the island’s west side were pinpointed. An overlay of their predicted coverage areas continuously updated as JD and his crew continued inbound.

Advances in modular software and virtual “black boxes” meant that the Warlord aircraft had an EW (electronic warfare) suite functionally equal to the now-retired F/A-18G Growlers. Suppression of maritime air defenses was even a mission that their crews were required to train to, usually as part of team with another rotorcraft flying in autonomous mode. Tonight though, JD preferred to *evade* the rebel’s air defenses, rather than confront them directly. Instead of anti-radiation missiles on his stub-wing rails, he had a load-out of eight short-range Griffin-C dual-mode IR/Laser air-to-surface missiles, and a twenty-millimeter gun pod.

With the multi-spectrum night-vision system built into his helmet-mounted cuing system, JD could soon see the craggy profile of Goat Island becoming visible in the distance. Via com-relay through Warlord 704, he also had secure voice contact with the SEAL platoon leader.

“We’re at LZ Bravo,” announced the Navy frogman. “We broke contact, but they’ll be on us again soon. Say ETA.”

“Warlord 710 will be overhead in... two minutes, thirty seconds,” JD answered, consulting his tactical display. “Engaging the TELs en-route.”

“Good luck! Their running for it.”

Thanks to some close coordination between Flo in the left seat, AW2 Stout at the sensor-operator station, and Squirrel back aboard the *Kyle*, the shot was already set up. While 704 maintained surveillance over the TEL convoy from a safe stand-off range, 710 would swing in low and hug the rugged coast-line of Goat Island. Masked by terrain, 710 would fire a volley of Griffin-C missiles once in range, which would automatically climb to altitude, and hopefully pick up the laser energy from 704’s target designator. At that point, they would arc back down toward the road, lock onto the heat-signature of the vehicles and go into IR mode for terminal guidance.

The “shot fans” on JD’s moving map tactical display made lining up for the complex shot easy. At his command, Flo triggered the first shot. A Griffin missile burst off the left-hand rail with a sound like a shotgun going off. It immediately climbed skyward, reporting its status back to 710 through a simple, high-speed data link.

“Missile away. Good link.” Flo reported, excitedly. “704 has it now... Good laser energy...”

“Fire two.” JD directed.

Flo triggered the next shot. Five seconds later, the third Griffin followed, and five seconds after that, a fourth missile was airborne. By time the last weapon left the launch rail, the first weapon had already struck its target. Three more closely spaced explosions lit up the night sky in rapid succession.

Flo called the hits over the ICS, but there was no time to confirm if all the TELS were destroyed. That could wait for later; every byte of data from both aircraft was being recorded for later playback anyway. Right now, Warlord 710 had other matters to attend to; namely, getting to LZ Bravo on-time for their overhead.

Per the plan they had worked out earlier that night in the DIVTACS session, the crew of 710 picked up their next waypoint, and directed 710 to provide covering fire in

autonomous mode. The landing zone was in a small jungle clearing some distance from the shore; it looked exactly the way it had in the simulator. After a quick reconnaissance pass, JD slowed Warlord 710 and dropped below the treeline. Before his wheels even touched down in the grass, a group of dark shapes emerged from the underbrush and rushed toward the waiting rotorcraft. In quick succession, all eight SEALs jumped aboard.

“Clear!” Yelled AW2 Stout into the ICS from the door-gunner position. Without delay, JD pulled in power and executed a rapid no-hover take-off. Apparently though, it was not rapid *enough*. Just as they shuddered their way through translational lift and rotorcraft’s pusher fans started applying forward thrust, a tracer the size of a Forth-of-July rocket cut right across the windscreen. That *definitely* wasn’t small-arms fire!

A second later – before JD could even react – the whole airframe resounded with a sharp, brief impact. Every MFD in the cockpit went black for a fraction of a second, but then came back on-line.

“Break Left!” commanded the normally calm voice of 710’s automated copilot over the ICS. JD didn’t question the call – even if it was from an software program. He raked the aircraft over on its side and pulled hard. For a moment, as the dark-green mass of jungle rushed up to greet him through the cockpit window, he thought he could feel a guiding hand adjusting his control-inputs—just like one of his flight instructors at NAS Whiting Field might have on an early contact flight. “Reverse turn,” Hal advised again a second or two later. Another huge tracer flew by harmlessly.

A large explosion lit up the jungle behind and below them and a few moments later, the robotic voice over the ICS announced “Threat clear. Proceed on course”

Not sure what had just happened, but positive that they had just survived a very close call, JD let out a tense breath and turned westward toward the first waypoint on their egress route.

“Thanks Hal,” he mumbled into the microphone.

