MEETING U.S. DEFENSE NEEDS IN THE INFORMATION AGE: AN EVALUATION OF SELECTED COMPLEX ELECTRONIC SYSTEM DEVELOPMENT METHODOLOGIES

by

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ABSTRACT

The proliferation of advanced information and communications technologies has significantly enhanced U.S. military capabilities and is creating a revolution in warfare. However, this proliferation has also created a new set of development problems—interoperability problems. To gain a better understanding of how interoperability issues can affect the overall performance of a theater of operations, a general theater system model is developed and then mapped into the domain of electronic systems. Analysis of the resulting theater electronic system model indicates that interoperability is critically important to the performance of the theater system. Documented real world evidence validates this point.

A cross-system integration methodology is needed to adequately address interoperability problems. A selected set of five complex electronic system development methodologies was investigated for possible application to the cross-system integration role. Criteria for an ideal cross-system integration methodology were defined and then used to evaluate the five methodologies. While none of these methodologies can satisfactorily address interoperability problems in its current state, combining two of the methodologies could form a core from which to develop a true cross-system integration methodology.

Current development and integration strategies are inadequate for developing the tightly coupled theater systems required for warfare in the information age. Adoption of a theater system product concept is recommended. The theater system product concept enables development of subsystems and upgrades to be decoupled from platform development while providing an integrated plan to guide cross-system integration activities.

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The dogmas of the quiet past are inadequate to the stormy present. The occasion is piled high with difficulty, and we must rise to the occasion. As our case is new, so we must think anew and act anew. We must disenthrall ourselves and then we shall save our country.

Abraham Lincoln
Annual Message to Congress
December 1, 1862

Like true Skunk Workers, the aerospace industry as a whole must start thinking in new directions.

Ben Rich
Skunk Works

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CHAPTER 1

Introduction

1.1 OVERVIEW

Since the first flight of a heavier-than-air aircraft at Kitty Hawk on December 17, 1903, aircraft designers have achieved tremendous performance gains in speed, altitude, payload, and range. While these improvements are impressive, evaluating the progress of aeronautics merely in terms of these performance measures would not provide an adequate description of the technology's evolution. In recent years, revolutionary developments in digital electronics and communications have altered basic concepts in military aircraft design and operation. For instance, in the past, with only mechanical flight controls at their disposal, engineers had no choice but to design inherently stable aircraft. Today, digital fly-by-wire control systems make possible the design of highly agile aircraft which are unstable—and would otherwise be uncontrollable by a pilot. The impact of information technologies on weapons systems is even more pronounced. Early air combat involved pilots from opposing sides shooting at each other with infantry arms they had carried in their cockpits. Today, engagements can take place beyond visual range and bombs can follow laser beams to their targets.

The advent of information technologies has enabled the Department of Defense (DoD) of the United States to acquire systems with capabilities far beyond what had been state-of-the-art just a few years earlier or had not even existed. Between 30 and 40 percent

of the cost of a new weapon system can be attributed to the development of the necessary electronics and software. As systems get "smarter", this percentage will only increase. With the declining level of defense expenditures driving industry to adopt lean production practices, the development process for hardware/software systems must be a focal point of efforts to get more "bang for the buck".

The goal of lean development of hardware/software systems poses complex acquisition challenges for DoD and American industry. Currently, the development of hardware and software in the defense industry faces the following factors:[1]

- "Material needs" can be satisfied by many combinations of mechanical and electronic systems (hardware and software).
- Technology development processes are heavily influenced by the DoD acquisition process.
- This DoD acquisition process, which evolved to procure mechanical systems, is mechanically-oriented and frequently has difficulty when developing information-based weapons systems.
- The administratively driven development process of defense electronic systems is often slower than the evolution of basic electronic technologies, which means that the final program result may be more costly than similar commercially available systems (Richards, 1994).

The combination of these factors and the proliferation of advanced information and communications systems has created a new set of development problems—**interoperability** problems. For instance, the modern fighter aircraft is a component of a larger "theater system" encompassing the munitions, platforms, and command and control assets in a theater of operations. Hence, it must be interoperable with other elements of the theater system. A cross-system integration methodology is needed to ensure interoperability. Planning for these considerations is essential to avoid costly and time consuming modifications late in the development cycle or after deployment.

[1] These factors were identified in the course of field research conducted by Martin Anderson and Alex Hou in support of the Lean Aircraft Initiative consisting of numerous interviews with both government and industry officials. The interview sample included officials from both sponsoring and non-sponsoring companies and government agencies.

As part of the Lean Aircraft Initiative, a research program studying the applicability of lean production principles to the defense aircraft industry sponsored by the Air Force and over 20 aerospace companies, this thesis evaluates a set of five complex electronic system development methodologies for applicability as a cross-system integration methodology and analyzes the technical and policy implications of the evaluation results.

1.2 OUTLINE OF THESIS

This thesis is based upon a combination of extensive literature review, including the most contemporary public documents from the Department of Defense, and upon field and phone interviews conducted under the auspices of the Lean Aircraft Initiative.

The remaining sections of this chapter discuss the challenge of reconciling the strategic needs of the American military with the declining level of defense expenditures in the post-Cold War world and the increasing importance of electronics and software in military systems. In addition, the role of electronics and software in the emergence of a new form of warfare is described through lessons learned during Operation Desert Storm.

Chapter 2 builds upon the earlier discussion of the emergence of a new form of warfare and develops a general model of a **theater system** which is then mapped into the electronic systems domain. This exercise provides a framework for understanding the nature of the interoperability problem. Documented real world examples are used to validate the existence of the interoperability problem. Externalities are used to help define the new integration challenge, and potential benefits of addressing this challenge are detailed.

A set of new methodologies for complex electronic system development is discussed in Chapter 3. Each of these methodologies has demonstrated significant improvements in development performance or shows potential for similarly significant improvements.

Chapter 4 describes the criteria that were developed to evaluate the methodologies for possible application as a cross-system integration methodology. Each methodology is

evaluated, and the results are discussed. Details of each individual evaluation are also included.

Chapter 5 discusses the technical and policy-oriented implications of the evaluation results. In addition to describing a possible foundation for a cross-system integration methodology, a new development and acquisition strategy is detailed. The chapter ends with a summary of conclusions and recommendations.

Appendix A contains a more detailed technical description of the practices behind one of the complex electronic system development methodologies evaluated in this thesis. Recommendations for further study are contained in Appendix B.

1.3 THE NEW CALCULUS

The end of the Cold War injected a high degree of uncertainty into the national security planning process of the United States. For decades, the subject of how to defeat the numerically superior forces of the Soviet Union and its Warsaw Pact allies in wartime had been the focus of defense planners, strategists, and wargamers in the U.S. and the other North Atlantic Treaty Organization (NATO) countries. Suddenly, our sworn enemies had become our new friends, triggering euphoria over the promise of a new world order and a peace dividend. The de-polarization of the world left defense planners without a clear threat to replace the Soviet Union.

However, while the collapse of the Soviet Union has fundamentally altered U.S. strategy and force planning, the need for powerful and decisive U.S. military capabilities endures. If the United States is to remain engaged in world affairs, the ability to bring military power to bear when appropriate to protect its interests, as well as those of its allies, must be maintained. Although there are a wide range of potential military threats to American interests, regional conflicts have become the new focus of U.S. military planning. These types of conflicts present several challenges for the U.S. military including numerous potential locales, smaller forward deployments, short warning times, distant deployments, and increasingly capable weapons in the hands of adversaries.

As a part of the reexamination of U.S. national military strategy, the Joint Chiefs of Staff (JCS) recommended that the United States should field forces capable of defeating

aggressors in two concurrent, geographically separated major regional conflicts (MRCs).[2] Recently, an evaluation of the capability of U.S. forces to achieve key operational objectives in future major regional conflicts was published by RAND. This study, called *The New Calculus: Analyzing Airpower's Changing Role in Joint Theater Campaigns*, took the two-MRC requirement as a given element of national military strategy and assessed U.S. military capabilities to fulfill the mission—focusing particularly on possible means of enhancing airpower's capabilities in joint operations.

The end of the Cold War greatly reduced the size of potential threats facing the United States. Instead of having to plan for engaging a massive force of 55,000 tanks, a large blue-water navy, and 7,500 combat aircraft, current planning for joint operations in a major regional conflict is focused on defeating an aggressor force composed of between 3,000 and 5,000 tanks, an equal number of armored personnel carriers (APCs), between 500 and 1,000 combat aircraft, and possibly ballistic missiles (Bowie et al., 1993). Currently, there are several nations in the world who either field forces matching this threat profile or possess the means to build up to these levels (Bowie et al., 1993).

Considering potential threats of this size, RAND's analysis concluded that the projected capabilities of U.S. forces would enable it to satisfy the two-MRC requirement, although the effectiveness of forces in the second theater would be highly dependent on the degree of concurrency of the two conflicts as well as the outcome of the first MRC. Regarding the role of ***airpower***, it concluded that ***"the calculus has changed and airpower's ability to contribute to the joint battle has increased"*** (Bowie et al., 1993, p. 83). The combination of modern airpower's lethality in conventional operations, which has been greatly enhanced by the employment of advanced precision-guided munitions and modern C4I (Communications, Command, Control, Computers and Intelligence) systems, and its strategic mobility and survivability make it a good match for the needs of short-warning MRCs.

To fully exploit the potential of airpower, the RAND study made a number of recommendations aimed at ensuring that U.S. forces could establish and maintain air superiority and enhance its ability to contribute to other aspects of the joint battle. Detailed

[2] In this context, concurrent major regional conflicts are conflicts that erupt sequentially but overlap so that they must be prosecuted simultaneously at times.

simulations indicated that equipping current fighters with AMRAAM (Advanced Medium Range Air-to-Air Missile) would ensure air superiority until some time around the year 2000. However, to ensure air superiority over the long term, simulations indicated that a next generation platform, such as the F-22, would be needed in addition to the continued development and procurement of advanced air-to-air missiles (Bowie et al., 1993).

The recommendation to equip our future air forces with more advanced munitions extended beyond the air superiority role to the strategic air offensive and ground campaigns as well. To supplement existing U.S. capabilities—based mainly on fighters and sea-launched cruise missiles—in strategic air offensive operations, the study advocated equipping long-range bombers with precision-guided munitions and standoff weapons, significantly increasing both the effectiveness of early attacks on strategic assets and the rate of destruction of these targets. To enhance the ability of U.S. forces to halt the advance of enemy ground forces and establish an assured defense, RAND's analysis indicated that employment of dispensers equipped with smart anti-armor submunitions, such as the Sensor Fuzed Weapon (SFW), could stop a force of 10 armored and mechanized divisions in approximately half the time required by the same forces armed with current weapons. Furthermore, B-2 bombers equipped with inertially-guided dispensers filled with smart submunitions could be used to provide additional anti-armor capability in the early stages of the conflict and further decrease the time required to halt an armored invasion (Bowie et al., 1993).

The analysis also indicated a need to procure additional fighters such as the F-15E, whose long range, heavy payload, and modern avionics make it a highly effective and versatile asset. ***Finally, a rapidly deployable theater C4I system—a goal believed to be achievable through the integration of current systems provided that planned upgrades materialize—was deemed essential to the effective and efficient prosecution of airpower's missions within the joint operations framework*** (Bowie et al., 1993).

Although equipping our forces with advanced munitions, advanced fighters, and rapidly deployable theater C4I systems would allow a smaller force structure to support U.S. national military strategy, these enhancements would surely require a considerable investment. Appropriating funds for this purpose could be difficult since changes in the international security and economic environments have created momentum for the

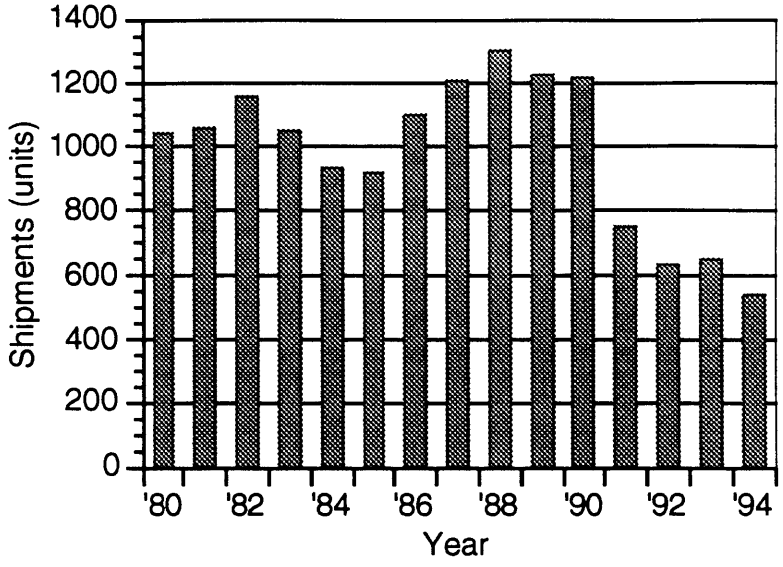
downsizing of the U.S. military and decreasing levels of defense expenditures. This is perhaps the real "new calculus"—cost is now as important as system performance. With the major budgetary impact being felt in procurement which is estimated to be down 47 percent from the peak years of the buildup during the 1980's, the greatest challenge for DoD in the post-Cold War era may be how to maximize its "bang for the buck".

If achieving greater efficiency has become an imperative for DoD, it has become a matter of survival in the aerospace industry. Aerospace industry shipments in 1993 fell 11 percent in real terms and were also expected to fall 11 percent in 1994 from 1993 levels (DoC, 1994). Historically, the industry earned at least half of its revenues from military sales. The worldwide decline in defense spending has reduced the demand for military aircraft, missiles, avionics, and other related equipment from U.S. suppliers. The most recent DoD budget request represented a cumulative real decline in defense spending of more than 40 percent since the peak of the buildup in 1985 (DoC, 1994).

Unlike past downturns in defense spending, the commercial sector has experienced a concurrent slump in demand for its products and is unable to sustain the industry's current level of capacity. Adding to the overcapacity problem are aircraft manufacturers from the former Soviet Union—currently operating at production rates less than one-third of capacity—who have joined the fray in vying for military aircraft sales in the export market (DoC, 1994).

While the aerospace industry in general has suffered greatly during the recent downturn, the military aircraft sector, where the U.S. Government historically accounts for 80 percent of all sales with Foreign Military Sales and direct exports collectively accounting for the remaining 20 percent, has been particularly hard hit by declining defense procurements (DoC, 1994). The resulting downward trend in total shipments of complete U.S. military aircraft is shown in Figure 1.1. While intensifying competition for shrinking defense procurement dollars has driven some companies to diversify into commercial markets or sell off their defense businesses entirely, many have decided to remain focused on the defense market and outlast the competition. For these companies, improving the efficiency and the effectiveness of their operations through the reengineering of business processes and implementation of leaner practices is paramount.

Figure 1.1: Shipments of U.S. Military Aircraft (1980-1994)



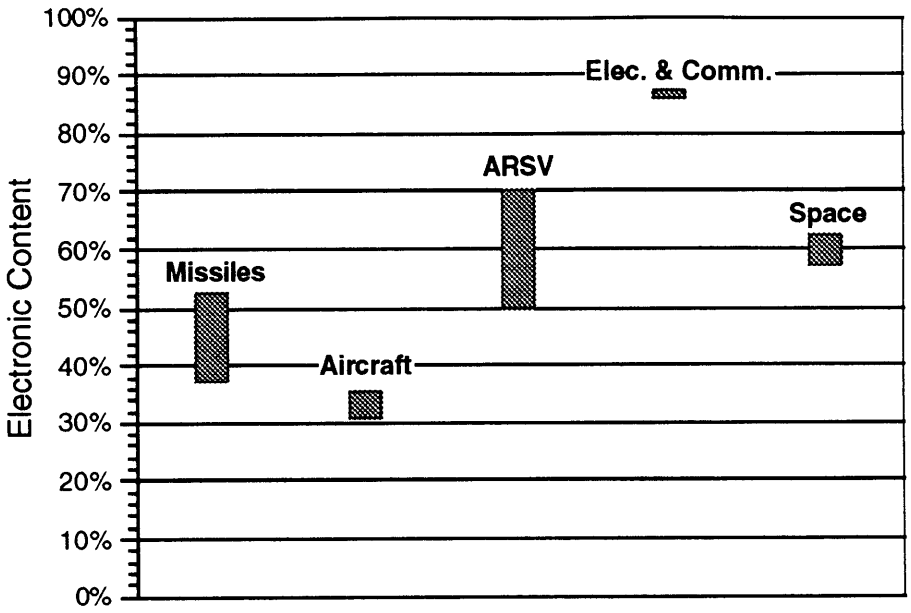
Estimates and forecasts for years 1993 and 1994 by International Trade Administration.
Source: U.S. Department of Commerce, *U.S. Industrial Outlook 1994.*

1.4 IMPORTANCE OF HARDWARE AND SOFTWARE

Electronic hardware and software are important elements in all the key factors for dramatically increasing U.S. capabilities for destroying enemy forces cited in *The New Calculus*: advanced munitions, avionics, and aircraft and enhanced and rapidly deployable theater C4I capabilities, such as those provided by AWACS and JSTARS (Bowie et al., 1993).

Another indicator of the importance of electronic hardware and software is the high electronic content of the components of a theater system. A chart illustrating the forecasted range of variation of electronic content for some typical defense systems is shown in Figure 1.2. Here, electronic content is the percentage of defense procurement and RDT&E (Research, Development, Test and Evaluation) outlays that are devoted to electronics hardware and software. Clearly, the data in Figure 1.2 indicate that all of the selected systems possess a substantial level of electronic content. Even aircraft, which have the lowest level of electronic content of the set of selected systems, are expected to have an electronic content of 30 to 35 percent. Missiles contain a higher level of electronic

Figure 1.2: Electronic Content Variation for Selected Systems, 1990-2001



Electronic content was calculated as percentage of procurement and RDT&E outlays devoted to software and electronic hardware. Forecasts for the years 1992-2001 by Electronic Industries Association.
Source: EIA (1991).

content, and the theater C4I systems—ARSV (Airborne Reconnaissance, Surveillance & Verification) systems, electronics and communications systems, and space systems[3]—possess the highest electronic content levels of all. Overall, the substantial levels of electronic content indicate that electronic hardware and software are integral elements of our military capabilities.

As evidenced by Defense Secretary Perry's recent statement that future battles could be won by the ability to gather, process and distribute battlefield information, the revolutionary impact of information on warfare has not gone unnoticed by top officials (Aldinger, 1994).

The confluence of two sometimes conflicting forces of change—the information-based revolution in warfare and shrinking defense budgets—means that the capability to develop and field high-quality hardware and software in a timely and affordable manner will be critical to the ability of our future armed forces to accomplish their missions.

[3] Space systems include C4I assets such as early warning satellites and communications satellites.

Moreover, maximizing the performance of a theater system requires these systems to be interoperable where appropriate.

The next section discusses how information and communications technologies have revolutionized warfare. The description is based on lessons learned during Desert Shield and Desert Storm and provides the context for our discussion of theater system models in Chapter 2. The description is particularly pertinent to the discussion of the theater electronic systems model which is used to explore theater system performance issues.

1.5 A REVOLUTION IN WARFARE

The United States and its coalition allies unleashed a radically new form of warfare in the night skies over the Persian Gulf on January 17, 1991. The prosecution of combat operations under this new war-form devastated the world's fourth largest military machine. By leveraging *knowledge* and *information*, U.S. and allied forces demonstrated an unprecedented degree of flexibility, precision, synchronization, and speed and achieved one of the most one-sided victories in history (Campen, 1992e).

It is ironic to realize that many of the ideas that led to such a stunning military victory were borne out of a combination of the American military's demoralization after the Vietnam War and its desire to be able to defeat an invasion of western Europe by numerically superior Warsaw Pact forces without having to resort to nuclear weapons. The Israeli victory against the overwhelming numerical superiority of Egyptian and Syrian forces in the 1973 Yom Kippur War provided clear evidence to American strategists that the starting ratios of forces do not necessarily determine the outcome of a battle and the side which seizes the initiative would have the advantage, regardless of who was strategically on the defensive. These lessons sparked an intense doctrinal debate within the defense community which culminated with the adoption of AirLand Battle doctrine in 1982 (Toffler and Toffler, 1993).

AirLand Battle emphasized deepening the battle to strike at the second, third, and subsequent echelons, deep strikes to knock out communications systems, air defenses,

command centers, and logistics lines, and urged officers and troops to seize the initiative and go on the offensive even when on the defensive strategically. In the event of an enemy breakthrough, counterattacks should be mounted at the weak points rather than frontally at the point of breakthrough (Toffler and Toffler, 1993).

Updated AirLand Battle formed the doctrinal underpinnings for operations in the Gulf. This was clearly evident from the outset of Desert Storm. Even before F-117A Nighthawk stealth fighters made their first strike against Baghdad, three Pave Low Helicopters from the U.S. Air Forces's Special Operations Wing led nine army attack helicopters in a streak across the Iraqi border with Saudi Arabia (Toffler and Toffler, 1993). Flying at thirty feet above the desert, they took out two early-warning radar sites with laser-guided Hellfire missiles. Moments later, an interceptor control station was destroyed by a laser-guided bomb delivered by a F-117A. These strikes created a blindspot in the Iraqi air defense network through which 668 coalition aircraft streaked toward their targets. Long-range interdiction strikes by air and ground forces disrupted the formation and movement of enemy follow-on forces. Cruise missiles and coalition aircraft armed with precision-guided munitions destroyed Iraqi command and communications systems blocking the flow of information up or down the chain of command. Some of the earliest strikes targeted microwave relay towers, telephone exchanges, switching rooms, fiber optic nodes, and bridges which carried coaxial communications cables. In addition, some Tomahawk cruise missiles dispensed ribbons of carbon fibers over Iraqi electrical power switching systems, creating power disruptions and wholesale shutdowns of power systems (Fulghum, 1992). A premium was placed on synchronized combined operations while frontal assaults on the strength of enemy forces were avoided.