“Please repeat your last,” replied the automated voice. “I did not understand your request.”

7. Phase VI: High-Fidelity Debrief

Time: 0505L (2105Z)

Almost four hours after recovering Warlord 710 and 704, there was still a curious crowd milling about the *Kyle’s* hangar bay. The DIVTACS kit had been set up again (this time on 704) and the night’s mission over Goat Island was being replayed now for perhaps the fifth time. Everyone on the ship apparently wanted to get a look; including the captain, who insisted on sitting in the left seat and having JD explain every last thing that had happened from launch to recovery. By switching back and forth between the recorded viewpoints of both 710 and 704, a comprehensive reconstruction of the engagement had been quickly pieced together, indicating with a high degree of certainty that all of the TELs had been destroyed. Of course, official confirmation of that would have to wait until the intelligence cell at CJTF completed their own analysis of the mission data, but in the meantime, some other interesting facts had come to light.

To begin with, the reason the DIVTACS was set up on 704, instead of 710 was that the latter aircraft—the one JD and his crew had been flying in—had *a rather large hole* in the fuselage from a 23mm anti-aircraft shell. The mobile gun system that had fired that round was neutralized moments later by an autonomously launched Griffin missile from 704. The entire incident was a stunning example of the survivability provided by the rotorcraft’s advanced, software-defined mission systems. Warlord 710’s Avionics Stack I (its primary avionics server) had been totally destroyed by the anti-aircraft shell; and yet the aircraft had suffered no pilot-perceptible loss of functionality. The secondary avionics server “Stack II” had been running parallel instances of all flight and mission applications, and when “Stack I” dropped-off the network, failover to those parallel instances was immediate and seamless. In the seconds following the event, the system was even able to help guide JD’s break-lock maneuver with verbal advisories and outer-loop control inputs. That had been a close one. Lidar-altimeter data indicated that they had been less than ten feet from slamming into the ground at one point.

Thoughts of that seat-clenching moment were turning over again in JD's mind as he finally escaped the hangar and bay and walked out onto the flight deck to watch the sun rise. Flo was outside as well, doing the same thing.

"You remember what you told Squirrel last night before we took off?" JD asked after a few casual words.

"About being a klutz?"

"No – about Hal having your back."

"Oh, yeah," Flo nodded. "I guess he had *both* of our backs, didn't he?"

"With a copilot like that, I might even survive the rest of this tour of flying with nuggets like you."

VI. CONCLUSION AND RECOMMENDATION

A. IMA2G – ARCHITECTURE OF CHOICE FOR THE FVL

Despite the risks of immature technology and organizational resistance along several critical paths, our findings indicate that IMA2G is an overwhelming a favorable model for the FVL’s joint common architecture. It supports the speed, agility, range and payload goals of the FVL program through significant SWAP reductions; will help ensure enhanced aircraft-availability by eliminating numerous points of failure; will reduce manpower footprint by streamlining field-maintenance and adding an unmanned option to nominally manned platforms; will provide a common architecture across manned and unmanned variants, facilitating Level-5 interoperability; and its hardware and software modularity will help contain costs for maintenance and life-cycle update.

If the scope of required attributes and outcomes listed in the program’s ICD is scaled back to a degree, other options short of fully-realized second-generation IMA might be feasible – but are probably ill-advised in the long-term. While first-generation IMA has be a unqualified success in recent commercial aircraft, it has yet to demonstrate cost-effectiveness in a multi-mission military platform. Detractors of such IMA-equipped aircraft as the F-22, for instance, point out the difficulty in integrating new capabilities into closely-coupled systems. IMA2G, which hosts most functions as un-modified software instances running in a virtual computing environment has genuine potential to combine the SWAP gains of earlier integrated avionics with the modular flexibility of federated mission systems. By contrast, the practice of added functionality to a military aircraft by installing an endless procession of marginally-integrated black boxes has already reached its practical limit. Evidence of this can be seen in the latest AH-64E “Guardian” Apaches, and recent block-upgrades to F-16C fighters, which make use of localized IMA architectures, grafted onto federated systems in order to deliver additional functions without added more LRU’s and unnecessary wiring. Though in theory, the same could be done for the FVL, we must question the wisdom of handicapping an entire family of aircraft from birth with core avionics design that is already rapidly becoming obsolete.

B. EMBRACE CHANGE, REDUCE THE RISK

A better option, in the opinion of this author, is to embrace fully the coming sea-change in the way avionics for manned aircraft are designed and implemented. Like all future combat vehicles, the FVL will be expected to handle an extremely complex set of mission functions; the complexity of the task requires an equally complex suite of systems in order to execute it—and the problem we find ourselves in today is that our present (document-driven) means of moving such complex systems from concept to reality is no longer adequate to the task.