1.5.1 Information as a Force Multiplier

During the Gulf War, information was leveraged as a force multiplier by three different classes of systems. These classes included precision-guided munitions, enabling systems, and theater C4I systems.

Precision-Guided Munitions

Perhaps the most poignant images of the war for the general public were formed by viewing news footage of Tomahawk after Tomahawk being launched by American naval forces, Iraqi gunners trying in vain to shoot down cruise missiles as they flew overhead on their way to strike targets with precision, and laser-guided bombs hitting their targets with pinpoint accuracy. The development of these and other precision-guided weapons—weapons based on information—was one of the most significant advances since the Vietnam War. Whereas collateral damage was accepted as an unavoidable consequence of military action in past conflicts, the advent of precision-guided munitions now enables targets to be destroyed with much greater accuracy, minimizing collateral damage. Sheer mass of firepower is now outweighed in importance by accuracy.

To fully appreciate the significance of this capability, it is useful to consider the past. During World War II, it required 4,500 sorties by B-17 bombers and 9,000 bombs to accomplish what a F-117A can do on one sortie with a single bomb (Toffler and Toffler, 1993). During the Vietnam War, accomplishing the same mission required 95 sorties and 190 bombs (Toffler and Toffler, 1993). While attempting to destroy the Thanh Hoa bridge, American pilots flew 800 sorties and lost ten planes without achieving success. The bridge stood intact until a flight of four F-4s armed with some of the earliest smart bombs accomplished the task in a single pass (Toffler and Toffler, 1993).

Enabling Systems

While smart weapons have proven to be an important force multiplier, the development and fielding of other enabling systems such as advanced avionics, ranging and targeting systems, electronic countermeasures, navigation aids, and night vision devices have also significantly enhanced the combat capabilities of our forces. These information-based systems enhance or extend the ability of the equipped asset to accomplish its mission and were another critical element of the success of coalition forces in Desert Storm.

Again, it is useful to look briefly backward to gauge these enhancements. Whereas the crew of a Vietnam-era M-60 tank had to find cover and come to a stop before firing, the crew of a modern M-1 Abrams tank can fire while on the move (Toffler and Toffler, 1993). Similarly, while the chances of a M-60's crew being able to hit a target 2,000 yards

away at night are slim, night-vision devices, laser ranging systems, and computerized targeting systems which compensate for heat, wind, and other conditions assure that the M-1 crew will score hits nine times out of ten (Toffler and Toffler, 1993). Clearly, the armored groups whose tanks are equipped with these enabling systems have a significant edge over forces that are not. As was the case with the early smart bombs, the Vietnam War also demonstrated the utility of advanced avionics. Before the fielding of advanced bombing systems, pilots could not do much "jinking" (erratic flight) and still have any chance of delivering their payload on target. The advanced bombing systems compensated for altitude, speed, and a moderate amount of jinking, affording the pilot a significantly higher degree of protection while enhancing his accuracy (Momyer, 1978). Modern systems can enable a pilot to use dumb bombs with a high degree of accuracy.

While some of the information-based capabilities such as smart bombs, advanced avionics, electronic countermeasures, and night-vision devices were available to some degree during the Vietnam War, the war in the Gulf marked the first combat use of the Global Positioning System (GPS). Whereas in Europe soldiers had been able to get their bearings relative to roads, towns, forests, and other landmarks, the desert was devoid of landmarks—even the sand dunes shifted. The precise position information provided by GPS receivers to coalition forces proved to be indispensable in allowing the desert sands to be navigated with a high degree of confidence (Schwarzkopf, 1992).

During the initial deployments of U.S. troops to Saudi Arabia, the Department of Defense was still in the process of evaluating portable commercial GPS receivers. However, early experiences of coalition troops with the receivers were so positive that the procurement processes were dramatically accelerated. By February, Trimble Navigation had supplied more than 3,000 commercial receivers and was rushing to fulfill orders for another 6,000. Magellan Systems Corporation had supplied approximately 2,500 hand-held receivers. It is estimated that well over 12,000 personal receivers were used by coalition forces. Priced around $3,000, the commercial hand-held receivers were compact and rugged enough for battlefield use. Their appeal was so high that some American troops had their relatives buy them at home and mail them to Saudi Arabia (Anson and Cummings, 1992).

Magellan GPS receivers were carried in air crew survival kits, enabling some remarkable rescue operations. GPS receivers could also be found on ships and landing craft and in tanks and other armored vehicles. Significantly, they were also used by forward observers who were directing air and artillery strikes. A soldier on the ground could locate his position with a hand-held GPS receiver, determine the range and bearing of a target with a laser range finder, and relay the precise target information to an air control officer for close air support or ground attack aircraft. Using its own GPS equipment, an aircraft could offset its bombing instruments and attack with surprise and precision. Thus, **a $3,000 hand-held device could provide an inexpensive but highly effective force multiplier for a $30 million dollar aircraft as well as enhance its survivability** (Anson and Cummings, 1992). The capability enhancing potential of GPS was clearly demonstrated in the first strike of the war by the successful helicopter raid on the Iraqi early-warning radar sites. According to the Pentagon's final report on the Gulf War, the raid was made possible because of night- and low-light vision technologies and the precise navigational capability afforded by the Global Positioning System (DoD, 1992).

Theater C4I Systems

While the media made the public aware of the capabilities of precision-guided weapons and other enabling technologies such as night-vision goggles and GPS receivers, two of the most powerful information weapons of all—AWACS and JSTARS—were relegated to relative obscurity. The E-3 Sentry, otherwise known as AWACS (Airborne Warning and Control System), is a modified Boeing 707 aircraft, crammed with computers, radar, communications gear, and sensors. In both Desert Shield and Desert Storm, the AWACS aircraft scanned the skies in all directions to detect enemy aircraft or missiles, sending targeting data to ground units and interceptors.

The ground-scanning counterpart of AWACS was the Joint Surveillance Target and Attack Radar System (JSTARS). The E-8A JSTARS aircraft is a modified Boeing 707 equipped with a multi-mode radar for detection and tracking of enemy forces, processing equipment, mission crew work stations, and command and control interfaces. Data collected on board are then relayed to six ground station modules that receive radar data

processed by the aircraft in real time. The data can then be analyzed by ground commanders for battlefield application (Swalm, 1992).

At the start of the Gulf crisis, the JSTARS system was still in development testing and at least three years remained before an initial production decision was to be made. However, its potential for locating Iraqi tanks was so impressive that the only two existing prototypes were deployed to Saudi Arabia. After JSTARS was declared operational, one of the aircraft flew every day with missions logging an average of 13 hours of flight time while covering the entire theater of operations with one orbit. At times, Joint STARS aircraft operated around the clock in the worst weather the Middle East had seen in decades (Swalm, 1992).

JSTARS was initially limited in operations to performing a surveillance role. After only two days, this limitation was removed and a weapons allocation officer was assigned to control his own F-15Es, especially in the campaign against tactical ballistic missile sites. Over the course of operations, Joint STARS evolved to serve in a C4I (Command, Control, Communications, Computers and Intelligence) capacity as part of an interconnected network of these assets, which included AWACS, the RC-135 Rivet Joint electronic eavesdropping aircraft, the Airborne Command and Control Center (ABCCC), and various Army and Air Force command and intelligence centers. Linking JSTARS and AWACS together provided coalition commanders with a comprehensive picture of enemy tactical movements on the ground and in the air (Swalm, 1992).

By all accounts, JSTARS was a boon for coalition forces. Ground commanders could track the movements of enemy forces on a real-time basis, from as far away as 155 miles, under all weather conditions. Aircraft directed by Joint STARS had a 90 percent success rate in finding targets on the first pass (Swalm, 1992). For interdiction missions, Joint STARS could use its synthetic aperture radar to provide real-time damage assessment and direct immediate re-attacks. On one occasion, two A-10s and an AC-130 directed by JSTARS destroyed 58 out of 61 vehicles in convoy (Swalm, 1992). In another instance, an Iraqi unit mustering to attack VII Corps was 80 percent disabled before it could engage any of the corps's units (Swalm, 1992). In a similar scenario, a unit of the Republican Guard preparing to launch a counterattack was detected by JSTARS and targeted from a ground station and destroyed by Army Apache attack helicopters (Swalm,

1992). During the early days of the war when the Iraqis attacked the Saudi town of Khafji, Joint STARS provided intelligence data indicating that the attack was conducted by only a small Iraqi force. JSTARS also played a significant role in hunting mobile Scud launchers, first locating their positions and then passing that information on to ground-based and airborne strike assets (Swalm, 1992). JSTARS further proved its worth as a C4I asset in the deconfliction role as well as in the detection and targeting of enemy forces. At one point early in the ground campaign, the JSTARS mission commander intervened to prevent U.S. Marine Corps forces from committing fratricide on the right flank of the British armored thrust into Kuwait (Swalm, 1992).

By the end of the war, the two JSTARS aircraft had flown 49 sorties, logging 535 hours of flight time, successfully detected over 1,000 targets, and controlled 750 fighters. The effectiveness of this developmental system was evidenced by the fact that close air support and interdiction aircraft consistently ran out of ammunition before they ran low on fuel once JSTARS became operational (Swalm, 1992). Attesting to the system's revolutionary capabilities, Air Force Chief of Staff General McPeak said, "We will never again want to fight a war without a Joint STARS kind of system."

While the precision-guided weapons and information-based enabling systems discussed earlier were important force multipliers for individual units or weapons platforms, the capabilities provided by AWACS and JSTARS were perhaps the greatest force multipliers of all because their extraordinary command and control capabilities enabled them to coordinate and synchronize the actions of multitudes of these individual assets and serve as force multipliers for the *theater.*

1.5.2 Synchronization and Speed

Facilitated by the proliferation and integration of computers, telecommunications equipment, networks, and satellites, operations in the Gulf War were prosecuted with unprecedented synchronization, speed, and intensity. One example of the degree of speed and synchronization that characterize warfare in the information age was General Schwarzkopf's famous end-run flanking maneuver. The fact that this sort of envelopment was attempted was not as astonishing as the speed with which it was executed. In retrospect, it appears that efforts by coalition forces to convince Iraqi commanders that a

frontal assault was imminent were aided by the enemy's belief that allied ground forces could not possibly advance at the high speeds required to accomplish an end-run (Toffler and Toffler, 1993).[4]

The management of airspace in the air campaign was another good example of the contribution of information technology to the increased level of synchronization and speed of modern warfare. Effective and efficient airspace management was a key factor in the success of the air war, keeping the 900 or so coalition aircraft in the air at any given time from running into each other without reverting to the wasteful block allocations of air volume and time that were used during the Vietnam War. In the Gulf, airspace management was heavily supported by automation, enabling airspace managers to visualize how the air volume from ground level to 100,000 feet was being used by mission planners and to deconflict airspace by location, altitude, and time (Campen, 1992a). Effective and efficient deconfliction is critical to achieving a high level of synchronization and integration of air operations. Without it, the effectiveness and intensity of an air campaign would be seriously degraded (Campen, 1992a).

Airspace management functions in the U.S. Ninth Air Force were performed with the aid of its Combat Airspace Deconfliction System (CADS) (Campen, 1992a). Running on commercial computer hardware, CADS depicted, analyzed, and deconflicted airspace by location, altitude, and time. Subsequently, an Air Control Order would be automatically generated and then inserted into Computer Assisted Force Management System (CAFMS)

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[4] Fully aware that the end-run would require the largest maneuver of armor in the desert in the history of the U.S. military, General Schwarzkopf nevertheless adopted the strategy believing that it was the most likely way to end a ground war quickly and decisively (Schwarzkopf, 1992). While the movement of the attacking coalition units to their pre-attack forward locations within the allotted time involved daunting challenges including the crossing of VII and XVIII Corps at a point in the desert called the "Mother of All Intersections", the logistical challenge of keeping the coalition forces supplied with ammunition and fuel was a potential Achilles heel of the flanking maneuver. These challenges were met by effective scheduling and traffic control, both of which were enabled by computers, telecommunications, and satellites. The level of synchronization and speed achieved in supporting the movement of the corps and the ground offensive was staggering. During the movement of the corps, supply routes saw a constant flow of traffic for 24 hours a day, seven days a week. The effort was perhaps best described by the words of the man responsible for logistics in the Gulf, Lt. General William G. Pagonis:

> By the time the pipeline was flowing at full speed, an average of eighteen trucks per minute was crossing through a single point on the northern route. This rate was sustained for an entire month. At one point, I had my helicopter land on the west side of the highway to check out a transportation movement-control point. The traffic was so dense that I couldn't get across to the east side of the road. We were finally forced to crank up the helicopter and fly to the other side (1992, p. 146).

and became part of the Air Tasking Order. CADS made use of enhanced graphics capabilities and a database containing maps of the entire world. Once the airspace requirements of each weapon system were manually entered, the system enabled the airspace manager to visualize airspace utilization over the combat area by location, by time, and in three dimensions. By enabling airspace managers to detect conflicts during mission planning, safe alternate routes could be proposed, minimizing the risk of fratricide by deconflicting airspace before the aircraft took off (Campen, 1992a).[5]

While the information systems in the Gulf were taxed to their limits in support of coalition operations, the degree of synchronization and speed displayed by allied forces during Desert Storm would have been much more difficult to achieve without their contributions. *Neither the air campaign nor the ground war could have been executed as smoothly with such a high level of coordination and intensity.* Once again, it is apparent that information has become paramount to the effective and efficient conduct of military operations.

1.5.3 Information Differential

A key factor behind the victory in the Gulf was the information differential. Allied forces had the capability to gather, communicate, and leverage information while the Iraqis did not. From the earliest moments of the war, the Iraqi command and control system was

[5] During Desert Shield and Desert Storm, daily tasking to all the bases and units supporting the theater air campaign was provided by an Air Tasking Order (ATO). Containing a huge amount of information, the ATO provided units with detailed instructions including specifications of targets, TOTs (time on target), ordnance loads, fuzing, and rules of engagement. The ATO also specifies details such as IFF (identify friend or foe) squawks, radio frequencies, identification routes and procedures, and air refueling times, altitudes, and contact points (Hyde et al., 1992). Lt. General Horner, designated as Joint Forces Air Component Commander, chose CAFMS (Computer Assisted Force Management System) to help generate and distribute the ATO. CAFMS provided just enough capability to get the job done—after extensive modifications and enhancements in hardware and software were made, that is. Ultimately, these enhancements allowed the system to perform just well enough to do the job. During Desert Storm, the system generated ATOs ranging in length from 900 pages to a peak of 982 pages during the ground war and distributed them to more than 175 addressees (Hyde et al., 1992).

Contained within the ATO were precise instructions to mission planners called the Air Control Order (ACO), which often exceeded 100 pages in length during the course of Operation Desert Storm. As many as 980 sorties per day had to be deconflicted during Desert Shield. During the 100 hours of the Desert Storm ground campaign, the deconfliction need was much greater with over 2,800 sorties being flown each day. These sorties were spread over an area of 93,600 square miles and utilized 122 different air refueling tracks, 660 restricted operating zones, 312 missile engagement zones, 78 strike corridors, 36 training areas, and 92 combat air patrol points. In addition, the coalition's air operations had to be thoroughly coordinated with the constantly shifting civil air routes of six independent nations (Campen, 1992a).

severely degraded, seriously disrupting the ability of the vaunted Iraqi war machine to function on both the tactical and strategic levels. Information differentials were the key to success during the conflict at all levels from the smallest tactical units to the highest levels of command. Military aircraft were central elements in this information-based war.

The concept of creating strategic advantage by degrading the enemy's control structure is not new. Ironically, Iraq's prime supplier of military hardware as well as its primary source of training and doctrine, the Soviet Union, first advocated the belief that the balance of military power in war could be tipped by attacking the enemy's control infrastructure (Campen, 1992b). Drawing from the wealth of experience gained during the Great Patriotic War, the Soviets developed a theory of information warfare known as Radio Electronic Combat. The objective of the doctrine was to degrade the enemy's command and control infrastructure by at least 50 percent through combinations of physical destruction, jamming, and deception. In Desert Storm, coalition air forces easily met that goal and in some instances achieved nearly 100 percent degradation of the command and control assets of the Iraqi military machine (Campen, 1992b).

The role of the F-117A Nighthawk stealth fighter in Desert Storm provided a good example of the information differential in practice. The stealth technology incorporated into the F-117A created an information differential by denying the enemy air defenses the knowledge needed to track and intercept or shoot down the plane. While other methods such as jamming may produce a similar end result, these methods utilize electromagnetic emissions to accomplish their task—emissions which can themselves be monitored and tracked. Thus, the information differential produced by stealth is greater because it accomplishes the task without creating alternative sources of information that the enemy could leverage. The F-117A's ability to use its information advantage to penetrate high-threat areas and deliver precision-guided bombs made it the platform of choice for attacking heavily defended high-value targets. In fact, the Nighthawks were the only planes to attack targets in downtown Baghdad, focusing on well-protected air defense centers and military command and control facilities. While the F-117As flew only two percent of total sorties, they accounted for 40 percent of strategic targets attacked and did not incur a single loss (Toffler and Toffler, 1993). The inherent tactical information differential employed by the F-117As was exploited to produce an even greater

information differential by attacking command and control facilities with precision-guided weapons.

There were other sources of information differential at the tactical level as well. First, the coalition forces had wide access to GPS receivers—many were of the hand-held variety—while the Iraqis did not. Thus, it was possible for allied forces to navigate the desert terrain quickly and accurately—a definite advantage in modern maneuver warfare. Coalition operations were also aided by the intimidation of Iraqi forces. Iraqi prisoners reported they were so afraid of being attacked by anti-radiation missiles they refused to turn on electronic equipment. Some were convinced that even receiving equipment would act as a magnet for instant death (Campen, 1992b). Allied forces had an additional advantage because of the large scale production, distribution, and utilization of battlefield "templates," overlays of Iraqi troop dispositions and barrier construction produced from satellite photos. In many instances, the templates revealed Iraqi positions down to the level of individual fighting positions. The information provided coalition forces with accurate knowledge of Iraqi positions, facilitating their destruction with precision at maximum range. Some even attribute the destruction of the 48th Guards with minimal allied casualties to the use of battlefield templates (Campen, 1992c).

At the strategic level, the Coalition also possessed a tremendous information advantage. Coalition commanders had access to satellites which provided high-resolution reconnaissance photographs and early warning of Scud missile launches; the Iraqis had no similar capability. AWACS and JSTARS could be linked to provide a "God's eye view" of the battlefield providing coalition commanders with a complete picture of all enemy movements on and over the area of operations; Iraqi commanders had no similar capability. While the allied C4I infrastructure was allowed to operate freely, early strikes targeting the Iraqi command and control structure disabled a highly centralized control network leaving the enemy forces deaf, dumb, and blind. Iraqi units in Kuwait, having been cut off from the ultimate source of authority in Baghdad, were further hampered by their inability to communicate with each other. Iraqi battalions were equipped with 14 different types of radios—none of which could communicate with each other. For instance, one battalion would be equipped with a British system while the adjacent battalion would be equipped with a Soviet system (Campen, 1992b).

To make matters worse, communications were often networked in a classic star archetype. One unit had eleven pairs of radios operating on eleven *different* frequencies. This allowed a central commander to control the flow of information to the individual elements under his command and, hence, the panic button. This configuration was dramatically different from that of a comparable U.S. Marine Corps unit where commanders shared the same frequency and information could flow in upward, downward, and lateral directions. The isolation was so severe that Iraqi commanders often had no idea that adjacent units had been attacked and were consequently surprised by the pace of the attack by coalition forces who had suddenly arrived on their doorstep without warning (Campen, 1992b).

It is clear that the ability to effectively and efficiently manage information is now and will continue to be a key for the successful prosecution of wartime operations. However, the availability of information is not enough by itself. Military forces must be able to effectively and efficiently gather, process, analyze, and distribute the information required for it to accomplish its objectives while denying that ability to enemy forces. To ensure success, forces must be capable of creating and sustaining an information differential.

1.5.4 A Dual War

While Desert Storm offered our first glimpse of warfare in the information age, the new war-form is still in its infancy. In fact, while some aspects of the war exhibited the precision and speed of information-based warfare, other aspects of the war were conducted with the same style of mass destruction that were characteristic of previous wars. The relentless carpet-bombing of the Republican Guards and other bunkered Iraqi front-line units by B-52s exemplified the older form of warfare employed during Desert Storm. As in previous wars, dumb iron bombs were used to wreak widespread havoc and destruction. This was the same sort of bombing campaign that had been conducted half a century ago during World War II (Toffler and Toffler, 1993).

It is likely that we have only witnessed the beginning of this revolution in warfare. While the older methods of mass destruction will continue to be employed in war for the foreseeable future, the world has witnessed a paradigm shift in warfare from

indiscriminate mass destruction toward selective targeting and precise destruction. Intrinsic to this shift has been a shift in strategic thinking away from "total war"—an extension of Clausewitz's notion of "absolute war"—toward an ideal of defeating an enemy without leveling the entire nation, an ideal expressed in the venerable writings of Sun Tzu who believed that "Generally in war the best policy is to take a state intact; to ruin it is inferior to this" (1971, p. 77).

The planning of offensive operations in the Gulf displayed just this sort of strategic thinking. Although no one had explicitly stated that Iraq was not to be destroyed as a nation, General Schwarzkopf assumed that the United States might still need Iraq to serve as a regional counterbalance to Iran and instructed his planners to devise a strategy that would cripple Iraq's military without laying waste to the country (Schwarzkopf, 1992). This emphasis on the precision destruction of military assets is further illustrated by the following passage from Schwarzkopf's own account of the war:

> We were driving the enemy into the pocket across the Euphrates from Basra, which our Air Force had begun referring to matter-of-factly as the "kill box." We bombed the hell out of every convoy we could find—but between air strikes we flew over the battlefield with Black Hawk helicopters equipped with loudspeakers. We kept telling the Iraqis in Arabic, "Get out of your vehicles, leave them behind, and you will not die. We will let you go home." A lot of them had already figured that out for themselves. A tank battalion commander who surrendered eventually told our intelligence officers: "During the Iran-Iraq war I loved my tank because it was the one thing that protected me. But during this war I hated my tank because it could kill me. It was drawing fire. I stayed out of it as much as I could and slept as far away as possible" (1992, p. 466).

While information warfare is still in its infancy and elements of the old mass destruction paradigm remain in use, the trend toward finer precision in warfare is unmistakable. Even dumb iron bombs, a ubiquitous tool of mass destruction and a mainstay of strategic bombing, will be "smartened" in the future with the addition of a guidance system being developed by the Joint Direct Attack Munition (JDAM) program (Fulghum, 1993c). Given this drive toward greater precision, the gathering, processing, analysis, and dissemination of information will continue to grow in importance in the future.

1.6 SUMMARY

The discussion in the previous section of the revolution in warfare suggests the idea that the new war-form raises the focus of performance from the level of individual units, tanks, or aircraft to the level of the theater. The emergence of this new form of warfare raises new complex systems issues related to improving the performance of the theater system. Currently, aircraft are important, but relatively autonomous, components of a theater system. Electronics and software are the keys to integrating aircraft into a synchronized, interoperable theater system. In the following chapters, we will explore some current issues in developing complex electronic systems for this environment.

CHAPTER 2

The New Integration Challenge

The impressive achievements of the U.S. military and its coalition allies during Desert Shield and Desert Storm heralded the dawn of a new form of warfare whose revolutionary impact will be felt for some time to come. Many old concepts regarding numerical advantages in troops and materiel necessary for mounting a successful campaign, long accepted as veritable laws of war, were shattered by the overwhelming success of the allied forces. The speed with which allied operations were conducted stunned both television viewers at home and hapless Iraqi soldiers in the field. News footage showing laser-guided bombs striking targets with pinpoint accuracy dazzled the public with the wizardry of high technology.

While the full extent of the implications of Desert Storm and the change in warfare that it portends will likely be the subject of debate in the foreseeable future, one thing is certain. The ability to acquire, process, fuse, analyze, and disseminate information effectively and efficiently is vital to military operations in the information age and will continue to grow in importance as new ways of exploiting information for military advantage are conceived and developed.

To understand the technical and policy issues resulting from the increasing presence of information technologies in military operations, a number of actions were taken as a part of this thesis effort. First, to develop a framework for understanding the

role of electronic systems in a theater campaign, a simple conceptual model of a general theater system was formulated. The general model was then mapped into the electronic system domain. Analysis of the resulting model raised a set of issues associated with the proliferation of electronic systems in a theater of operations. Evidence was gathered from documented real world experiences, including experiences from Desert Shield and Desert Storm, to validate that these problem areas did in fact pose significant challenges. These challenges were then refined in light of current constraints.

2.1 THEATER SYSTEM MODEL

To help comprehend the ramifications of the information revolution on warfare, it is useful to develop a general model of a theater system. Once a general model has been established and general categories of systems defined, the model can be mapped into the domain of electronic systems. After mapping the general theater system model into the electronic system domain, the interconnections among the different categories can then be studied to develop an understanding of the possible implications of the use of electronic systems and information technology for military operations.

2.1.1 General Model Logic

One approach to developing a general theater system model is to define it in terms of the desired *result* of the use of military power at a localized tactical level. For instance, why does a gunner launch the Hellfire missile at an enemy tank? The gunner fires a missile to disable or destroy a piece of the enemy's military capability. Hence, we can posit that the desired *outcome* is to degrade or destroy an enemy military capability. A true theater system will have many desired outcomes.

Once a set of desired *outcomes* has been established, the rest of the model formulation process can be accomplished by backing away, step-by-step, from the desired objective and considering what is needed at each point in the chain to achieve the goal. The procedure is a generalization of the "dynamic programming" approach used in optimizing control problems. The first question to consider is fairly evident.

What degrades or destroys enemy military capabilities?

The degradation or destruction of an enemy capability is accomplished through the use of weapons. Munitions are the actual instruments that are used and expended to fulfill the desired objective. Having identified one category of systems, we can now take another step back to identify the next category.

How are weapons and munitions brought to bear against enemy capabilities?

Weapons must be employed within a range of effectiveness to have utility. Thus, this issue concerns the means by which a weapon can be transported to the battlefield so that it may be employed within its effective range. Tanks, aircraft, ships, and foot soldiers are all examples of "platforms" which bring weapons to bear on enemy capabilities. Now that two elements of a theater system—*munitions* for degrading enemy capabilities and *platforms* for bringing munitions to bear within an effective range—have been identified, the means by which platforms and munitions are brought to bear against the enemy must be explored.

How are the actions of the platforms directed, controlled and coordinated?

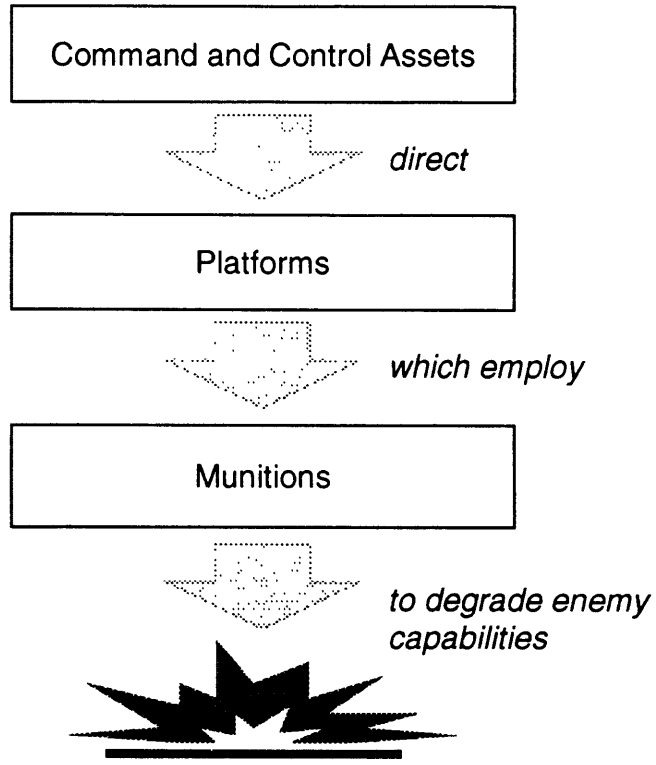
The use of platforms must be managed to ensure that the desired enemy capabilities are targeted by the platforms' munitions while minimizing the chances for friendly forces to accidentally attack each other. Command and control assets are required to fulfill this role. These systems allow platforms and their munitions to be used in a systematic, rational manner.

The answers to these questions provide the basis for three broad system categories that compose the generalized theater system model—munitions, platforms, and command and control assets. A depiction of the general model is shown in Figure 2.1.

Munitions

Munitions are expended to accomplish the objective of the mission. They directly effect the degradation or destruction of enemy capabilities and are also destroyed in the process. This category includes all sorts of expendables such as grenades, bullets, artillery shells, conventional bombs, and many kinds of missiles. While munitions may exhibit features characteristic of systems included in other categories (e.g., some may consider cruise

Figure 2.1: General Theater System Model



missiles as platforms), the employment of these systems as expendables differentiates munitions from the platform and command and control asset categories in this theater system model, which are designed to be used more than once.

Platforms

Platforms are systems that are used to bring munitions into an effective space for employment against an enemy capability. This category covers a range of systems including fighter and bomber aircraft, tanks, battleships, helicopters, and even individual soldiers. Their single most defining characteristic is that they are not expendable and are used many times to deliver munitions.

Command and Control Assets

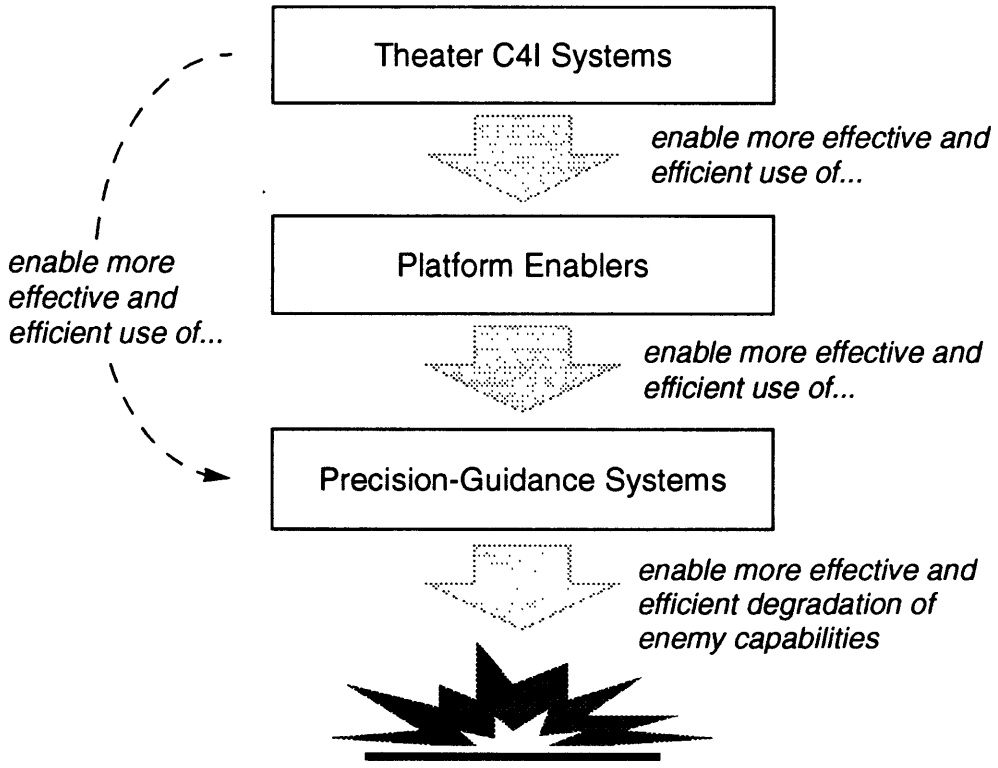
Command and control assets are systems that are used to direct, control and coordinate the use of platforms (and occasionally munitions) with the aim of enhancing the chances for successfully and efficiently achieving the desired objective. This category encompasses a

range of systems from couriers and signal flags to high performance asynchronous transfer mode broadband communication systems and JSTARS.

2.1.2 The Electronic Systems Domain

The electronic systems domain is an important part of the theater system model. Since this domain is essentially a subset of the general model formulated in the previous section, the mapping of the general categories into the electronic systems domain is fairly straightforward. The general categories of munitions, platforms, and command and control assets correspond to the electronic systems categories of precision-guidance systems (PGSs), platform enablers, and theater C4I systems, respectively. A depiction of the theater electronic system model is shown in Figure 2.2.

Figure 2.2: Theater Electronic System Model



Precision-Guidance Systems

Precision-guidance systems reside at the bottom of this domain and are a subset of the munitions category. Precision-guided munitions (PGMs) are munitions equipped with these electronic systems. PGSs include such systems as laser-guidance systems, fire-and-forget systems, sensor fuzing, and the proposed "brilliant" systems of the future.

Platform Enablers

Platform enablers are systems carried by platforms which allow them either to use their weapons or to use them more effectively. They can also provide basic platform functionality (e.g., digital flight control systems) or enhance platform capabilities (e.g., GPS receivers). A prime example of the enabling power of this category of systems was the opening strike by helicopters against Iraqi early warning radar sites. The Pentagon's final report on the Gulf War indicated that the raid was made possible by platform enablers. GPS receivers afforded the crews a precise navigational capability, and the night- and low-light vision devices allowed the helicopters to operate under the cover of darkness (DoD, 1992). Other examples of platform enablers include advanced radar systems, inertial navigation systems, laser target designators, and LANTIRN navigation and targeting systems.

Theater C4I Systems

This category of electronic systems enables platforms to use their enabling systems—and, consequently, their munitions—more effectively. These systems monitor the status and movements of opposing forces and direct and synchronize the use of platforms to insure that the appropriate targets are attacked. Moreover, these systems also help keep friendly forces out of each other's way. In the future, a theater C4I system may be able to directly influence the performance and employment of precision-guidance systems. This effect is represented by the dashed curve shown in Figure 2.2. This kind of capability is already in process with the planned Block 4 upgrade for the Tomahawk cruise missile (the upgrade program is also known as the Tomahawk Baseline Improvement Program), which will include a data link so that a missile could be retargeted or rerouted in-flight (Kandebo, 1994). New concepts, such as the Shark (Silent Hard Kill) weapon which is intended to locate and destroy both emitting and non-emitting radars, make use of sensor data from

JSTARS, AWACS, and satellites to provide guidance into the general vicinity of a target (Fulghum, 1993a). Examples of theater C4I systems include Joint STARS, AWACS, and airspace deconfliction systems.

2.1.3 Theater Electronic System Dynamics

Within the theater electronic system model, the dynamics of the theater electronic system and the importance of electronic systems becomes clear. While conventional munitions such as dumb bombs or rockets can be effective, precision-guidance systems provide a force multiplier by enabling more effective and efficient degradation or destruction of enemy capabilities.[1] Platform enablers support more effective and efficient use of precision-guidance systems. Theater C4I systems coordinate platforms and their enabling systems, which allows them to be employed more effectively and efficiently. The effective and efficient use of platforms and their enabling systems produces, in turn, more effective and efficient employment of precision-guidance systems. Moreover, in the future theater C4I systems will be able to bypass the platform enablers in some instances and directly enhance the performance of precision-guidance systems.[2]

Clearly, the theater system will perform at a peak level when all the component systems and interconnections are working effectively and efficiently. We can better understand the importance of complex system integration by investigating how the total system degrades when the interconnections break down. Problems can arise when component systems from any category or the interconnections within and among categories are not functioning well.

Component System Problems

Precision-Guidance System Problem

For example, assume that the precision-guidance systems are not performing up to par. In fact, consider what would happen if the PGS-equipped precision-guided munitions performed no better than dumb munitions. While platforms (and C4I systems in the future) would no longer be able to leverage the force multiplier afforded by PGSs, the

[1] Evidence of this is available in Section 1.6.1 of Chapter 1.

[2] Examples include the Shark weapon and the Block 4 Tomahawks discussed in the previous section.

performance of the enablers and the theater C4I assets as a system could still facilitate more effective and efficient detection and targeting of enemy military assets.

Platform Enabler Problem

Problems with platform enablers could hamper the use of PGMs (or any kind of munition for that matter) and significantly diminish the chances of completing the mission successfully even if the functioning enabling systems could make use of data from C4I systems. In the worst case, failures in enablers providing basic platform functionality, such as digital flight control systems, would result in the destruction of the platform itself and perhaps the death of the crew.

Theater C4I System Problem

Problems with C4I systems can have dire consequences for the overall performance of the theater system. Consider the predicament of the Iraqi forces during Desert Storm when their highly centralized control structure was severely degraded from the outset of the air campaign. Without an effective command and control system, units belonging to one of the world's largest military machines could do little except defend themselves or surrender in the face of highly synchronized coalition military operations. Having the finest platforms equipped with the best enablers and precision-guided munitions may make little difference in shaping the ultimate outcome of the theater campaign if the actions of the platforms cannot be synchronized and directed against opposing forces.

Interconnection Problems

A crucial dimension of a well coordinated system is its "interoperability"—the ease of integration among many otherwise discrete system components. The effects of interoperability problems are discussed in the subsections that follow.

Intracategory Interoperability Problem

While these linkages are not explicitly shown in Figure 2.2, they can be very important to the overall performance of the theater system. For instance, the utility of JSTARS during Desert Storm would have been greatly diminished if it were not capable of communicating directly with coalition commanders on the ground or other theater C4I systems such as AWACS and ABCCC (Airborne Command and Control Center).

PGS—Platform Enabler Interoperability Problem

If a problem occurs with the connection between PGSs and platform enablers, the consequences are similar to the effects of having a faulty PGS. The effectiveness of PGMs could be seriously impaired—perhaps even preventing the platform from using the munition at all. A problematic connection could result in the shelving of a more advanced precision-guided munition in favor of a less capable weapon that can interface more seamlessly and reliably with the platform and its enablers.

Platform Enabler—Theater C4I System Interoperability Problem

Even if the other elements of the theater system are still performing well, a defective connection between platform enablers and C4I systems could degrade the overall performance of the theater system. The effect of poorly performing or faulty communication links between theater C4I systems and platforms on the ability to effectively and efficiently employ platforms against enemy capabilities can be just as deleterious as enemy degradation of theater C4I assets. Consider an extreme case where the communication link is of such poor quality that C4I assets are essentially unable to influence the use of platforms against opposing forces. For the purposes of accomplishing the objectives of a specific sortie or mission, the C4I systems might as well have been destroyed by enemy forces. Although the consequences are not as dramatic if the problems with the communication link are less severe, an inadequate level of interoperability between platform enablers and theater C4I systems can affect theater operations in the same way as enemy jamming and is tantamount to a self-inflicted degradation of C4I capabilities.

PGS—Theater C4I System Interoperability Problem

While the utility of this linkage has yet to be widely exploited or even explored, inefficiencies in this interconnection could create significant problems for theater forces who had hoped to exploit this link. Again, inadequate interoperability can be just as deleterious to theater system performance as enemy jamming.

2.1.4 Implications of the Theater Electronic System Model

The analysis of the theater electronic system model detailed in the preceding section yields two main implications:

- The ability to develop high-quality precision-guided munitions, platform enablers, and theater C4I systems is critical to the performance of the overall theater system.
- Interoperability among the different categories of systems involved in a theater campaign is just as vital to the capability of the theater system as the performance of discrete systems in isolation. In fact, it may actually be *more* vital.

Currently, the lion's share of development energies and system integration activities are focused on optimizing the performance of individual systems or platforms (Rich and Dews, 1986). However, the analysis of the simple theater system model suggests that there may be a greater challenge—the interoperability problem—that needs to be addressed.

2.2 VALIDATION OF THE INTEROPERABILITY PROBLEM

Evidence of interoperability problems can also be found in the documented real world experiences of U.S. and allied forces during Desert Shield and Desert Storm. For instance, the Pentagon's Conduct of War report stated that the transmission process for the air tasking order (ATO) was slow and cumbersome because of inadequate interoperability among the different systems deployed by the Army, Navy, and the Air Force (DoD, 1992). During Desert Shield and Desert Storm, the U.S. Air Force used CAFMS (Computer-Assisted Force Management System) to generate the ATO, but this was not a system used by the other services. In fact, CAFMS was not even standardized among all USAF tactical units. Communications interoperability problems made the situation more difficult. Some Army aviation units obtained the ATO by collocating with or commuting daily to Air Force units with CAFMS connections. For some Navy units, the fastest, most reliable and effective means of ATO distribution was shuttling it in hardcopy or by floppy disk each

night from the Tactical Air Control Center to command carriers in the Red Sea and the Persian Gulf. Copies of the ATO were then flown to other carriers and ships by helicopter (Hyde et al., 1992).

The difficulty of the complex systems integration task was compounded by the deployment of several generations of analog and digital tactical communications equipment. The Army itself deployed three different generations of tactical communication systems: the digital Mobile Subscriber Equipment (MSE), the Tri-Service Tactical Communications (TRI-TAC) system with both analog and digital capability, and an older analog system known as the Improved Army Tactical Communications System (IATACS). TRI-TAC interoperated with the other two systems, but MSE and IATACS were not interoperable. Thus, TRI-TAC had to serve as an interoperability bridge between the two systems (Wentz, 1992).

The tactical, service-unique systems were linked to long-haul communications by the TTC-39A automatic circuit switch and the TYC-39 automatic message switch (Toma, 1992). However, network interface problems were encountered between the TTC-39A tactical switch in Riyadh and a commercial gateway switch in Dranesville, Virginia. It required a team of government engineers working with their commercial counterparts from AT&T and GTE almost three months to isolate and remedy an incompatible interswitch signaling problem. Switch interface problems were also experienced between the U.S. Marine Corps Unit Level Circuit Switch and the TTC-39A circuit switch. The problem was resolved by a software modification (Wentz, 1992).

The rapid buildup of air forces in Desert Shield quickly overwhelmed the quick reaction communications capabilities that accompanied the deployment of air units. While there were plans for air operations in the Gulf, there were no plans for data communications networks for the air units that were deploying to the theater with their laptops and PCs. The communications resources of the U.S. Tactical Air Command were quickly exhausted by the pace and magnitude of the buildup of air forces, which ultimately used up virtually all of the Air Force's tactical communications assets as well as some of its strategic communications resources (Campen, 1992a).

Tactical communications planners had substantially underestimated the volume and variety of data transmission that would be required by automated combat support

systems. Plans based on experiences with telephones and teletypes were inadequate to meet the needs of data communications required by the thousands of PCs deployed to the Gulf. To support the scope and scale of the combined air operations in the Gulf, troops in the field engineered and improvised the largest tactical military network ever built over a five month period, using many components to perform tasks for which they were never intended (Campen, 1992a).

Even the airborne communications network that was vital to the success of the air campaign had to be improvised. Ultimately, the network provided the capability to plan, execute, and monitor operations through tactical data links that enabled real time exchange of voice and radar displays. However, communications connectivity problems between the Tactical Communications Center (TACC) in Riyadh and the growing fleet of theater C4I aircraft—some of which were orbiting at distances from Riyadh that were far beyond UHF radio range—had to be solved first. This was especially important since the far-ranging aircraft included AWACS, JSTARS, Rivet Joint (signals intelligence), and ABCCC aircraft, which control and employ fighter and strike aircraft. To resolve the problem, the Air Force inserted communications relay aircraft into the network, including EC-135L aircraft that were borrowed from the Strategic Air Command, and installed remote radio ground stations in the forward combat zones (Campen, 1992a).