Model-Based Systems Engineering (MBSE), and Modular Open Systems Architecture (MOSA) are already painting the way forward. Public-private-sector consortiums such as FACE (Future Airborne Capabilities Environment) are pressing ahead establishing new industry-wide technical standards to help modular mission software finally become a reality; while in Europe, the SCARLETT group (SCAlable and Reconfigurable ElecTronic Technology) is channeling government investment into model-based testing for the next generation of integrated avionics.

In light of the clear immaturity of such technology as deterministic multi-core processing and high-assurance virtualization, it is tempting to tread a cautious path with the FVL. The entire program must, indeed, find its footing in an acquisition environment made pessimistic and hostile by the high-profile struggles of the F-35 Joint Strike Fighter. A tepid and hesitant advance rarely makes for effective military strategy on the battlefield though, and we suspect that it will do no better within the framework of major military systems acquisition.

If we allow our pessimism to translate into lukewarm investment in the coming revolution in aviation systems design, we will almost surely create a self-fulfilling prophesy. Radical improvement does not occur without committed support. Ideas are not enough. Ironically, the best way to reduce risk is occasionally to pick the opportune moment and charge full-speed ahead. With regard to model-based avionics design, testing and validation—the key discipline that will allow us to build a successful IMA2G Joint Common Architecture—that time is upon us now.

C. RECOMMENDATION FOR FURTHER RESEARCH

Though this study of software-defined avionics for the next generation of rotary-wing military aircraft may have succeeded in answering a few of the questions initially posed, the most salient result is probably the list of critical research areas it has highlighted. These directions for further study fall into three broad categories: technical, organizational, and operational.

a. Technical Research Directions

- Study of candidate Model-Based Systems Engineering methodologies to determine which is best-suited for developing military software/hardware solutions, including capturing the complexities of human-cyber interaction.
- Rigorous testing to verify if current and emerging technology can assure deterministic performance in multi-core processing, including in installations where one or more cores are deactivated.
- Survey of how advanced deterministic network applications in the automotive industry may point the way toward parallel developments in military aviation.
- Model the technical requirements that would be needed to create the built-in tactical simulator concept described in this paper.

b. Organizational Research Directions

- Study and develop proposed methods to integrate data-model-based design into the military acquisition system, from initial requirements development, all the way to operational testing.
- Survey both successful and failed open-source technical standards in the IT industry to help determine how best to implement one for military avionics.

c. Operational Research Directions

- Assess predicted manpower-requirements resulting from optionally-manned FVL aircraft that provide extended air-service availability to theatre commanders.

- Identify new mission-sets that the unique characteristics of such aircraft might allow in the future. Based on results, determine an ideal force-structure of FVL variants.
- Study the impact that built-in tactical training simulators would have on aircrew readiness. Would they be utilized enough in the deployed environment to justify their development?

APPENDIX A. DEPLOYABLE INTEGRATED VIRTUAL TACTICAL SIMULATOR (DIVTACS)

In Chapter V of this study, we introduced a proposed concept whereby an IMA2G-equipped FVL aircraft could provide deployed aircrews with their own high-fidelity tactical simulator. We refer to this notional system as DIVTACS, or deployable integrated virtual tactical simulator, and illustrate the concept below.