Ground-based and airborne command and control assets were connected to form an integrated command and control network. This was accomplished through the use of a system known as TADIL (Tactical Digital Information Link). U.S. and Saudi AWACS, Navy E-2C aircraft and Aegis cruisers, Army Hawk and Patriot air defense sites, and other ground-based surveillance radars were a few of the systems which were made interoperable. When JSTARS was deployed to the theater, it too was integrated into the Air Operations Network through the use of an Airborne Interface System (AIS) buffer. This integration activity made several generations of technologies interoperable for airspace control, producing a complex integrated system that supported up to 3,000 combined air sorties per day and controlled more than 25 air defense sites and six carrier battle group air defense platforms (Toma, 1992).

While these achievements are indeed impressive, we cannot expect that our next adversary will allow us to spend five months integrating our disparate systems and make them interoperable after deploying to the theater.

Although the evidence discussed thus far has focused on theater C4I systems, they were not the only ones that experienced interoperability problems. There were also **interoperability problems between platforms enablers and munitions.** For example, the pilots in one squadron of F-16As wanted to use the CBU-87 cluster bomb unit in its attacks against second echelon Republican Guards forces in Kuwait since they felt it was one of the best weapons for that mission. Unfortunately, they were not able to deliver the munition with the desired accuracy because the F-16A's computer did not have the software to employ the weapon effectively. To use the weapon, a pilot had to "lie" to the computer by telling it that it was carrying CBU-52s, which the computer was programmed for, and then trying to compensate manually for the difference in weapon characteristics by guessing an amount to offset from the aimpoint the computer would determine for a CBU-52 (Lenorovitz, 1991b). Predictably, the accuracies were less than desired, and they had to stop equipping the fighters with CBU-87s. This is a good example of a munition-platform enabler interoperability problem, which degraded the effectiveness of one of the best-suited munitions for the mission to the point that the squadron stopped arming its fighters with it.

Interoperability problems also accounted for the only failure out of six flight tests which performed operational concept demonstrations of an all-weather, Inertial Navigation/Global Positioning System (INS/GPS) precision-guided munition. Conducted between early February and late March 1993, this testing was intended to help evaluate technologies for possible use in the JDAM program. The only failure occurred during the third test when the munition did not separate properly from the Block 40 F-16C test aircraft because of a data bus problem (Fulghum, 1993b).

While there are more real world examples where interoperability was a problem, it is clear from these examples that the interoperability problem is all too real and that measures need to be taken to deal with it.

2.3 CONSTRAINTS

In the process of devising a solution to the interoperability problem, it is also necessary to consider other factors that could constrain possible solutions. The following is a list of some of the factors which need to be accounted for in a solution:

a) *No clear adversary.* The U.S. does not have a clear adversary in today's uncertain world. Our forces must be prepared to handle a range of contingencies since there is great uncertainty about who and where they might have to fight, who might be our allies, and how large the conflict might be.

b) *Declining defense outlays.* Cuts in the defense budget will likely result in lower levels of procurement, a smaller force structure, and less overseas basing and pre-positioning of troops and equipment than in the past.

c) *Long service lives.* Historically, defense systems tend to have longer service lives than were originally intended at the outset of development. In addition, since DoD will not be able to afford as many new systems as it has in the past, fielded systems and newly developed systems may have their service lives stretched out even longer than in the past.

d) *Rapid improvement of technology.* Theater systems and their constituent parts have a high degree of electronic content. The performance of electronic hardware and software technologies continues to advance rapidly and shows no signs of slowing down. The performance of these technologies that are such an integral part of theater systems can improve dramatically over the service lifetime of a fielded system.

Factors **a** and **b** mean that an integrated theater system should be both flexible and rapidly deployable and that cross-system integration activities should be able to be performed rapidly if necessary. Factors **c** and **d** point to the need for newly developed theater and component systems to be upgradable, evolvable, and maintainable.

2.4 RESULTING DEVELOPMENT CHALLENGES AND BENEFITS OF BETTER INTEGRATION

The theater system model indicates that there are two classes of problems that are important to the overall performance of a theater system:

- Single system development problems.
- Cross-system integration or interoperability problems.

Single system development problems associated with the development of hardware/software systems are well documented and are the subject of numerous studies and research programs. However, while single system development has long been the focus, **interoperability** is critical to the performance of the overall theater system. In fact, inadequate interoperability is just as, if not more, important to theater system performance and amounts to self-inflicted degradation of military capabilities.

Any solution to the interoperability problem needs to consider the budgetary climate and international security environment resulting from the rise of the "new world order". Thus, **the new development challenge is to ensure the interoperability of systems through rapid cross-system integration while producing a theater system that is flexible, rapidly deployable, upgradable, evolvable, and maintainable.**

Enhanced interoperability holds great promise for increasing U.S. military capabilities. The following list provides a sample of the possible **benefits.**

1. More information could be transmitted by secure data link rather than voice communications which are easier to intercept.
2. Good PGM-C4I interoperability could allow platforms to operate with greater stealth since the platform would not have to use its own emitters to guide the munition to its target.[3]
3. Better interoperability can enable in-flight retargeting or rerouting of munitions, such as cruise missiles, to minimize collateral damage and ensure that primary targets are struck.

[3] Coarse guidance could be provided by systems such as JSTARS, and terminal guidance could be performed by the munition's on-board systems.

4. Platforms could employ the best munitions for their missions.[4]
5. U.S. forces could operate more seamlessly with forces from other services and different countries.
6. Theater systems could deploy rapidly with a ready information infrastructure.
7. "Buddy system" tactics could be more easily employed since data and information from a specific platform enabler could be shared with other platforms that were not similarly equipped.
8. Intelligence could be placed in the hands of the warfighters in a timely and efficient manner.[5]
9. Tactical and strategic situational awareness would be significantly enhanced.[6]
10. Enhanced interoperability would enable more efficient planning and dissemination of orders and plans such as the Air Tasking Order.[7]

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[4] This would significantly increase the flexibility and robustness of the capability of multi-role platforms.

[5] For instance, the most recent satellite imagery of a target area could be provided to pilots enroute to the objective.

[6] Fighter pilots could use AWACS- and JSTARS-supplied data as well as its own sensor data to provide a more complete tactical picture of the space around them and enable better discrimination between friend and foe. Data fusion could be used to display the information in a more intuitive manner. Theater commanders could be provided a "God's eye view" of all movements of enemy and friendly forces on or above the battlefield.

[7] This would enable faster planning cycles and, hence, a faster pace of operations.

CHAPTER 3

New Methods for Complex Electronic System Development

This chapter contains descriptions of the methodologies for complex electronic system development which were selected for evaluation in this thesis. This set included the following methodologies:

- The rapid development process used to develop the flight control software for the DC-X
- The GritTech rapid development process
- Ptolemy-supported hardware/software codesign
- The RASSP (Rapid Prototyping of Application Specific Signal Processors) design methodology[1]
- Cleanroom software engineering

"Complex electronic system" is an umbrella term used to denote any system or group of systems which contain a large amount of electronic[2] hardware and software. Complex electronic systems can range from RAM-based field programmable gate arrays

[1] Note that both Ptolemy-supported hardware/software codesign and the RASSP design methodology are grouped together loosely under Section 3.3, "Hardware/Software Codesign."

[2] For the purposes of this thesis, other types of systems, such as photonic or optoelectronic, could also fall under the broad category of "electronic systems."

or digital signal processors running assembly code algorithms to JSTARS and beyond to include what we have denoted as "theater systems".

These systems are inherently "complex" because of the dramatic increase in the complexity of the hardware and software that are used in the development of even "simple" products. Consider, for instance, the development of a printed circuit module. The number of semiconductor gate equivalents contained by a typical (6 inch x 9 inch) printed circuit module increased by a factor of 20 between the 1980s and the 1990s. In the 1980s one of these modules ran at clock speeds between one and five megahertz. In the 1990s a module of similar size might run at clock speeds of 50 MHz or more. The size and complexity of the software contained in the modules has also displayed a similarly explosive rate of growth. Today, one of these modules may store more than four megabytes of code and/or data.

This growth in complexity is also evident at the avionic system level. The F-4s that saw combat in Vietnam did not have a digital computer on board and had no software. The first fighter aircraft equipped with digital computers were developed in the 1960s. These systems, which performed fire control tasks, required between 100 and 200 four- to eight-bit words of assembly language code. In the 1980s the software requirement had grown to approximately 400,000 eight- to sixteen-bit words of a combination of assembly language and higher-order languages to perform more complex functions including fire control, navigation, engine control, built-in-test, electronic warfare, flight control, stores management, and controls and displays (EIA, 1988).

This shift from solving relatively simple problems in software to solving problems of much greater complexity occurred during the mid 1970s. The F-16As, developed during the 1970s, were equipped with seven computer systems, 50 digital processors, and 135,000 lines of code (EIA, 1988). Produced in the late 1980s and early 1990s, the F-14D has 15 computer systems, 300 digital processors, and 236,000 lines of code. The B-2 reportedly has over 200 processors and approximately 5 million lines of code (Anderson and Dorfman, 1991). Currently, the F-22 has approximately 1.3 million lines of code on board, and has 4 million lines of code when the fighter's support systems are included.[3] Even transport aircraft exhibit this explosive growth in hardware and software complexity.

[3] Telephone interview with Chris Blake, Avionics IPT leader, F-22 SPO. July 16, 1994.

The C-17, which is the most computerized, software-intensive, transport aircraft ever built, has 56 computerized avionics subsystems which use 19 different types of embedded computers incorporating over 80 microprocessors and nearly 1.36 million lines of code (GAO, 1992).

The explosive growth in the complexity of hardware/software systems has made the development of these systems all the more difficult. The rate of increase in difficulty of system design and integration problems threatened to outstrip the rate of improvement of methods developed within existing paradigms. This realization provided the impetus for the creation of the methodologies discussed at length in the remaining sections of this chapter.

Accompanying this explosion in hardware/software system complexity has been a similarly rapid rate of adoption of information and communications technologies by nearly every combat and support function performed in a joint theater of operations. This proliferation of computational power on the modern battlefield has created both new opportunities and new development and integration challenges.

The widespread distribution of computational and communications technologies throughout combat and support functions has fueled the growth of an ever-expanding complex web of linkages among physically-distinct hardware/software systems. However, the desire to exploit the potential benefits of leveraging these linkages—such as the effective and efficient formulation and distribution of an air tasking order and the enhanced situational awareness provided by fusing on-board and off-board sensor information—has been tempered by the difficulty of making the various hardware/ software systems involved interoperable.

The exploration and discussion of the theater electronic system model in Chapter 2 highlighted the vital importance of ensuring the interoperability among the different elements of a theater system. Analysis of the model revealed the intrinsic importance of interoperability in maximizing the overall performance of a theater system. In fact, inadequate interoperability is tantamount to a self-inflicted degradation of theater system capabilities. Documented experiences from Desert Shield and Desert Storm indicated that interoperability was indeed a real problem for coalition forces, who were fortunate enough

to have had the luxury of five months to improvise systems that provided just enough capability, just in time (Hyde et al., 1992).

To ensure interoperability among the different elements of a theater system, a methodology for performing cross-system integration and, hence, developing complex electronic theater systems needs to be devised. With this in mind, a set of complex electronic system development methodologies was investigated with the hope of finding a methodology that could be directly applied in the cross-system integration role or could at least provide a starting point for the development of a suitable methodology. Each of the methodologies described in this chapter has produced significant improvements in the development of complex electronic systems or shows great potential for producing similarly significant improvements. These methodologies will be evaluated in Chapter 4 for their applicability to cross-system integration in order to address the interoperability problem.

3.1 RAPID DEVELOPMENT DC-X STYLE[4]

For the past several years, McDonnell Douglas Aerospace-West (MDA-W) has been developing a flight software development process known as RAPIDS (Rapid Prototyping and Integrated Design System). McDonnell Douglas Aerospace has applied RAPIDS to more than 15 projects including several flight and ground test programs including Single Stage Rocket Technology (SSRT) and Ground Based Interceptor. Phase II of the SSRT Program, awarded to MDA-W in August 1991, provided another opportunity to demonstrate the effectiveness of this methodology.

As a result of customer insight, software development, cost, schedule and reliability issues were closely scrutinized early in the program. This provided MDA-W with the opportunity to propose the use of a non-traditional process based on an integrated system level approach to the Guidance, Navigation, and Control (GN&C) design.

The entire Operational Flight Program (OFP) used by the Delta Clipper Experimental (DC-X1) was designed, coded, integrated, and tested in 24 months. The

[4] This section is based upon phone interviews with Mr. Matt Maras of MDA-W and Dr. Jo Uhde-Lacovara of JSC's Rapid Development Laboratory and publications which they provided (Maras et al., 1994; Uhde-Lacovara et al., 1994).

66,000 source lines of Ada code were used by the DC-X1 to complete nine system level static fire tests and three fully successful flight tests. Encompassing an autonomous GN&C capability, the flight control portion of the OFP was developed entirely within the integrated design and rapid prototyping environment.

In addition to the flight software (FSW) developed with this approach, test code, representing high fidelity models of the vehicle, its aerodynamics, sensors and actuators, and winds were also designed by employing the same methodology. Almost 70 percent of the new vehicle software developed for the DC-X1 program was produced with the integrated design environment, using automated code generation (Maras et al., 1994).

3.1.1 The Traditional Approach

The traditional approach to developing flight software displays the symptoms of what Hammer and Champy (1993) refer to as "process fragmentation". Engineers skilled in particular problem domains formulate detailed requirements for the systems and subsystems. During the requirements design phase, engineers develop and test candidate GN&C algorithms. A non-real-time engineering simulation is created to compare the performance of different algorithms. Several reviews are scheduled during this phase resulting in the elimination of some algorithms from further consideration. Following the selection of an algorithm or a set of algorithms, a requirements document is written.

These requirements are then passed on to other organizations which interpret the requirements and translate them into actual computer code. Once the code is written and tested, it is delivered to organizations responsible for the integration of the hardware with the software and testing of the resulting system. Typically, this is where many unforeseen problems arise—late in the schedule where problems are most difficult and costly to fix. Corrections are especially costly when changes to the requirements must be made. For example, a change in the mission requirements may necessitate changing the flight software requirements. These changes can require extensive modifications to the FSW. To make matters worse, the change process is usually conducted in the same fragmented, sequential manner as the original design iteration.

3.1.2 The RAPIDS Process

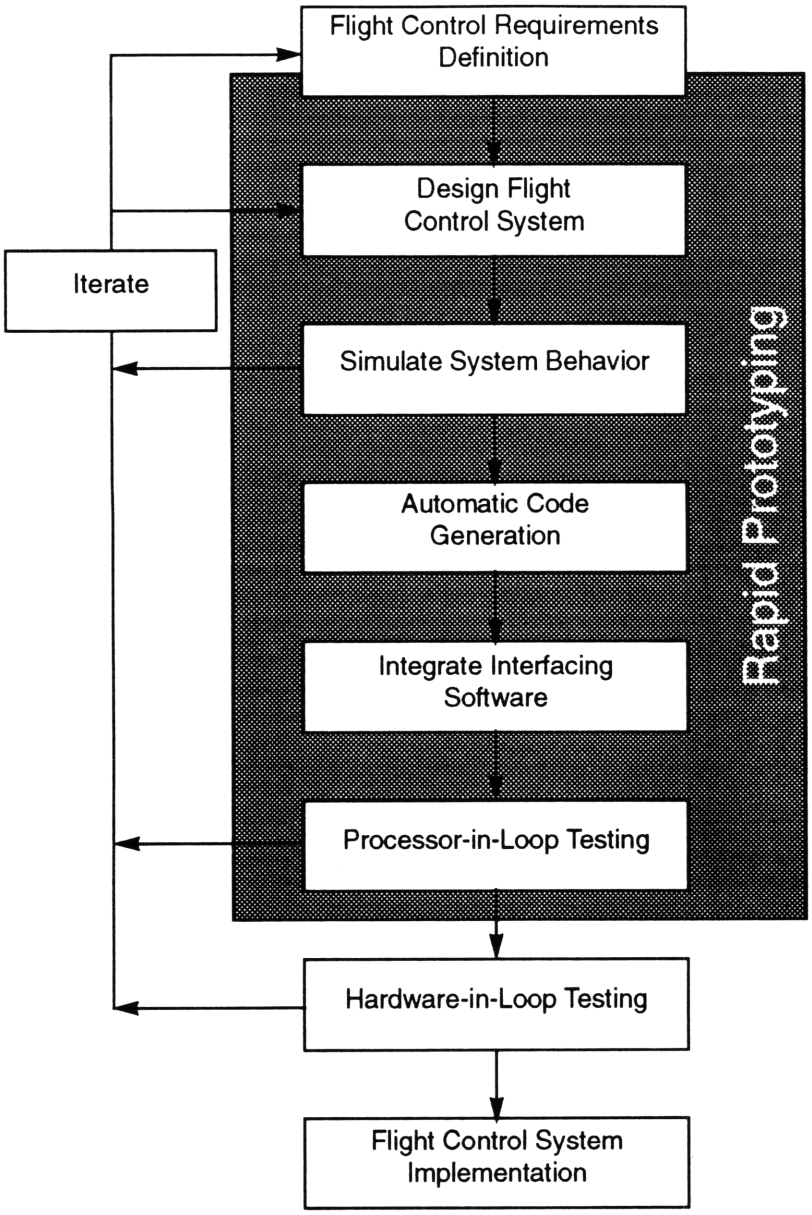
RAPIDS is a highly iterative process utilizing rapid prototyping techniques. Each rapid prototyping cycle develops a complete GN&C system from requirements definition through design and implementation on a target processor. Processor-in-loop (PIL) testing is performed once the initial working FSW prototype is developed.

This approach allows problems with software design, implementation, or hardware selection to be discovered early in the development cycle. This cycle of concurrent requirements and software development and PIL testing is repeated until FSW with the desired performance and quality is produced. The approach employed by RAPIDS is a spiral development approach where developers "build a little, test a little". This process is illustrated in Figure 3.1.

Each RAPIDS design cycle involves phases which can be found in a traditional process—requirements, design, development, and integration and test—that are performed with varying degrees of concurrency. Cycle time decreases with each iteration while the quality of the FSW increases. Whereas a traditional approach may require years to complete a single design cycle, initial iterations of a RAPIDS process may require months and then only weeks as the design matures. Ultimately, the design cycle may be on the order of a few days or less. However, regardless of the length of the design cycle, configuration control and complete software validation testing are maintained.

A designer in a RAPIDS process is part of a small, integrated team and is involved for the whole design, development, and validation process. Using an integrated team of system designers means that the distinctions between systems engineering, GN&C engineering, and software engineering break down—a single team member may be asked to perform any of these functions over the course of a development program. Whereas in the past each functional discipline would own only a portion of the final design and only a certain phase of the program, the RAPIDS design team has ownership of the entire process and end product. Indicators are that end-to-end ownership of the product and process tends to be more efficient and promotes a more productive work environment for the designers (Maras et al., 1994).

Figure 3.1: RAPIDS Spiral Development Process



Note: Hardware-in-loop testing involves the actual flight hardware. Processor-in-loop testing is performed with commercially equivalent hardware.

3.1.3 RAPIDS Toolset

The RAPIDS toolset integrates requirements analysis through hardware and software testing in a workstation environment using an integrated set of commercial off-the-shelf software development and simulation tools. The graphical user interface toolset captures

design details being implemented by GN&C experts and then automatically generates source code and documentation that can be targeted to the actual flight vehicle computer system. The environment is currently based on commercially available products including ISI's (Integrated Systems, Inc.) $MATRIX_X$/SystemBuild/AutoCode/AC-100™ and Cadre Teamwork.

$MATRIX_X$/SystemBuild is a graphical software tool that enables users to develop data flow block diagrams of the desired system using elementary building blocks. These elementary blocks can be organized into "Superblocks" which become procedures or subtasks. This construction process yields highly modular software designs which can facilitate the development of generic software libraries and the reuse of software. After construction is completed, the software data flow diagrams can be interactively tested in a non-real-time environment. Time and frequency domain analyses can also be performed interactively.

The AutoCode tool can automatically translate the block diagram representations into FORTRAN, C, or Ada source code. The source code can then be integrated with other interfacing software—software necessary for the code to run on the target processor such as a real-time operating system device driver, compiled and run on the AC-100 real-time computer to verify real-time and PIL performance.

3.1.4 Benefits of the RAPIDS Process

The ultimate benefit of this approach is a cost reduction because of the smaller software development staff necessary to support initial requirements definition through test and integration. The reduction in software development staffing is possible since the application or GN&C designer does the majority of these activities within an integrated, graphical workstation environment. Other benefits of the methodology include the following:

- Software is not a schedule critical item, and the best design can be implemented at flight time because it is not limited by the typical six to twelve month lead time required by a traditional process to make software changes. The design that flies can be based on the best available data and algorithms from all previous testing.

- Challenging milestones, which are typical of fast paced programs, can be met while maintaining or enhancing the quality of the final software product.
- The rapid prototyping process allows major errors and design flaws to be discovered earlier in the program when they are cheaper and easier to correct.
- Requirements can be verified early in the development program.
- Metrics tracked during DC-X1 software development indicated that the RAPIDS process can result in productivity improvements greater than 25 percent.

The Navigation, Control & Aeronautics Division at NASA's Johnson Space Center employed a similar process to construct a simulation of the Soyuz Assured Crew Return Vehicle flight software and demonstrated substantial productivity gains when compared to COCOMO model estimates. The data are shown in Table 3.1.

Table 3.1: Soyuz Simulation Project Metrics

	Phase 1	Phase 2
Number of Superblocks	55	371
Number of SLOC	4102	25045[a]
COCOMO Estimated Total Staff-Hours	3400	11658
Estimated Total Staff-Hours	1830	7720
SLOC per Staff-Day	18	22[b]
Productivity Increase (Actual vs. COCOMO)	85%	50%

Source: Uhde-Lacovara et al. (1994)

a. This figure includes the lines of code produced in Phase 1.
b. Reuse of Phase 1 software is assumed. Thus, the number of SLOC from Phase 1 was not included in calculating this value.

3.2 RAPID DEVELOPMENT THE GRITTECH WAY

Recognizing that the rate of complexity growth in electronic hardware and software was rapidly outdistancing the ability of its engineers to keep pace, GritTech[5] began to experiment with rapid development processes and enabling technologies to determine if

dramatic improvements in productivity could be made. The basic question addressed in formulating a rapid development process was how to change the traditional process to exploit more fully the potential of design automation tools.

At GritTech the traditional development process for a typical module involved 30 or more discrete steps which were performed in a sequential, isolated fashion. Experience with this process taught the designers that the traditional process would often lead to the propagation of flaws which would remain undiscovered until late in the development cycle where rework can be a most costly and time consuming process. For instance, a small misinterpretation of the customer's specifications on the part of the contractor early on in the development process could embed a flaw in the design that could escape detection until field tests are conducted at the end of the development chain. Corrective action in this case could very well be a lengthy and expensive process. Even when errors remain undetected for only a few steps in a sequential process, the result could be significant budget and schedule overruns.

GritTech's answer to the productivity problem was to search for development processes which tightly integrated the diverse tasks so that they could be performed in parallel with rapid feedback and feedforward of information among all tasks. They believed that productivity would increase dramatically if the person doing a task could see the impact of a contemplated change on the results of all other tasks within minutes, rather than months.

3.2.1 General Process Characteristics and Philosophy

The rapid development process is composed of several technical and procedural elements. The relative importance of an individual element depends on the type of development project at hand. Reflecting a kind of "skunk works" approach to project management, the designers responsible for the undertaking are given a wide degree of latitude in tailoring the process to the needs of the current project.

In addition, designers involved in rapid development projects generally have more responsibility for the project than designers working on a more traditionally managed

[5] This is a pseudonym for a defense electronics firm's rapid development group whose practices were studied for this thesis. The pseudonym is being used, at the request of the firm, in the interests of preserving confidentiality.

program. For instance, the actual system designers are often personally involved in meetings with the customer. Project managers are also more involved with the day-to-day work of the designers, often getting involved in actual design activities themselves. The combination of broader responsibility for designers and more involvement by project managers facilitates better assessment of the current status and rate of completion of project work.

The rapid development designers are all high caliber engineers. If some "ilities"[6] are not required to satisfy customer requirements and are tailored out of the official project process in order to meet tight scheduling constraints, the individual designers will still try to account for them informally as a part of exercising "good engineering practice". For instance, consider a technology demonstration project under such time pressure that tasks such as explicit design activities, which are meant to ensure a certain degree of expandability, are tailored out of the official project process. However, a project engineer may still include some spare pin locations on a board in order to easily accommodate the addition of more memory or processing power in case it becomes necessary to increase the functionality of the system in the future.

A major tenet of the rapid development operating philosophy is to utilize all available means to enhance productivity and to allow the designers to experiment with new technologies to accomplish this. This tenet manifests itself operationally in a number of ways. For instance, designers in the rapid development group at GritTech utilize the Internet to get advice from outside experts. Frequently, assistance and advice can be obtained for free from the many technically-oriented newsgroups on UseNet. Source code applicable to a project at hand can also be found via ftp (file transfer protocol) or gopher sites. This tenet has also manifested itself in the willingness of designers to experiment with and adopt new design tools. In several instances designers have even adopted new design tools and used them for the first time on actual projects that were already in process, believing that the tools would help them perform their tasks better and faster.[7]

Typical rapid development projects do not attempt to extend the state-of-the-art in electronic hardware and software technologies. Most involve exploiting state-of-the-shelf

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[6] "ilities" is shorthand for a class of design considerations such as manufacturability, affordability, supportability, scalability, upgradability, producibility.

technologies in new ways to produce a desired capability or set of capabilities. Demanding schedules are part of the norm.

To reduce the risks involved with development projects, the group does not usually attempt projects unless it has had some prior experience with the technologies involved. In some cases the group has even conducted some rapid prototyping activities before submitting a bid to ensure that risks are understood. Sometimes even hardware components will be part of the rapid prototyping effort. To further reduce risks involved in a development project, rapid development engineers will use real data whenever it is available since simulated data can be imperfect.

3.2.2 Examples of Rapid Development

As previously mentioned, GritTech's rapid development process and operating philosophy allow engineers extensive latitude in tailoring the process to the particular needs of the project. Moreover, most of the projects performed by the rapid development group at GritTech do not involve product line systems. Hence, it is useful to briefly examine a couple of rapid development projects—one hardware/software system and one software application—to gain a better understanding of the methodology.

Hardware/Software System Development

A good example of the application of GritTech's rapid development philosophy to hardware/software system development involved the design and development of an acoustic processor. The objective was to take a power-hungry, computation intensive system and develop a portable, low-power system providing equivalent functionality. Since the chosen low-power processor provided only a fraction of the original system's computational power, it was necessary to decrease the computational load of the algorithms without appreciably degrading the performance of the system. Adding to the challenge was a four month development schedule.

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[7] Another aspect of this constant search for new tools and methods is the group's resistance to standardization of tools and processes. According to rapid development engineers, the traditional usage of standardization—one in which tools and processes that are standardized remain the company's standard even though much better tools and processes may exist—overly constrains the ability of a designer to use the best available tools and methods.

Since simulation models were not available for some components that had been chosen for use, the hardware design needed to be prototyped and verified before the actual printed circuit board was fabricated. While wire wrapping—the traditional prototyping technology—can be relatively inexpensive, it was not flexible enough for the project's demanding schedule. The wrapping of the initial design can take a week, and corrections to the design can be time consuming and are often not properly documented, which can cause significant problems during hardware debugging. Consequently, a new, flexible prototype technology was chosen—Field Programmable Interconnect (FPIC) devices and Field Programmable Circuit Boards (FPCBs).[8]

Utilizing the flexible prototyping technology, the prototype could be dynamically reconfigured based on changes to the schematic—a capability that proved its worth on many occasions. For instance, an easily-acquired SRAM (Static Random Access Memory) was used initially instead of the desired SRAM since the special, low-power SRAM selected for the design was unavailable at the start of hardware development. When the desired components were delivered, the design schematics were updated to account for the different packaging and pin layout, and the new netlist was downloaded to the FPCB within minutes. In the course of development, a bit-swap error was detected which could have forced an entire bus change and a one day delay if wire wrapping had been used. Instead, the FPCB-FPIC combination enabled a corrected design to be up and running within minutes.

The flexibility of the prototype technology allowed the hardware design to be completely debugged in one week without the aid of computer simulations. A conventional printed circuit board layout was performed concurrently with the hardware design verification effort, and schematic changes made as a result of the debugging effort were automatically included in the printed circuit board (PCB) layout. After only one week of testing, the PCB was shipped for fabrication using the identical netlist that had

[8] The FPIC is a commercially-available RAM-based passive routing device, containing over 900 usable input/output pins. The FPCB is a multilayer circuit board accommodating an array of pin sockets and a mounting area for one or more FPICs. A circuit is constructed by placing components on the board and configuring the FPICs. The FPIC also has a dedicated logic-analyzer diagnostic port. Extensive software tools for translating netlist information into component placement, FPIC internal routing, and logic-analyzer configuration information are also available from the vendor. FPIC and FPCB are trademarks of Aptix Corporation.

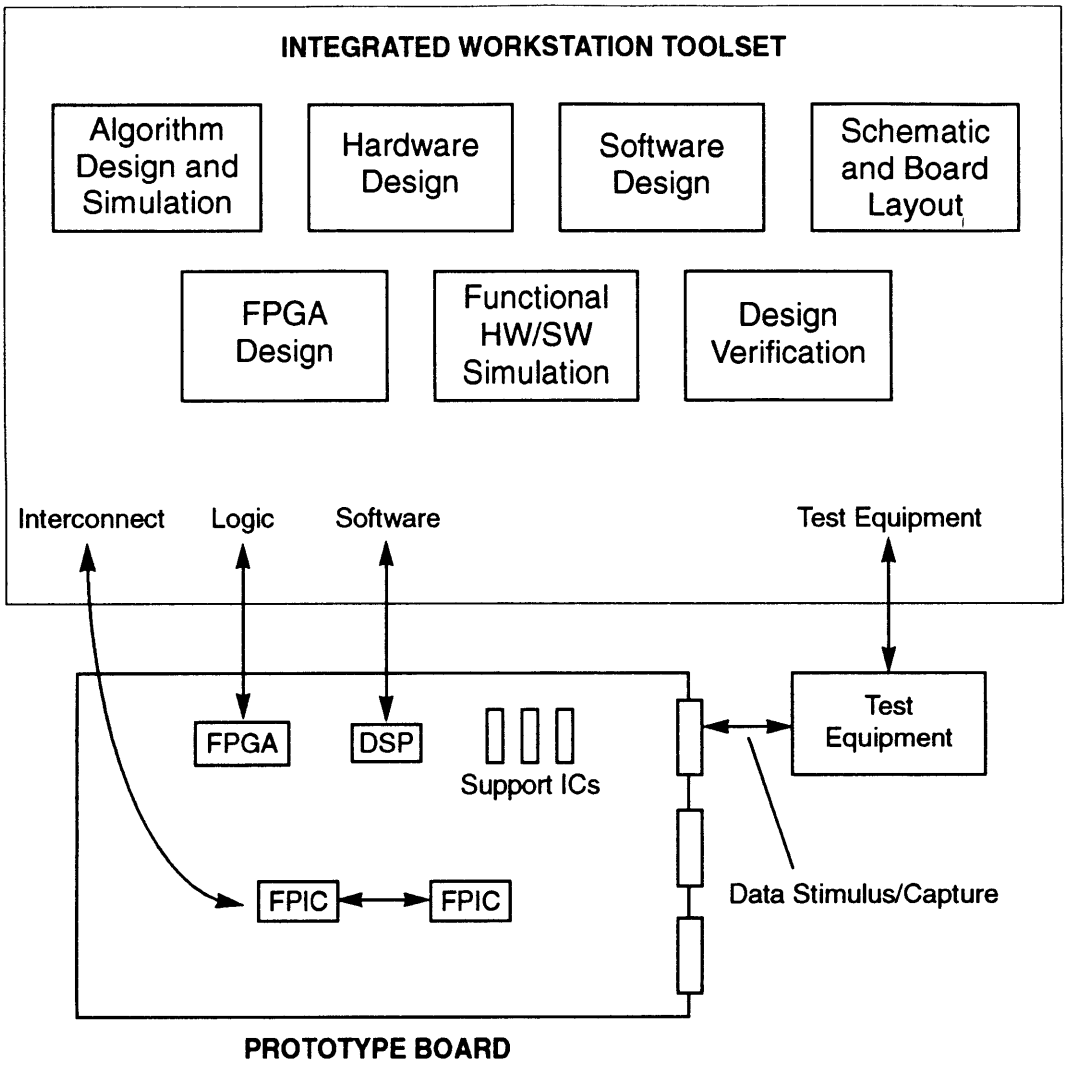
been validated on the prototype. When the bare PCB was delivered, the components were dropped in, and the system was thoroughly tested. After two days of testing, no defects were discovered, and the board was declared finished with no cuts or jumpers required. No problems have been reported in subsequent operational use.

While the PCB was being fabricated, the application software was being coded and tested using the integrated development environment, which included the FPCB-FPIC prototype, an in-system processor emulator, networked logic analysis instruments, a "reference design" from a previous project, and additional signal processing analysis tools running on a workstation. A depiction of this environment is shown in Figure 3.2. The combination of the ability to control the hardware and test equipment from the workstation by downloading and uploading code, data, and sequencing information and the ability to orchestrate the use of the various assets with operating system scripts provided designers with a powerful, integrated rapid development environment. Moreover, having a completed printed circuit board in a little more than one month enabled the designers to focus their efforts on developing more sophisticated algorithms during the remaining three months and achieve better field-test results.

In addition to the speed of development afforded by the integrated environment, application software development was further accelerated through the use of several routines that were obtained from bulletin boards on the Internet. These routines provided the needed throughput with minimal modification.

According to the designers, the success of the rapid development project could be attributed to the use of a combination of newer technologies which resulted in a major reduction in development time. Compared to estimates of traditional development effort based on a benchmark of 15 staff-months/board for typical module development productivity, the hardware/software effort required only 16 percent of the engineering staff-months. Thus, by combining an integrated development environment with programmable prototype methods, the GritTech rapid development engineers achieved a factor of six improvement in productivity.

Figure 3.2: Integrated Development Environment



Incremental Software Development

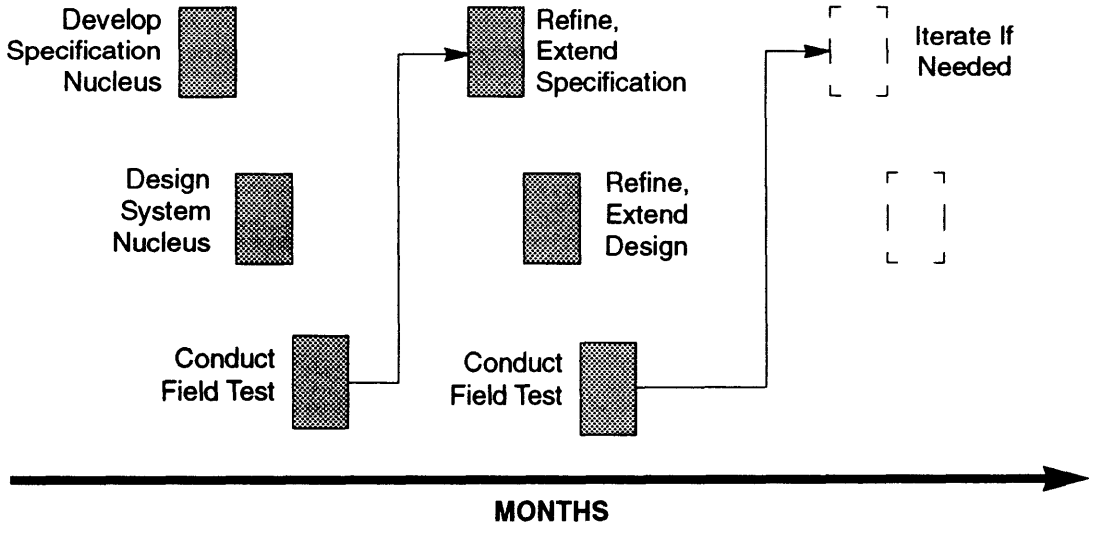
Another example of rapid development in action was the use of the process in the development of a launch data visualization and advising system. This particular project arose from the customer's desire to exploit newly available data visualization capabilities for a launch vehicle program in 1991. Over 50,000 pressure, temperature, wind direction, and other sensors were in use during launch preparations. The data stream from these sensors was being preprocessed and displayed to operating personnel in the form of instantaneous numeric values. The customer identified a need to display this information

graphically, provide trend information at a glance, enable comparisons to past launches, and perform related functions.

Rapid development engineers developed a core analysis and display system in about a month after project launch. This initial release was then installed for evaluation on computers at the launch facility, off-line from actual launch operations. Incremental release of the most recent version for customer evaluation occurred approximately every five weeks. Feedback included the suggestion to add capability to call up video views of the launch vehicle and the launch pad. The GritTech engineers discovered that the incremental development and release approach also helps to build a good working relationship with the customer in addition to speeding up the development process. Design cycles tend to get progressively shorter with each iteration, partly because the integration of software modules is performed many times and gets progressively easier.

The incremental development process is depicted in Figure 3.3. Incremental development utilizes a series of quick low cost field trials of progressively more complete systems. This approach differs considerably from the traditional approach which defers field testing until the end of a multi-year, full scale development program.

Figure 3.3: Incremental Development



In the incremental development process, software design and development can begin as soon as some part of the system specification has been developed. Typically, the specification or portion of a specification is translated into a field-testable design in about a month. The customer is then supplied with a copy of the current software for operational or test range evaluations of the design with the GritTech designers providing support. This field testing is especially important for evaluating the design of user interfaces and displays. Based on the results of the joint evaluation, the specification is extended or revised, and the design is incrementally expanded and/or refined during the next cycle.

The rapid development group has found from past experiences that the optimum time period for providing customers with opportunities for hands-on evaluation is approximately once every four to ten weeks. The result is a design that rapidly evolves into a well-suited, highly functional system with minimal need to expend resources on performing rework resulting from erroneous assumptions and interpretations of requirements.

As was the case with the acoustic processor example, using a highly integrated set of software development tools facilitated a substantial reduction in the time and effort required for system development. One tool allowed software engineers to design the graphical user interfaces (GUIs) by manipulating basic GUI building blocks available from a palette. Once the elements were arranged to the satisfaction of the engineer, the actual source code was produced through automatic code generation. As a rule the generated code was not touched unless problems could be explicitly traced to it. Another tool which helped speed development enabled designers to execute the code and see how it worked without having to compile it first. Software libraries also facilitated the reuse of previously developed and verified software modules.

Since the launch data visualization system uses virtually all commercial off-the-shelf workstation and video hardware, development productivity was only measured with respect to the software development benchmark of 10 standard lines of code per staff-day. By using a highly integrated suite of software development tools in conjunction with an incremental development approach, the rapid development team was able to develop this system and demonstrate an 8:1 improvement in productivity in spite of having to absorb a significant revision to the performance requirement.

3.2.3 Rapid Development Productivity Performance

To date, the rapid development process has been used on 20 different small to medium sized projects at GritTech, demonstrating significant productivity improvements over a traditional process in each case. The improvements in productivity afforded by the rapid development methodologies and tools for these projects are summarized in Table 3.2 and Table 3.3 for software and hardware development, respectively. The rapid development projects have consistently exhibited two to four times the productivity that would be expected of a traditional process.

Table 3.2: Software Rapid Development Results

Environment	Productivity Improvement (versus benchmark)
Tailored DoD-STD-2167A	3 to 4:1
Other	3 to 8:1

Table 3.3: Hardware Rapid Development Results

Module Size	Type	Productivity Improvement (versus benchmark)
6 inches x 9 inches (54 square inches)	Microprocessor-Based	2 to 6:1
8 inches x 16 inches (128 square inches)	Logic-Based	2 to 4:1

3.3 HARDWARE/SOFTWARE CODESIGN

Methodologies to support the codesign of hardware/software systems were developed in response to problems with the traditional process for developing these systems. The traditional process partitioned the problem into hardware and software elements early in the development cycle, and then proceeded to develop the two designs in parallel with very little or no interaction until the end of the process when they were integrated for system testing. Predictably, the classic approach exhibits many symptoms of a fragmented process.

Typically, the integration of the hardware and software near the end of the development cycle is laden with unforeseen problems—many of which can be attributed to the lack of interaction between the hardware and software design groups. Any design changes at this point in the process are likely to significantly impact the system's cost and development schedule. In many instances, even when integration itself does not reveal any problems, the overall system performance can be disappointing. Frequently, the blame is laid at the feet of the programmers. However, in many cases, the real fault may lie in the design of a development process which imposes an artificially crisp distinction between hardware and software design.

3.3.1 Generic Hardware/Software Codesign Process

An alternative approach is to recognize the high degree of coupling that exists between hardware and software for most complex electronic system design problems and employ a more flexible design process, where hardware and software development proceed in parallel with feedback and interaction between the two as the overall system design matures. The final hardware/software partitioning decision can be made after evaluating alternate design architectures with respect to such factors as performance, programmability, reliability, and manufacturability. This type of approach may be termed "hardware/software codesign".

According to Kalavade and Lee (1992), hardware/software codesign strategies can be applied to different levels of design problems including:

- *Processor Design.* An optimized application-specific processor can be developed by tailoring both the instruction set and the program for the application. This type of codesign problem is very difficult.
- *System-Level Design.* Hardware/software codesign can also be performed at the system level, where an algorithm is partitioned between custom hardware and software running on programmable components. The hardware would typically include discrete components, application-specific integrated circuits (ASICs), DSP cores, microprocessors, microcontrollers, or semi-custom logic developed using FPGAs or logic synthesis tools. Since there are many possible

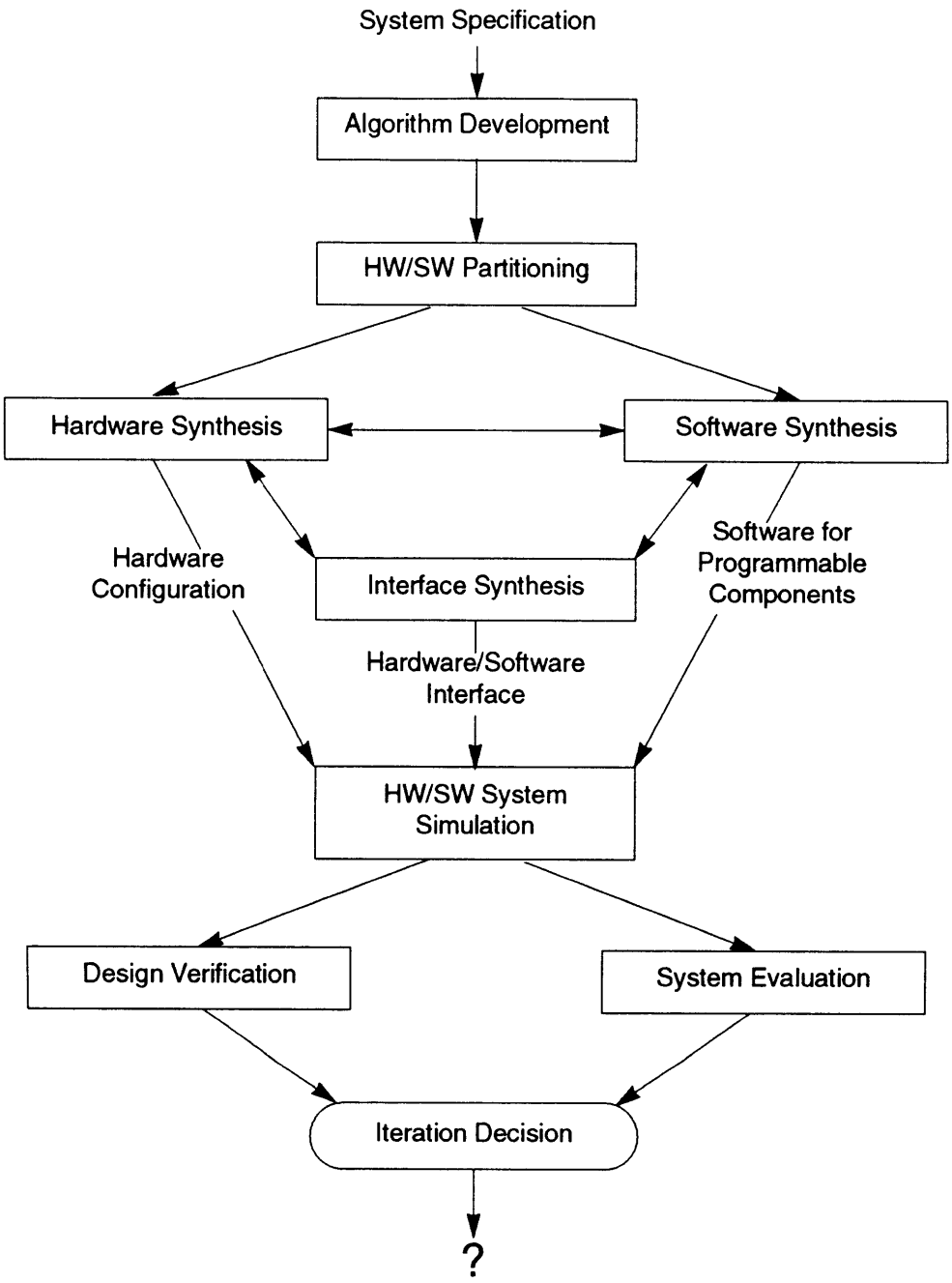
ways to partition a given design between hardware and software components, evaluating design configurations with system-level simulation of hardware and software allows the design space to be more thoroughly explored and is an integral part of codesign.