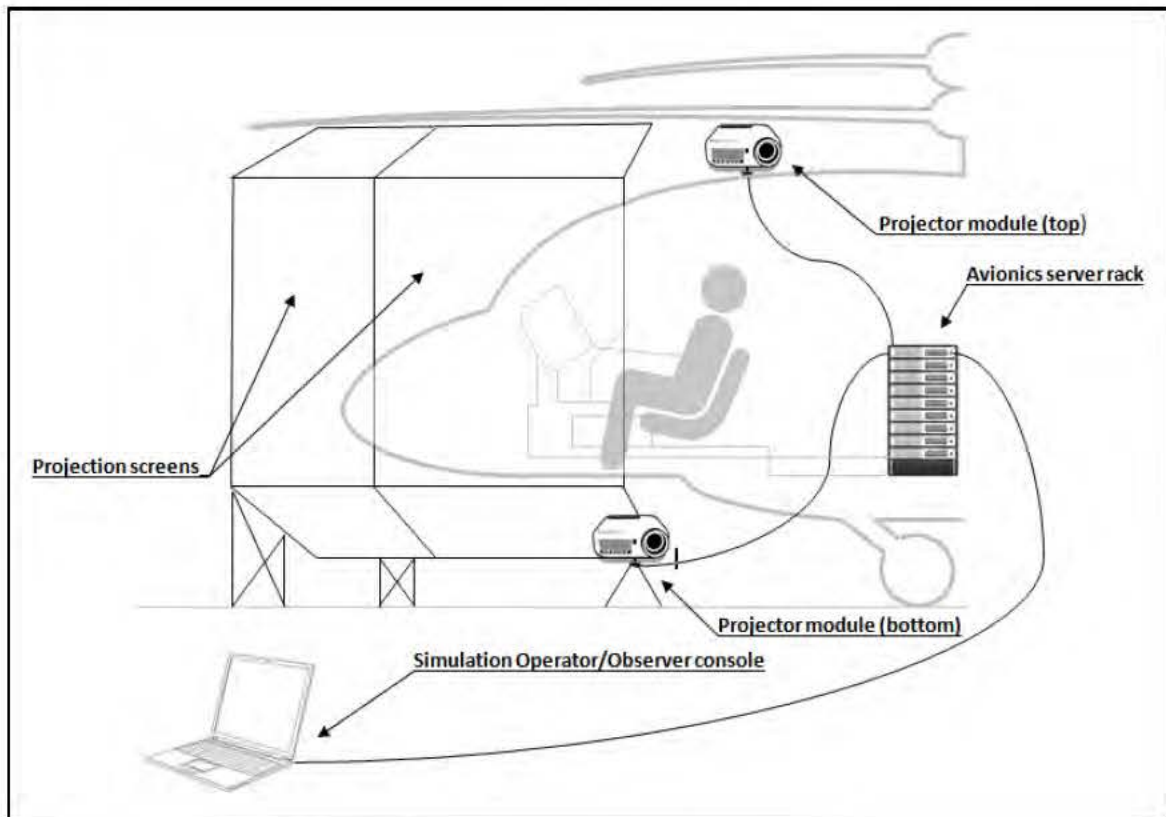


Figure 5. DIVTACS notional configuration

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APPENDIX B. TRL DEFINITIONS, DESCRIPTIONS, AND SUPPORTING INFORMATION

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory	System concepts that have been considered and results from testing laboratory scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard	Fidelity of breadboard technology increases	Results from testing laboratory breadboard

TRL	Definition	Description	Supporting Information
	validation in a relevant environment.	significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include “high-fidelity” laboratory integration of components.	system are integrated with other supporting elements in a simulated operational environment. How does the “relevant environment” differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a proto- type system that is near the desired con- figuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before

TRL	Definition	Description	Supporting Information
			moving to the next level?
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

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APPENDIX C. CURRENT AND EMERGING STANDARDS IN AVIONICS

ARINC 429; Mark 33 Digital Information Transfer System (DITS).

Paper and PDF copies available (for a fee) at:

http://www.aviation-ia.com/cf/store/catalog.cfm?prod_group_id=1&category_group_id=1

ARINC 629; Multi-Transmitter Data Bus.

Paper and PDF copies available (for a fee) at:

http://www.aviation-ia.com/cf/store/catalog.cfm?prod_group_id=1&category_group_id=3

ARINC 653; Avionics Application Software Standard Interface.

Paper and PDF copies available (for a fee) at:

http://www.aviation-ia.com/cf/store/catalog.cfm?prod_group_id=1&category_group_id=3

ARINC 664/AFDX; Aircraft Data Network.

Paper and PDF copies available (for a fee) at:

http://www.aviation-ia.com/cf/store/catalog.cfm?prod_group_id=1&category_group_id=3

MIL-STD-1553; Military Standard: Aircraft Internal Time Division Command/Response Multiplex Data Bus.

Multiple resources can be found at: <http://www.milstd1553.com/>

Various PDF editions can be accessed at:

http://everyspec.com/MIL-STD/MIL-STD-1500-1599/MIL-STD-1553B_NOTICE-4_23430/

MIL-STD-1773; Military Standard: Fiber Optics Mechanization of an Aircraft Internal Time Division Command Response Multiplex Data Bus.

PDF copy available for download at:

http://everyspec.com/MIL-STD/MIL-STD-1700-1799/MIL-STD-1773_25257

IEEE 1394; IEEE Standard for a High Performance Serial Bus.

Current (2008) version available at:

<http://standards.ieee.org/findstds/standard/1394-2008.html>

AS6802; Deterministic Ethernet and Unified Networking.

PDF copy available (for a fee) at: <http://standards.sae.org/as6802/>

FACE Technical Standard; Future Airborne Capability Environment Technical Standard.

Current (2.1) version available at: <http://www.opengroup.org/face/tech-standard-2.1>

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