- *Application-Specific Multiprocessor System Design.* The codesign of an application-specific multiprocessor system is challenging since it involves choosing a suitable number of processors, an interprocessor communication (IPC) strategy, and the design of the application software. Since software synthesis requires partitioning and scheduling the code among the processors, scheduling techniques must be capable of adapting to changing hardware configurations. Thus, developing an application-specific multiprocessor system is an iterative process, involving tradeoffs associated with selecting an optimal hardware configuration and software partitioning.

A generic hardware/software codesign process is shown in Figure 3.4. The objective of a codesign methodology is to produce a hardware/software system design that meets a given set of specifications while satisfying a set of design constraints. Given a system specification, a designer can utilize high-level functional simulations to develop a suitable algorithm without making any assumptions concerning specific implementation details. The next step is to partition the algorithm into hardware and software while satisfying requirements such as speed, complexity, and flexibility. Operations that are computationally intensive with fixed operations are usually allocated to hardware. Algorithm components that may vary for different situations, are less computationally intensive, may require field programmability, or are not likely to change with time can be allocated to software (Kalavade and Lee, 1993).

Once the initial partitioning has been performed, the process of synthesizing the hardware, software, and interface designs can begin. These three activities are tightly coupled. Changes in one synthesis area significantly affect the others. Hardware synthesis activities include selecting the programmable processor, which directly impacts the software synthesis activity of selecting a code generator, and determining the appropriate number of processors and their connectivity, which, in turn, influences the code

Figure 3.4: Generic Hardware/Software Codesign Process



partitioning decision and hardware/software interface synthesis. Choices involved in custom hardware synthesis can range from generating custom data paths to generating masks for FPGAs. As a part of custom data path design, the register word lengths must be selected (Kalavade and Lee, 1993).

Depending on the chosen hardware configuration, software synthesis can involve partitioning and scheduling the code across multiple processors and synthesizing the code for interprocessor communication—decisions which depend heavily upon the selected architecture. Partitioning among different processors may be performed with the intent of optimizing cost functions such as communication cost, memory bandwidth, and local and global memory sizes. In addition, if the hardware configuration includes use of fixed-point processors, some algorithmic modifications might be required to minimize finite precision effects, such as limit cycles and quantization errors (Kalavade and Lee, 1993).

Interface synthesis involves adding latches, FIFO (first in, first out) registers, or address decoders in hardware and adding code to handle input/output operations and semaphore synchronization in software. Iterating to explore different design options is the common method for solving this cyclic problem (Kalavade and Lee, 1993).

After the hardware, software, and interface synthesis tasks have been accomplished, the hardware/software system design can be simulated within a heterogeneous simulation environment. Since the simulated hardware must run the generated software, the simulation environment should allow for the interaction of a number of different simulators in the event that various specification languages are used.

Simulation results can then be used to verify that the design works as intended and meets the given system specifications. If the specifications are not satisfied, another iteration will be needed. Whether it is necessary to perform another iteration of the entire codesign process or just portions of the process will depend on the nature of the shortcoming. The simulation results and the hardware and software configurations chosen for the specific system design can also be used to evaluate the system in terms of performance and estimates of other factors including power requirements, die area, component and bus utilization, and manufacturing costs. After using these estimates to evaluate the design, the designer may choose to repartition the system and experiment with different designs (Kalavade and Lee, 1993).

Currently, there are several programs that are developing design environments which support hardware/software codesign or are attempting to incorporate those ideas into a larger system engineering methodology while developing the enabling tools. The next two sections provide a sample of these efforts.

3.3.2 The Ptolemy Project

Developed at the University of California at Berkeley, Ptolemy is an environment for prototyping and simulating heterogeneous systems.[9] Heterogeneous systems are systems involving subsystems having different models of computation and, hence, fundamentally different approaches to design and simulation. According to Dr. Mark Richards of ARPA, Ptolemy's framework allows a designer to mix and match multiple models of computation more effectively than most design systems. Ptolemy facilitates the interaction of diverse models of computation through the use of object-oriented principles of polymorphism and information hiding.

Since the start of the Ptolemy project in 1990, there have been numerous advances in design, simulation, and code generation. Many of these advances have been incorporated in Ptolemy in the realms of dataflow modeling of algorithms, synthesis of embedded software from such dataflow models, animation and visualization, multidimensional signal processing, hardware/software partitioning, VHDL (VHSIC Hardware Description Language) code generation, and managing complexity through the use of higher-order functions.[10]

Ptolemy employs object-oriented software principles in attempting to achieve the following goals (Buck et al., 1994):

- *Agility.* The Ptolemy environment should support distinct computational models to enable each subsystem to be simulated and prototyped in a manner that is appropriate and natural to that subsystem.
- *Heterogeneity.* Ptolemy should enable distinct computational models to coexist seamlessly in order to investigate interactions among subsystems.

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[9] The Ptolemy software is available for the Sun 4 (sparc), DecStation (MIPS), and HP-PA architectures. System installation requires 90MB of disk space and at least 8MB of physical memory. A scaled-down demonstration version, called Ptiny Ptolemy, is also available for the same architectures but only requires 12MB of disk space. A copy of Ptolemy can be obtained on tape by calling (510) 643-6687 or via anonymous ftp from ptolemy.eecs.berkeley.edu. Other on-line information resources can be found in the newsgroup comp.soft-sys.ptolemy and on the World Wide Web at http://ptolemy.eecs.berkeley.edu.

[10] The project joined ARPA's RASSP program, the subject of the next section, in 1993 as a technology base developer.

- *Extensibility.* Ptolemy should support seamless integration of new computational models and allow them to interoperate with existing models with no modifications to the Ptolemy environment or existing models.
- *Friendliness.* Ptolemy should employ a modern graphical interface with a hierarchical block diagram style of representation.

Ptolemy has been used for a wide range of applications including signal processing, telecommunications, parallel processing, wireless communications, network design, radio astronomy, real-time systems, and hardware/software codesign.

In the hardware/software codesign application area, Ptolemy is a very powerful tool since all parts of a hardware/software system can be modeled using the various domains included in the environment. Modeling both hardware and software within a single framework allows a designer to explore tradeoffs between hardware and software implementations of different functions (Buck et al., 1994). Another advantage of being able to develop hardware and software simultaneously in a design and simulation environment is that software development does not have to wait for a hardware prototype to be ready in order to start. In fact, if the manufactured hardware configuration is the same as the simulated hardware/software system, the actual production software code will have already been developed and verified.[11]

3.3.3 Rapid Prototyping of Application Specific Signal Processors[12]

Initiated in 1993, the Rapid Prototyping of Application Specific Signal Processors (RASSP) program is a four-year ARPA/Tri-Service initiative aimed at creating a new process for the development of military signal processors. The program's objective is to dramatically improve the process for the development of complex digital systems—

[11] A good example of how Ptolemy can be used in hardware/software codesign to explore the design space can be found in Kalavade (1991).

[12] Although this program is really just getting started, RASSP's concepts merit discussion since they provide a glimpse of design methodologies and capabilities that could be available in the near future. In fact, according to Dr. Mark Richards, RASSP program manager, substantial progress has already been made during the program's first year. This description is based on many interviews (live, phone, and email) with Dr. Richards and others at ARPA as well as the papers referenced herein.

particularly embedded digital signal processors[13]—in the areas of specification, design, documentation, manufacturability, and supportability.

Major Goals

The major goals of the RASSP program are:

- 4x reduction in concept-to-fielding cycle time
- Commensurate improvements in quality, life cycle cost, and supportability
- State-of-the-art at the time of fielding
- Systematic design capability at all levels from concept to manufacture
- Commercialization and promulgation of the RASSP process

RASSP Approach

The RASSP approach has three key thrust areas—design methodology, processor architecture, and design automation. The first key thrust is an incremental refinement of the design methodology. As currently envisioned, the design methodology will be based on concurrent engineering practices, using a top-down, VHDL-based design approach. The methodology will also seek to involve users early and often throughout the design process.

The second thrust is in the area of processor architecture. RASSP will foster the use of modular hardware and software architectures through the separation of communication, computation, and control functions and scalable interconnects.

The final thrust is the development of a seamlessly integrated and comprehensive set of CAD tools. Tools to support all the "ilities" are to be included as well as manufacturing and system engineering.[14] The design environment would also facilitate true hardware/software codesign and hardware and software synthesis. Hardware and software reuse libraries and an enterprise framework would also be incorporated into the EDA (Electronic Design Automation) infrastructure.

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[13] While signal processors were chosen as a focal point for the RASSP program, it is hoped that the processes and tools developed during the program will be broadly applicable to the domain of complex digital systems.

[14] "ilities" is shorthand referring to a broad set of design considerations including manufacturability, affordability, supportability, upgradability, and many others.

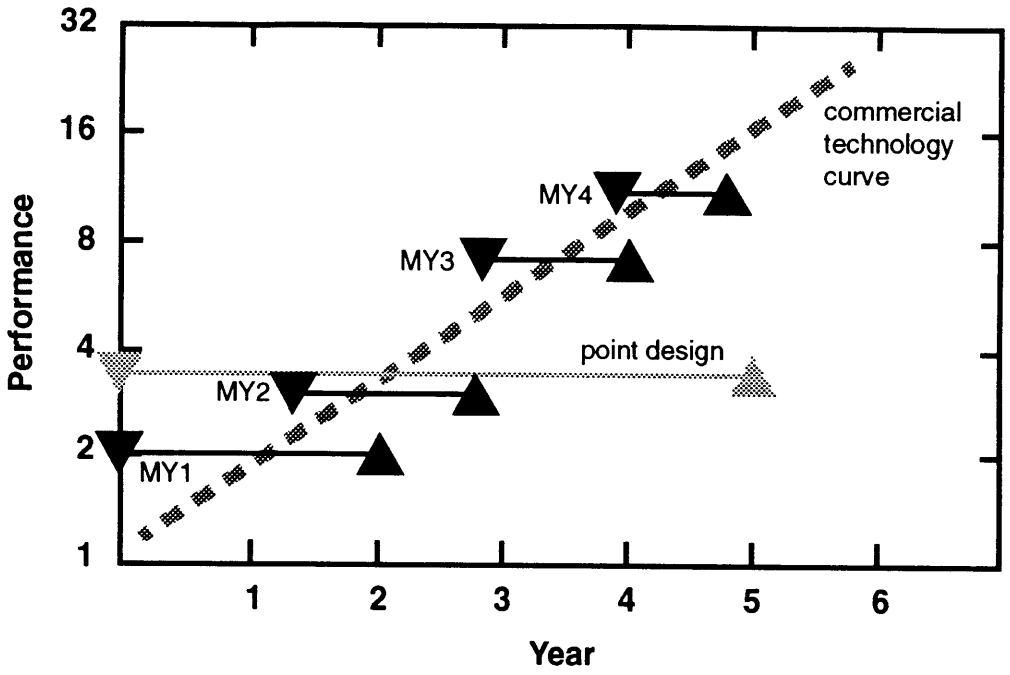
RASSP Design Methodology

Two major components of the design methodology being explored by the RASSP developers are top-down concurrent design and the model year concept of design. The RASSP design methodology is derived from a top-down approach to system engineering, starting with a formal specification which is successively refined to finer and finer levels of detail until the design is finished. Concurrent engineering concepts are applied to modernize the traditional top-down approach and are expected to contribute significantly to the goal of reducing design cycle time by a factor of four. Through the use of EDA tools, RASSP hopes to be able to provide the designer with estimates of factors such as size, weight, power, cost, and reliability early in the design cycle while the designer is still experimenting with different algorithms and system architectures.

The RASSP design methodology is also experimenting with a model year approach to design. Traditionally, DoD has emphasized the development of the best possible technology at the time of initial concept development. The development of military signal processors is no exception. The result of this point design approach is usually the development of highly optimized custom hardware, interfaces, and software in an attempt to maximize performance. Moreover, insisting on the use of custom design requirements frequently results in very long development cycles. Not only does this introduce a significant delay in the delivery of prototypes to potential users for operational evaluation, but it can also lead to the procurement of systems that are already obsolete by the time they are fielded. Typically, upgrading point designs is also a difficult and expensive proposition because of the highly optimized design of the original system.

In contrast to this traditional approach, the model year design methodology—derived from the practices of top commercial electronics companies—primarily utilizes existing hardware and software technology to rapidly develop a baseline system based on a subset or relaxed set of specifications. The resulting prototype can be delivered to the user for test and evaluation earlier than with the traditional approach, which also allows the designers to get user feedback faster. Subsequently, the design can be upgraded to correct any functional problems and insert more recent technology into the system. Over the length of time required to field a point design, a hardware/software system designed according to the model year philosophy may evolve through several design cycles

Figure 3.5: Model Year Design vs. Point Design



Source: Richards (1994).

(Richards, 1994). Thus, the model year approach to design can place a capability in the hands of the user earlier and enable the fielded system to keep pace with the rate of technological advance. A conceptual depiction comparing the point design and model year design approaches is shown in Figure 3.5.

As illustrated in Figure 3.5, the model year methodology assumes the performance of commercially available technology improves rapidly. As long as commercial technology continues to improve rapidly, the successive refinement of a system design through the use of several short design cycles will produce better performance than the point design approach even if the original model year design sacrifices some desired performance. Moreover, the improved level of performance can be achieved with a markedly decreased dependence on costly, hard-to-maintain custom hardware and software (Richards, 1994).

Use of a model year approach also creates a number of benefits for the user. First, a higher-performance signal processor can be acquired for a lower design cost. Second,

since the processor is based on standard supportable technology, life cycle support costs are lower. Evolving model year prototypes supply the user with prototype hardware and software early and often, providing a means for discovering flaws in the system specifications while they are still correctable. The result is a product that is well suited to the needs of the user (Richards, 1994).

RASSP Architectural Concepts

The RASSP architectural concepts do not prescribe a specific processor design. Rather, they form a flexible framework for DSP design and provide architectural guidelines to be observed in order to realize the full potential of the model year design paradigm. The architectural concepts include scalability, modularity, flexible interfaces, heterogeneity, and life cycle support (Richards, 1994).

- *Scalability.* Although the program is focusing on the embedded DSP domain, the performance range that must be addressed is still sizable. To meet the objectives of the RASSP program, architectural ideas should be scalable to satisfy performance requirements ranging from a few megaflops to tens or possibly hundreds of gigaflops.
- *Modularity.* An efficient model year development process cannot be achieved unless each succeeding design cycle is able to build upon the work of previous cycles. Thus, processor architectures must facilitate the design and reuse of hardware and software in a modular fashion to allow portions of the processor to be upgraded without a wholesale redesign of the system.
- *Flexible Interfaces.* The processor subsystems should employ interfaces based on scalable, open hardware designs and software communication protocols. Since the interfaces to the actual sensor and to displays or data processors will generally be beyond the control of the RASSP designer, flexibility in interface capabilities will be a must. The combination of modularized hardware with standard interfaces between modules will localize the impact of design changes to the portions of the system being redesigned or upgraded.

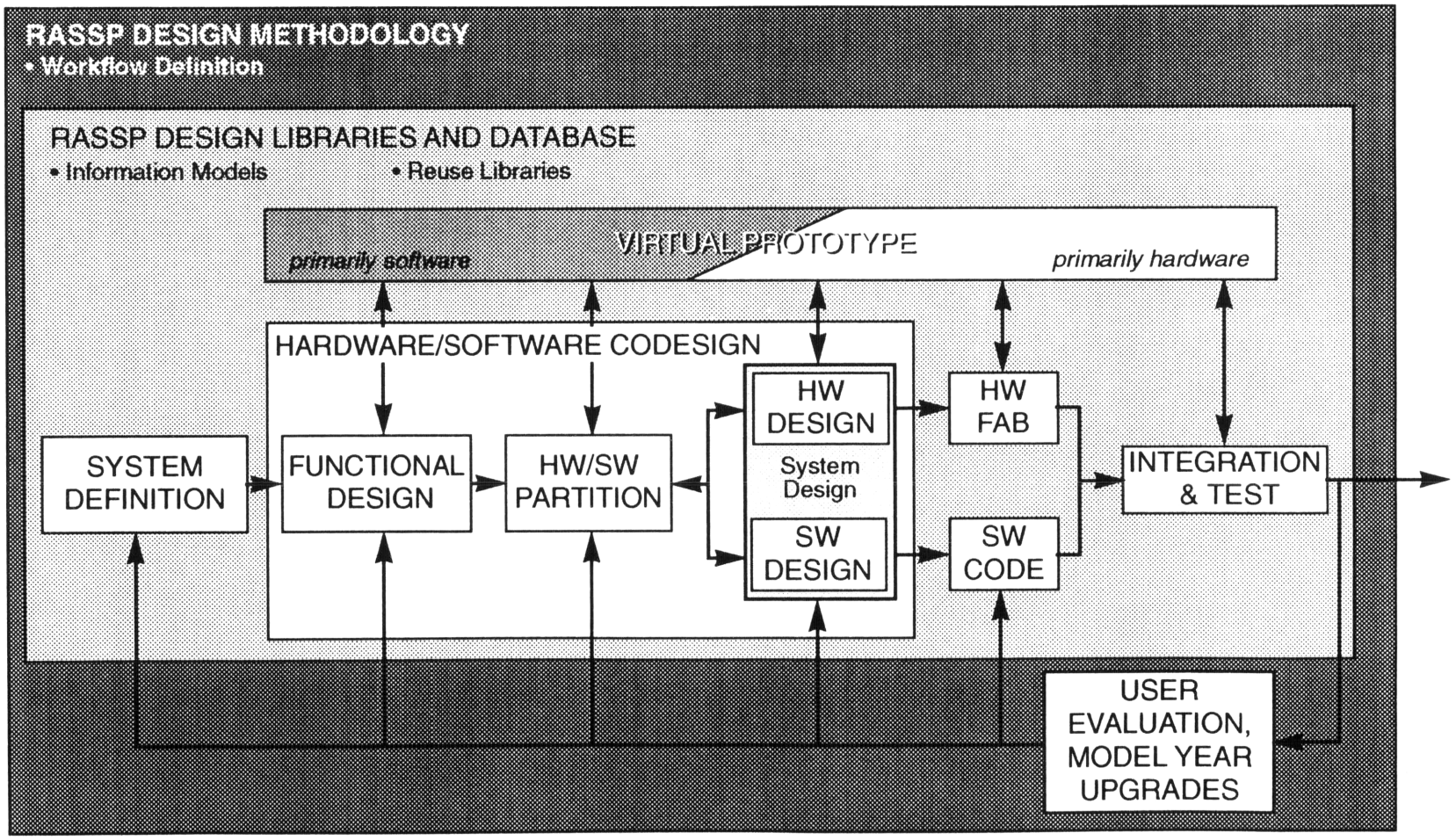
- *Heterogeneity.* A key point is that RASSP is not biased toward any one particular implementation technology, such as ASICs or programmable devices. Instead, it is assumed that the RASSP design system must be able to handle combinations of custom, hardware programmable, and software programmable implementation techniques. In terms of the hardware mix, a RASSP processor could include custom ASICs, FPGAs, and a fully programmable embedded processor composed of commercial off-the-shelf DSPs, RISC processors, and high performance computing modules. This mix of computing elements illustrates the need for architectures (and a design system) capable of managing heterogeneity.
- *Life Cycle Support.* This architectural requirement addresses concerns related to upgradability and testability. The use of modular hardware and software and flexible interfaces within a model year design framework will ensure that the system will be upgradable. RASSP processors will be designed for extensive hierarchical testability from the start as part of the concurrent engineering thrust to improve product quality and reduce the cost of field maintenance and support.

RASSP Development Environment

As currently envisioned, the RASSP development environment will support the designer from the earliest phase of requirements capture to the most detailed board and ASIC design, enabling full requirements traceability, virtual prototyping, and a smooth transition into manufacturing. A streamlined depiction of the RASSP design flow is shown in Figure 3.6. The development process starts with requirements capture during the system definition phase. RASSP is currently investigating the feasibility of using VHDL-based simulatable specifications as a portion of the processor requirements specification. A VHDL specification would implicitly represent both hardware and software functionality and could then be expanded, refined, and partitioned into explicit hardware and software modules.[15] Ultimately, the VHDL specification could be used as an input to synthesis

[15] Technology base contractors have already released a version of a VHDL-based specification language incorporating area, speed, and power constraints. In addition, work has already begun on developing VHDL libraries of common microprocessor models.

Figure 3.6: RASSP Design Flow



tools or reuse libraries. In addition, a simulatable specification could be used to specify a test bench at the highest level of system definition. More detailed tests could then be derived from this "master test" as the design matures while maintaining traceability to the original system-level test (Richards, 1994).

After the system requirements are specified, a functional design of the system comprising algorithms and control is developed to satisfy the requirements without allocating specific functions to hardware or software. The next step is to partition the functional design into hardware and software implementations. At this point major architectural tradeoffs are investigated to determine how the functionality should be divided between hardware and software and how the allocated functionality should be implemented, such as which parts of the algorithm need to be implemented in FPGAs rather than in code on an embedded processor or which parts of the software must be written in assembly language instead of a higher-order language. Other tradeoffs could involve choosing between a single or a multiple processor configuration or choosing a particular microprocessor or DSP for use in the system. These architectural choices will have major downstream implications for performance, cost, and supportability. Once the partitioning of the system design into hardware and software has been completed, the hardware and software designs are then refined and evaluated. The hardware/software codesign process—functional specification, partitioning, and hardware and software design and evaluation—is iterated as required in order to obtain a solution which meets performance requirements while satisfying constraints such as cost, form factor, and power. To this end, tools capable of providing early estimates of performance, cost, and physical characteristics need to be available to the designer to enable the development of a robust processor design (Richards, 1994).

The hardware/software design process is augmented through the use of design databases and virtual prototyping. In order for the model year design methodology to be both efficient and effective, synthesis and reuse of both hardware and software modules must be promoted and facilitated by the design environment. This requirement implies the need for a comprehensive database system capable of displaying multiple views of the design data throughout the development process. To further enhance the efficiency and effectiveness of the design process, virtual prototyping is used to explore design options

and ensure specifications compliance and traceability. The virtual prototype is comprised entirely of software during the early stages of the process, but increases in hardware content as the design matures. Advanced hardware and software co-simulation technology, such as the ability to mix different models of computation and the ability to allow simulation tools, emulators, and hardware interact through simulation backplanes, is required for the potential of virtual prototyping to be realized (Richards, 1994).

A full-fledged RASSP development environment will also include many high-level systems engineering tools not shown in Figure 3.6. Examples of such tools include workflow management tools, cost models, advisors to assist the designer in making early architectural decisions, "ilities" analysis tools to aid in evaluating designs for such concerns as reliability and manufacturability, and documentation and report generation tools (Richards, 1994).

Although current computer-aided design and computer-aided software engineering tools for hardware and software development are relatively mature, integrating these tools across design levels and vendors is still a non-trivial task. Further, while some tools exist for higher level tasks such as requirements capture, functional specification, and algorithm development, they are not as mature as the lower level tools or as well integrated with one another as the lower level tools. In addition, efforts to integrate these higher level tools with the lower level tools are in their infancy. Consequently, while the integration of the lower level tools will certainly be addressed, the development, refinement, and integration of the high level system engineering tools will likely engage a larger portion of the program's efforts (Richards, 1994).

3.4 CLEANROOM SOFTWARE ENGINEERING

Early software development was based entirely on craft practices, characterized by a reliance on trial-and-error methods and the talents of individual programmers. This sort of development, which is still in use in many organizations, designs software in an unstructured, bottom-up manner. The conventional wisdom is that no program can be developed defect free. Rather, debugging is the standard method of getting software to work properly. The ensuing rapid growth in demand for additional functionality has led to

tremendous growth in the complexity of software designs, complicating the already difficult task of writing correct programs.

A significant advance in software development capabilities came with the advent of structured programming techniques in the 1970s. This improvement was precipitated by Dijkstra (1969) who advocated eliminating the use of GOTO statements and restricting control logic to just three forms: sequence (begin-end), alternation (if-then-else), and iteration (while-do). The arbitrary branching allowed by the GOTO statement provided programmers with great freedom in designing control structures and was considered to be the mainstay of programming ingenuity and creativity (Mills, 1986). However, this freedom was a double-edged sword. Undisciplined use of GOTO statements frequently resulted in the development of "spaghetti code"—programs with extremely complicated control structures. Up to this point, writing spaghetti code seemed to be necessary to satisfy the demands of the customer, and the three control structures appeared inadequate compared to the power of GOTO statements. Rank and file programmers were surprised to discover that the control logic of any flowchartable program—even spaghetti code—could be replicated by utilizing combinations of the three primitives. Furthermore, in contrast to spaghetti code, the structured programming approach defined a natural hierarchy among its instructions (Mills, 1986). Adopting this approach allowed developers to write structured programs in a top-down fashion. Many organizations also implemented code reviews to augment debugging. Implementation of structured programming produced significant quality and productivity improvements over the traditional trial-and-error methods, as shown in Table 3.4.

However, even with the aid of structured programming practices, software development remains largely dependent on craft-based practices. Conventional methods can be categorized as follows (SET, 1993):

- *Process-oriented.* These methods were strongly influenced by the sequential flow of computation supported by traditional programming languages, such as COBOL and FORTRAN. Identifying the principal processes of the system and the data flows among these processes is the focus of these methodologies. Yourdon's Structured Analysis and Structured Design is an example of a process-oriented system development method.

- *Data-oriented.* These methods are based on the importance of data files and databases in large business and industrial applications. In data-oriented methodologies, system processes are designed to support the data processing requirements of the application. Information Engineering is an example of a data-oriented method.
- *Object-oriented.* These system development methods focus primarily on objects and classes. A system is developed by designing the interaction of objects—identifiable entities encapsulating states and behavior—to generate a desired outcome. Coad-Yourdon object-oriented analysis and design is an example of this type of methodology.

Unfortunately, the use of these methods has not significantly elevated software development above its craft origins. Similarly, the introduction of advanced SEEs (software engineering environments), new life cycle models, and maturity models have yielded some improvements in quality and productivity, but not the quantum leaps that were hoped for. While these innovations are important, they do not address the root cause of the problem—the lack of a science base for software development (SET, 1993).

Cleanroom engineering addresses the quality and productivity problems by applying rigorous practices to achieve intellectual control over the project. It also establishes an "errors are not acceptable" attitude and makes quality a team responsibility. Furthermore, the software's reliability is certified through the application of statistical quality control methods. When compared to traditional and structured programming methods, the number of defects encountered during development and operational use is dramatically lower for software developed with Cleanroom engineering practices. Moreover, Cleanroom practices yield major improvements in productivity. Data comparing the defect densities and productivities of traditional, structured programming, and Cleanroom practices are shown in Table 3.4.

3.4.1 Fundamental Principles of Cleanroom Engineering

Cleanroom engineering, developed at IBM's Federal Systems Division in the 1980s, is named after the cleanrooms used to fabricate VLSI (Very Large Scale Integrated) circuits.

Table 3.4: A Comparison of Software Development Practices

Development Practices	Development Defects/KLOC	Operational Defects/KLOC	Productivity (LOC/Staff-Month)
Traditional	50 - 60	15 - 18	unknown
Structured Programming	20 - 40	2 - 4	75 - 475
Cleanroom	< 5	« 1	> 750

Source: SET (1993).

Like its namesake, Cleanroom engineering has no tolerance for defects. The ultimate objective of Cleanroom software engineering is to develop error-free software that functions perfectly from the first time it is tested to the end of its operational life.

The following sections describe four fundamental principles behind Cleanroom engineering: defect prevention, intellectual control, separation of development and testing, and certification of the software's reliability.

Defect Prevention

Cleanroom engineering espouses a "get it right the first time" attitude. Defects are not the result of bugs in the source code. Defects are the result of faults in one or more aspects of the development process. In fact, if the defect density of the software under development exceeds five defects per thousand lines of code, the offending software is discarded. The defects are examined to determine how the process failed and how the process can be improved to prevent the failure from recurring. The improved process is used to develop replacement software.[16]

Intellectual Control

Intellectual control is the ability to clearly understand and describe the present problem at the desired level of abstraction (SET, 1993). Schedule overruns, cost escalation, high defect densities, and the labor-intensive, craft nature of current software development practices are all symptoms of a process that is not under intellectual control. To achieve intellectual control, engineers must be equipped with theoretically sound intellectual tools

[16] Dr. Harlan Mills, one of the originators of Cleanroom engineering, has suggested that perhaps the most important tool for Cleanroom is the wastebasket (Mills and Poore, 1988).

and processes that give them a high probability of producing a correct solution. Enabling engineers to achieve and maintain intellectual control over projects is at the heart of the Cleanroom philosophy.

Separation of Development and Testing

Cleanroom engineering principles dictate that development and testing functions must be separated. Designers are not allowed to execute or test their own code. Only testers can compile and executed the software being developed. This may seem counterintuitive at first, but the reasons behind the separation are sound. First, since the developer cannot rely on debugging as a development crutch, he or she will focus more attention on writing correct software, rather than on finding and fixing errors. Second, debugging frequently imbeds deeper errors that are difficult to detect. Adams (1984) studied every failure report for nine of IBM's most widely used software products over several years and tracked each to its origin. In most cases the cause of the failure had been introduced by a fix for another failure.[17] The defects introduced by the fixes may not be found until the integration testing phase or during operational use by the customer. Debugging tends to produce software that is locally correct but globally incorrect.

Reliability Certification

Software reliability certification in Cleanroom engineering provides scientifically valid data that can be used to write warranty statements for software product quality. Reliability certification also provides feedback to development and management regarding the effectiveness of the software development process. Software is not released unless it meets or exceeds the mandated level of reliability.

3.4.2 Cleanroom Engineering Practices

The concepts expressed in the principles of Cleanroom engineering are reflected in its practices. The following sections describe some of the key practices behind Cleanroom engineering.

[17] The problem of bad fixes is well documented. In addition to the Adams study, Endres (1975), Fagan (1976), Jones (1978), Myers (1976), Shooman (1983), and Thayer (1978) all address the topic.

Structured Data

Increasing demands for software capability have resulted in the explosive growth of a data flow jungle that is just as tangled as the control flow jungle that existed before the advent of structured programming. Since arrays and pointers represent arbitrary access to data just as GOTO statements represent arbitrary access to instructions, Cleanroom practices recommends that randomly accessed arrays and pointers should not be used (Mills, 1986). These data structures should be replaced with such structures as queues, stacks, and sets. These structures are considered safer since their access methods are more disciplined (Head, 1994). In addition, while it may take more thinking to design programs without arrays, the resulting designs are better conceived and usually have more function per instruction than programs that utilize arrays. According to Mills (1986), independent estimates indicate that programs utilizing structured data flows have up to five times as much function per instruction than would be expected of programs utilizing arrays.

Incremental Development

Incremental development is used to help give designers intellectual control over the problem as well as maintain focus on the task at hand. By partitioning the development problem into manageable increments (usually less than 10,000 lines of code and less than eight staff months of effort), intellectual control over the development of complex systems can be established. Each increment defines a complete, user-executable system with added functionality over previous increments. Once an initial understanding of the requirements is achieved, the system is partitioned into increments based on criteria such as increment size, component reuse, and development team skills. While the requirements for unprecedented systems may not be entirely known, the portions that are known should be stable. Additional requirements can be brought under control and introduced at reasonable intervals. Increments may also be left open in certain aspects for later updates. Thus, further steps of requirements determination can be performed with each increment specification (SET, 1993).

Team Organization

Cleanroom projects involve three different types of teams: specification, development, and certification. Specification teams are responsible for preparing and maintaining the system specifications. Configuration management is the responsibility of the specification team.

Development teams design and build one or more of the software increments. The resulting source code is handed over to the certification team who compiles and tests the software. Development teams are also responsible for isolating and making any necessary changes to the increment. The number of development teams used on a project depends on the size of the system to be developed.

Each certification team prepares test cases for an increment. When the increment is submitted for certification, the team performs the testing and prepares the certification report. A certification team executes and tests the code but does not modify it in any way. Failures are reported to the appropriate development team for correction. As was the case with development teams, the number of certification teams depends on the size of the system to be developed.

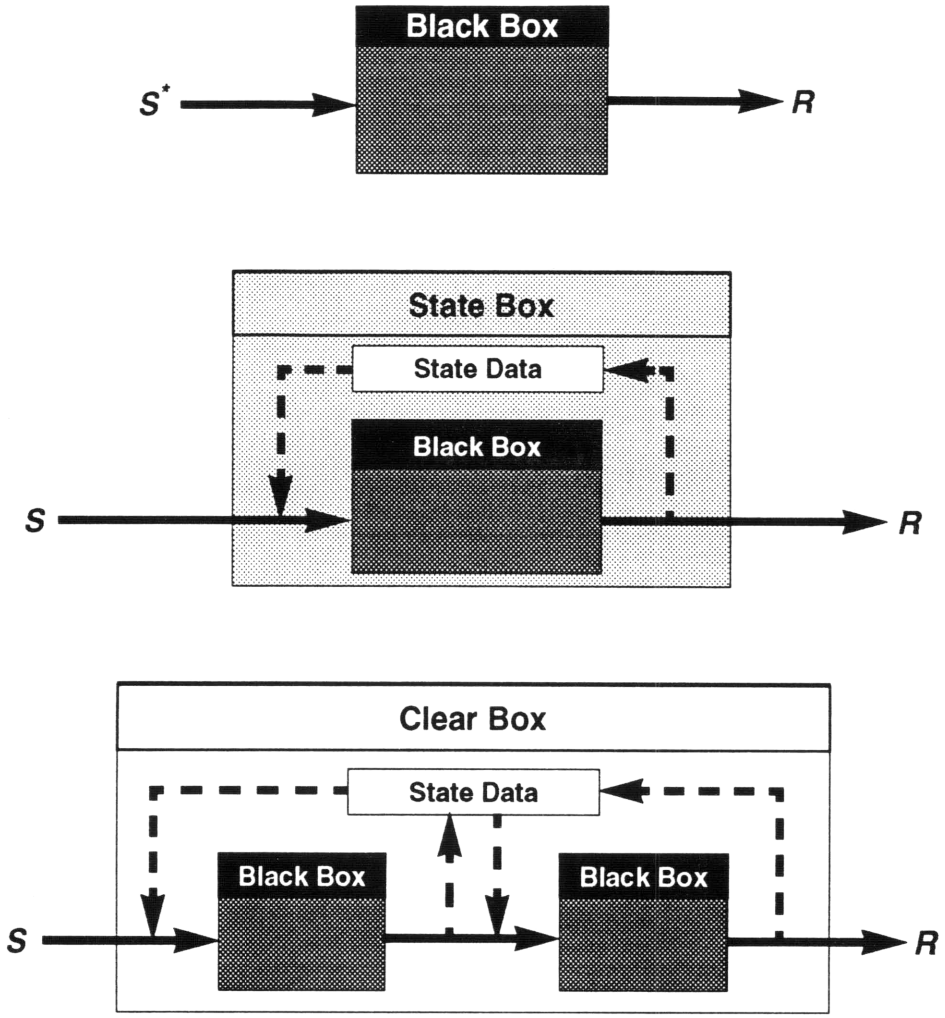
Engineers can serve on more than one team. For instance, an engineer may work on the specification team and the development team. However, engineers are not normally members of the development and certification teams because of the principle of separation of development and testing (SET, 1993).

Box Structure Design

Cleanroom provides a rigorous basis for developing software by exploiting the fact that programs are rules for mathematical functions. The specification for a program must define a function that completely describes the behavior required for the software to fulfill its intended role. Finding and documenting this function is a specification task. Designing and implementing a correct procedure for the specified function is a development task.

The mathematical nature of software is leveraged in Cleanroom through the application of box structure mathematics to software specification and development. In fact, **the underlying mathematical foundations of box structures permit the scale-up of analysis and design to systems of arbitrary size**. Consequently, specifiers and

Figure 3.7: Box Structure Diagrams



Note: The clear box structure is shown with a sequence process structure.

developers only need to work with three classes of functions: black boxes, state boxes, and clear boxes. Each of these box structures exhibits identical external behavior, but with an increasing degree of internal visibility. Figure 3.7 depicts the three box structures.

The technical details of box structure design are crucial for understanding the implications of this method. Details are provided in Appendix A. Important elements of the methodology will be highlighted below.

A black box provides an implementation-free, object-oriented description of software. This box structure only describes the software's external behavior in terms of a

mathematical function that maps a stimulus history, S^*, to a response, R. Since the black box view excludes all details of internal structures and operations, it also provides a description of the user's view of system behavior.

A state box provides a data-oriented view that begins to define implementation details by modifying the black box to represent responses in terms of the current stimulus, S, and state data that contains the stimulus histories.

A clear box provides a process-oriented view that completes the implementation details by modifying the state box view to represent responses in terms of the current stimulus, state data, and invocations of lower level black boxes.

The effective use of box structure design methods for the development of systems is guided by the application of six basic box structure principles: referential transparency, transaction closure, state migration, common services, correct design trail, and efficient verification.

Referential Transparency. Each object is logically independent of the rest of the system and can be designed to satisfy a well defined "local" behavior specification.

Transaction Closure. The principle of transaction closure defines a systematic, iterative specification process to ensure that a sound and **complete** set of transactions is identified to achieve the required system behavior.

State Migration. State data is identified and stored in the data abstraction at the lowest level in the box structure hierarchy that includes all references to that data. The result is that state data can easily be transferred to the lowest feasible level.

Common Services. System parts with multiple uses are defined as common services for reusability. In the same way, predefined common services, such as database management systems and reuse objects, are incorporated into the design in a natural manner. The results are smaller systems and designs which accommodate reuse objects.

Correct Design Trail. It is important to insure consistency in the entire design trail when correcting an error.

Efficient Verification. It is only necessary to verify what is changed from one refinement to the next since all elements of the design are referentially transparent.

Designing software with box structures is performed in a top-down manner. Once the top-down design is completed, the clear boxes can be implemented in code. The software code is verified by demonstrating the equivalence of the program and the design represented by the clear box refinement. While system design proceeds in a top-down fashion, the implementation of the design is accomplished in a bottom-up fashion. Designing top-down and then coding bottom-up allows the developers to exploit fully the principle of common services during the design phase and generalize the common services as much as possible during the coding phase.

Functional Verification

In Cleanroom engineering, functional verification is used instead of unit debugging.[18] These functional verifications typically yield surprising improvements in design, even for the best software engineers. As a result, the developed software can be smaller and faster than previously thought possible, delivering more functionality per instruction. In addition, using functional verification allows quality to be designed into the software. According to Cobb and Mills (1990), functional verification leaves only two to five defects per thousand lines of code to be fixed in later phases of the life cycle whereas debugging leaves 10 to 30 defects per thousand lines of code. In contrast to functional verification, debugging attempts to test quality into the product. However, since more than 15 percent of the corrections merely introduce newer, deeper errors, testing quality into software is not possible (SET, 1993).[19]

Statistical Testing

Cleanroom engineering makes use of statistical usage testing to certify the reliability of the developed software in terms of its MTTF (Mean Time To Failure). The application of rigorous statistical theory allows both quality control of the software being developed and process control over the development of the software.[20]

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[18] A more detailed discussion of functional verification practices is available in Appendix A.

[19] DeMarco (1982) contains an excellent analysis which demonstrates the validity of this point. Testing seems to be capable of eliminating half of the software defects. However, this factor of two improvement is overwhelmed by the extreme variability in the quality of software being produced today.

[20] A more detailed discussion of statistical testing practices is available in Appendix A.

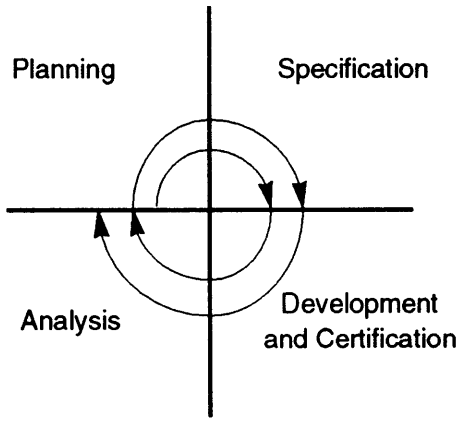
3.4.3 Cleanroom Engineering Process

Cleanroom projects follow a defined process which details the control structure between all processes and practices to be used in the project. Organizations which practice Cleanroom software engineering typically possess a set of defined processes where each defined process is intended for use with a different class of development project. Each of these defined processes, in turn, can be tailored to satisfy the specific needs of the project at hand.

Large development projects employ a spiral development process which partitions the problem into smaller, more manageable projects or spirals. Decomposing a large problem into smaller pieces reduces risk by establishing intermediate evaluation points. This allows projects to be redirected if necessary. Partitioning the development problem also enables the use of intermediate deliveries. This practice can be used to keep development efforts focused, elicit user feedback, and help assess the progress of the project. Figure 3.8 depicts the Cleanroom spiral development process.

Each spiral is divided into four quadrants or phases: planning, specification, development and certification, and analysis. The planning phase is where the project blueprint is devised. During this phase, the appropriate defined process model is chosen and tailored to the needs of the current development project. If an appropriate process model does not exist, a suitable process must be designed. Other planning activities include conducting risk analyses and setting objectives for each spiral (SET, 1993).

Figure 3.8: Cleanroom Engineering Spiral Development Process



During the specification phase, system specification development activities are performed. Typically, this involves close cooperation between the specification team and the customer and system users. Specification development tasks include analyzing the problem and solution domains. Problem domain analysis involves reverse engineering similar systems, developing the usage profile in the form of a Markov model, and formulating black box specification models. The formulation of black box functions is a critical task since it defines the functional behavior of the system to be developed. By defining the functional behavior of the system, the specification establishes *what* is to be done, not *how*. Solution domain analysis can involve such activities as reuse analysis and rapid prototyping. In Cleanroom engineering, the rapid prototyping process is similar to the standard Cleanroom process. The rapid prototyping process also includes planning, specification, development, and certification phases. However, once these phases have been completed, experiments can be conducted to acquire any additional information that may be necessary for specification development. While the specification team is responsible for prototype development and experimentation, development and certification teams are also typically involved in the process. When the prototyping effort ends, system modules that were developed and certified are placed in the project reuse repository and can be used by the development team to design and build the final product.

The construction plan for the spiral is also produced during the specification phase. Its purpose is to lay out a plan for the activities of the development and certification teams. The construction plan contains the actual modules and functions that are to be developed for each increment. Since each increment is integrated with the previous ones, the plan also defines the cumulative functionality that will need to be certified following the development of each increment.

The third phase of a spiral is the development and certification phase. Development and certification activities are performed in parallel. Development activities include designing each increment top-down with box structures, implementing the design in code, and verifying the correctness of the code through functional verification. Typically, design languages and automated code generation are used as much as possible to translate designs into code. During this time, the certification team formulates test cases. Once the development team delivers the source code for the current increment, it is

integrated with the previous increments and tested. If defects are detected, it is reported to the development team for correction. The corrected code is delivered to the certification team for re-evaluation.

Analysis is the final phase of the Cleanroom spiral. The results of the development cycle are analyzed in this phase. In addition, system demonstration and follow-up appraisals can be conducted (SET, 1993). The results of the work performed in this portion of the development cycle serve as inputs to the planning activities of the next spiral.

Each successive spiral builds on the work of the previous spirals. For instance, the specification for the overall system is developed in an iterative spiral. Each specification iteration further extends and/or refines the system specification.

3.4.4 Proven Benefits

Cleanroom is not a blue sky concept. The methodology is currently in use by many software engineering organizations across the United States and internationally as well. The implementation of Cleanroom engineering methods has consistently produced significant improvements in quality and productivity. A sample of the results of some Cleanroom projects is shown in Table 3.5.

Table 3.5: Sample of Cleanroom Results

Year	Project	Results
1987	Flight control 33 KLOC (Jovial)	• Completed ahead of schedule • < 2.5 defects/KLOC before any execution • Defect-fix effort reduced by a factor of five
1988	Commercial product 80 KLOC (PL/I)	• Certification testing failure rate of 3.4 defects/KLOC • Deployment failures of 0.1 defects/KLOC • Productivity of 740 LOC/staff-month
1989	Satellite control 30 KLOC (Fortran)	• Certification testing failure rate of 3.3 defects/KLOC • 50% quality improvement • 80% productivity improvement • Productivity of 780 LOC/staff-month
1990	Research project 12 KLOC (Ada and ADL)	• Certified to 0.9978 reliability • Certification testing failure rate of 1.7 defects/KLOC

Source: Cobb and Mills (1990), Mills (1991).

A technology transfer effort implemented Cleanroom engineering processes and practices at a Picatinny Arsenal software engineering center and achieved impressive improvements immediately. The Picatinny software engineers improved their productivity by a factor of three on the very first increment on which the new methodology was used. The failure rate also displayed dramatic improvement. The failure rate for the first increment was only 0.24 failures per thousand lines of code (Sherer et al., 1994).

Even partial implementation of Cleanroom processes and practices seem to make substantial improvements. Head (1994) reported significant improvements from implementing just a few of the Cleanroom practices at Hewlett-Packard. A defect density of one defect per thousand lines of code was achieved on the first application of these practices to a project.

CHAPTER 4

Evaluating the New Methods

Now that we have described some of the fundamental ideas and practices behind a selected set of complex electronic system development methodologies, we must define a set of criteria by which to assess their utility for cross-system integration. Once a set of criteria and a rating scheme have been devised, the evaluations can be conducted to determine which methodology, if any, can be used to address the interoperability problem.

4.1 THE CRITERIA

To define a set of criteria that would characterize an ideal cross-system integration methodology, general characteristics of high performance product development processes were considered as well as relevant system design and interoperability issues. The characteristics of lean product development and high performance software engineering processes were considered along with the system design issues associated with the types of interoperability problems discussed in Chapter 2. Successive rounds of distillation removed criteria that were thought to be redundant or nonessential for the purposes of this thesis. The final set of criteria is not a comprehensive checklist of everything necessary to solve the interoperability problem and successfully integrate disparate systems. It does, however, define a key set of process traits, which have been widely associated in other contexts with successful product development processes, and system design issues that

Table 4.1: Ideal Cross-System Integration Methodology Criteria

Process Characteristics	• Defined • Configuration management • User involvement • Transparent • Tailorable • Rapid development cycle • Scalable methodology • Defect-free • Continuous improvement & lessons learned
System Design Issues	• Security • Robustness • Manufacturability • Supportability • Upgradability • Scalable architecture • Intrasystem HW/SW codesign • Cross-system HW/SW codesign • Munition-platform interoperability • PGM-C4I interoperability • Cross-platform interoperability • Platform-C4I interoperability • Cross-C4I interoperability • Cross-service interoperability • Multinational interoperability • Military-commercial interoperability • Integrated master requirements • Integrated master requirements traceability

should be encompassed by an ideal cross-system integration methodology. The final set of criteria is shown in Table 4.1.

The first nine criteria fall into the category of process characteristics. The rest of the criteria are system design issues that should be accounted for by an ideal cross-system integration methodology. The criteria are defined and the reasons behind their selection are discussed in the subsections that follow.

4.1.1 Process Characteristics

Defined

A cross-system integration methodology should follow a defined process. Experience has shown that developing hardware/software systems with an ad hoc approach usually results in poor project performance. Poor system performance and the all too familiar schedule and cost overruns are usually the results of a poorly defined process. Even if the project is successful, the lack of a defined process diminishes the chances that the success can be repeated (Boehm, 1976; Cusumano, 1991; Paulk et al., 1993a and 1993b).

Configuration Management

The system design configuration must be kept up-do-date so that designers can have the most current information at their disposal. This is a basic function for hardware/software system development (Paulk et al., 1993a and 1993b; Cusumano, 1991). Configuration management activities include identifying the design configuration at certain points in time, systematically controlling changes to the design configuration, and maintaining the integrity and traceability of the configuration throughout the development cycle.

User Involvement

Users must be involved throughout the development process to ensure that the system meets their needs, which are often different from the stated requirements (SAF/AQK, 1992; IBM, 1990). A higher degree of user involvement enables the designers to gain a better understanding of the users' "true" requirements. This is particularly true for programs where man-machine interfaces are a factor.

An example of the utility of user involvement can be found in the discussion of GritTech's rapid development process located in Chapter 3. Without user involvement, the rapid development engineers would not have known to address the unstated requirement for a capability to call up video views of the launch vehicle and the launch pad. Adding this functionality to the system would have been significantly more problematic and costly to accomplish later in the development cycle.

The design of AH-64 Apache crew station provides another example of the utility of user involvement in the development process. Conforming to MIL-STD-704A, the Apache's electronic systems were interconnected with its two onboard generation systems

so that a single generator could supply power for all the electronic systems in case one of the generators failed or was switched off. No one had anticipated that both generators could be switched off in-flight, which happened once inadvertently while flying nap-of-the-earth during the flight test phase. The pilot's partially rolled up sleeve caught both generator switches, switching off electrical power for all onboard systems except for the few items powered by battery. Only the skillful reactions of the crew averted a tragedy. Accordingly, the generator switches were subsequently redesigned to be lever-locked in the "on" position (Amer et al., 1992).

Transparent

The methodology should be easily understood by designers and managers alike. In addition, the process should allow development progress to be easily measured and tracked on a continuous basis. Transparency allows problems to be identified earlier in the development cycle when they are not as costly to fix. A lack of transparency is a commonly cited problem for project management, particularly in the development of software-intensive systems (Paulk et al., 1993a and 1993b; SAF/AQK, 1992; Cusumano, 1991).

Tailorable

A single, defined process cannot be appropriate for all possible development projects. SDC's (System Development Corporation) experiments with a factory approach to software development in the mid-1970s, documented in Cusumano (1991), failed in part from the use of the standardized process on projects with widely varying needs. Predictably, the factory approach worked well on the types of development projects for which it was designed but produced disappointing results when applied to projects that were beyond the intended scope of the process (Cusumano, 1991). Attempting to define a single standard process to handle all situations typically results in a non-transparent, byzantine process that is unwieldy at best (Hammer and Champy, 1993). Thus, an ideal process should be tailorable to meet the particular needs of a project.

Rapid Development Cycle

A rapid development cycle, a basic element of lean or total quality product development processes (Womack et al., 1991; Ling, 1993; Clausing, 1994), is important for a number of reasons. First, a rapid development cycle places new capabilities in the hands of the warrior faster. Moreover, rapid development cycles are needed to insure that systems are state of the art when fielded. Currently, development cycles are so lengthy that some systems can be obsolete by the time they are fielded. Rapid development cycles can also facilitate timely upgrading of current systems to keep their capabilities at or near the rapidly improving state of the art in hardware and software technology. In addition, if it is necessary to perform any cross-system integration tasks after our forces have deployed to a theater of operations, those tasks must be accomplished as quickly as possible.

Scalable Methodology

An ideal methodology would be efficient and effective for both relatively simple and extremely complex systems integration. For instance, there are processes that appear extremely efficient and effective for developing small systems. However, when applied to a larger development project, information flows which were crucial to the success of the process for smaller projects can break down—particularly the informal channels, primarily due to the larger number of people involved.[1] Similarly, design methods that work well for small problems can be swamped by the number of constraints and variables involved in solving larger, more complex design problems. Moreover, a scalable methodology is needed to keep pace with the increasing complexity of cross-system integration problems.

Defect-Free

An ideal methodology should aim to "get it right the first time" and develop a high-quality, defect-free finished product. Unfortunately, while this is usually the goal, the finished product has not always lived up to these expectations in the past. In spite of the myriad process and product standards that have been imposed on defense contractors, systems have been deployed with known defects. For instance, CAFMS, a computer system used

[1] This sort of problem is well documented in the literature by Lawrence and Lorsch (1967), Lawrence et al. (1976), and Lawrence and Lorsch (1986).

to develop air tasking orders, was deployed to the Gulf with several known software defects. In all, there were 81 major software changes made during Desert Shield and Desert Storm. While some were the result of the growing scale of operations, many changes were made to fix known problems that had been brought to the field and others that appeared during Desert Shield (Hyde et al., 1992).

Defect prevention practices must be a part of a methodology to fully satisfy this criterion. In the absence of defect prevention practices, methodologies which aim to produce a defect-free product can only partially satisfy this criterion since they tend to rely on substantial amounts of testing to detect defects for subsequent removal rather than preventing their introduction. Defect prevention is significantly more effective for assuring product quality than testing (Head, 1994).

Continuous Improvement & Lessons Learned

Continuous improvement, an essential element of total quality development (Clausing, 1994), should be part of an ideal cross-system integration methodology. Continuous improvement and documenting lessons learned are critical for fostering organizational learning.[2] While defect prevention activities are covered by the defect-free criterion, there are certainly numerous other process aspects that could be improved. For instance, it may be possible to accelerate the pace of development activities by rearranging certain elements in the workflow. In addition, technical and process-related lessons learned during each project should be documented so that they are not forgotten. Subsequent projects should benefit from this knowledge, not just the individuals who participated. Toyota's "lessons learned" books provide a good example of this (Ward et al., 1994). For example, one book is comprised of lessons learned in fender design and contains approximately 60-72 different key ranges of specifications that would ensure the manufacturability of fender designs. These lessons learned books, which exist for every body part, allow Toyota designers to ensure their designs are manufacturable from the start (Ward et al., 1994).

[2] The subjects of learning organizations and organizational learning are well documented by Senge (1990) and Argyris (1991 and 1993).

4.1.2 System Design Issues

Security

Information systems and communications should be secure from enemy tampering and eavesdropping. Considering the ad hoc nature of the coalition information infrastructure and our widespread use of computers for operations and logistics planning and management, serious damage could have been inflicted by computer viruses or other kinds of tampering. Communications must also be secure to deny the enemy information about our activities and movements. Evidence indicates that Iraqi forces did monitor the radio channels used by allied airborne forward controllers to vector attack aircraft into "killing boxes". The Iraqis were able to capitalize on the reluctance of the air forces to change call signs and frequencies and keep some of their assets out of harm's way. In one reported case, coalition monitors heard the commander of a mobile Scud unit radio his superior that he was pulling units because F-16s were coming after him (Campen, 1992c).[3]

Robustness

Our systems must be able to operate as well as possible in the face of enemy attempts to degrade our capabilities, such as jamming. If the Iraqis had utilized the jammers they possessed, the Navy fleet satellite communications system and its piggy-backed Air Force satellite communications system might have been severely disrupted, if not silenced. The Iraqis possessed four Soviet-made UHF jammers that were capable of generating from 1 to 2.5 kilowatts. This would have been more than enough to close down the links that carried 95 percent of wartime traffic to and from the U.S. Navy (Campen, 1992c).

Manufacturability

An ideal methodology should produce a design that is manufacturable. Manufacturing processes should be able to produce the integrated system and all its components in an

[3] There were also some instances when Iraqi eavesdropping was leveraged to the advantage of allied forces. In some cases U.S. F-15Es would use Wild Weasel (radar suppression aircraft) call signs to confuse Iraqi air defenses. F-4G Wild Weasel call signs were based on beer names, and F-4G crews would call out "Magnum" to alert other friendly aircraft that they had launched a HARM antiradiation missile. One case involved an F-15E crew that was being tracked by an Iraqi surface-to-air missile (SAM) radar. Since there were no F-4Gs in the area to attack the SAM site, the F-15E crew called out "Michelob...Magnum!" whereupon the Iraqis immediately shut down the radar without firing ("Radio Deception Used to Trick Iraqis," Aviation Week & Space Technology, April 22, 1991).

efficient, affordable manner. Since the design of a product can, by some estimates, determine as much as 70 to 80 percent of manufacturing productivity, it is critical to address manufacturability issues during the design phase (Suh, 1990). Design for manufacturability is another basic element of lean product development (Womack et al., 1991; Ling, 1993; Clausing, 1994).

In the past, manufacturability problems have required costly redesign efforts to correct. Printed wiring boards, used extensively throughout the LANTIRN system (Low-Altitude Navigation Targeting Infrared for Night), had to be redesigned because the hand-made boards tended to fracture when machined and could not pass the required acceptance tests (Bodilly, 1993b). Manufacturability problems with the AMRAAM (Advanced Medium-Range Air-to-Air Missile) missile led to the establishment of the $330 million AMRAAM Producibility Enhancement Program (Mayer, 1993). Manufacturability problems and a failed aluminum casting process forced a very costly redesign of the stealthy TSSAM (Tri-Service Standoff Attack Missile), and have provided ammunition to those calling for the cancellation of the program (Morrocco, 1993; Fulghum, 1994e; Fulghum and Morrocco, 1994).

Supportability

Systems should also be easy to maintain in the field. Historically, maintenance costs of hardware/software systems exceed that of original system development. If operations and maintenance costs are included in a software life cycle cost breakdown, they account for 67 percent of the total life cycle cost (Cusumano, 1991).[4] From the hardware perspective, maintenance tests and diagnostics should be easy to perform and crucial areas should be as easily accessible as possible. Similarly, software components should be easy to access, test, and replace.

Supportability has become an increasingly important consideration in the development of weapon systems and their subsystems. Both the Air Force's Advanced Tactical Fighter and the Army's Light Helicopter competitions placed great emphasis on supportability issues (Nordwall, 1993; Bond, 1991; Kandebo, 1991). Supportability

[4] This usually reflects the costs imposed by a defective product and a flawed process that developed it. Activities in this portion of the life cycle are needed to fix errors that escaped detection during development and to give it the functionality that users really wanted.

problems with Pratt & Whitney's F100-PW-100 and -200 engines—used in the Air Force's F-15 and F-16 fighters, respectively—provided a major part of the motivation for the initiation of the Alternative Fighter Engine (AFE) competition. In addition to addressing the stall-stagnation problem, the AFE competition addressed the F100's extremely short lifetime—the period of time between depot overhauls—and its high maintenance requirements which drove up operating costs (Camm, 1993a).

Upgradability

Considering the typically lengthy service lives of many defense systems[5] and the rapid pace of improvement in hardware and software technology, an ideal methodology should yield an upgradable product. This would allow a fielded system to keep pace with technology over its service lifetime with greater ease and less expense than is required by current approaches.

Scalable Architecture

An ideal methodology should produce a system architecture that can be extended to fulfill the evolving needs of the user over the service life of the system. Typically, systems will be called upon to perform functions that were not part of the original design requirements or are much larger in scope. An ideal methodology should yield an architecture that can scale up to meet the new challenges. Recent events point to the need for scalable architectures. CAFMS was not designed to handle the number of air bases or the size of the ATO required in Desert Storm. Fortunately, we had the luxury of five months with which to enhance the system with additional processors and storage devices, some of them newly acquired, and with software changes engineered in the desert (Hyde et al., 1992).

Current efforts to add data fusion capabilities and other enhancements to AWACS presents another example where non-scalable architectures are causing problems. Although AWACS performed brilliantly during the Gulf War, the demands of the scope and pace of allied operations were beginning to push the system to the limits of its capabilities (Lenorovitz, 1992a). Unfortunately, the aging centralized mainframe computer architecture makes it more difficult to enhance system capabilities or add the

[5] For example, the F-4 has been in service since the 1960s, and the F-15 and F-16 fighters have been in service since the 1970s.

latest in distributed computer hardware. For instance, the 1500 lb. electronics unit that drives the AWACS displays is not programmable which makes it difficult to devise and implement better ways to display data with software modifications. Making similar enhancement or upgrades for JSTARS aircraft is much easier because of its distributed, open architecture which utilizes high-speed commercial off-the-shelf engineering workstations (Hughes, 1994a; 1994b).

Intrasystem HW/SW Codesign

An ideal methodology should allow for interaction and tradeoffs between hardware and software development to balance flexibility, performance, and cost within each separate system. Traditionally, system functionality is partitioned between hardware and software early on in the development process, and subsequent development activities are pursued with little or no interaction between the groups responsible for the implementations. The result is often unsatisfactory performance. Codesign allows more interaction and tradeoffs between hardware and software implementations. This allows a more thorough exploration of the "design space" which yields an end product that provides a better balance of single system flexibility, performance, and cost.

Cross-System HW/SW Codesign

Hardware/software codesign is useful in the cross-system integration context as well. Cross-system hardware/software codesign would allow for tradeoffs among component systems to produce an integrated system that better balances flexibility, performance, and cost.

Munition-Platform Interoperability

Platforms must be able to use the best munitions available for their mission. Therefore, munition-platform interoperability must be ensured. The F-16A/CBU-87 case discussed in Chapter 2 is a good illustration of the need for this class of interoperability problem to be addressed. Had the decision not been made to take enough F-4Gs out of desert storage to equip an active and a reserve squadron, the Air Force would not have had a viable SEAD (suppression of enemy air defenses) capability until the planned 1995 procurement of Block 50D/52D F-16Cs (Fulghum, 1993a). These aircraft will be equipped with a

targeting system which will allow it to use the HARM missile (Fulghum, 1993a). The HARM missile is vital to the SEAD role, but only a few types of aircraft are equipped with the platform enablers that are necessary to use the munition.

Assuring munition-platform interoperability is extremely important since even "minor" problems can significantly degrade overall system performance. The AMRAAM program experienced both the difficulties involved in integrating AMRAAM software with various aircraft systems and the adverse effects of minor software problems. For instance, in one four-on-four test, all four missiles failed to hit their targets. Three missiles failed because the radar detected false targets. The failure of the fourth missile was caused by a software problem—a constant that the missile's computer used in some calculations was wrong—that required only a few lines of code to be changed (Mayer, 1993).

PGM-C4I Interoperability

This criterion reflects the possible development of a capability where precision-guided munitions (PGMs) could be guided, targeted, and re-targeted by theater C4I systems. The Block 4 upgrades for the Tomahawk cruise missile will provide this type of capability (Kandebo, 1994). Similarly, the AGM-154 JSOW (Joint Stand Off Weapon) is expected to achieve this type of capability through a preplanned product improvement which will add data links for input from off-board sensor systems such as those on board JSTARS and AWACS aircraft (Fulghum, 1994d). An ideal cross-system integration methodology would ensure that this kind of interoperability is achieved.

Cross-Platform Interoperability

This type of interoperability could allow platforms to share data with each other to provide a more complete picture of the operating environment. This type of capability could also provide a redundant source of information in case on-board systems are knocked out or malfunction. This type of interoperability would also enable platforms to make use of information provided by sensors located on other platforms. Before cutbacks removed the five-year line of funding for the F-4G from the budget, SEAD planners had hoped to equip F-4Gs and F-16Cs with an Improved Data Modem (IDM) so that targeting information provided by the F-4G's sophisticated sensors could be passed to HARM-equipped F-16Cs that were not similarly equipped (Fulghum, 1993a; 1994a). Although the elimination of

the F-4G's line of funding forced the cancelation of the planned IDM upgrade[6], the potential benefits of cross-platform interoperability have been recognized and should be addressed by an ideal cross-system integration methodology (Fulghum, 1994a).

Platform-C4I Interoperability

Platforms must be able to interact with C4I assets. The utility of systems such as AWACS and JSTARS would be greatly diminished if they could not communicate effectively with platforms and vice versa. This type of interoperability can also help platforms distinguish friend from foe.

The F-16 HTS (HARM Targeting System) and JTIDS (Joint Tactical Information Distribution System) are good examples of how platform-C4I interoperability can significantly enhance the performance of the theater system. The performance of newly fielded AN/ASQ-213 HTS-equipped, F-16 Block 50/52D aircraft in the SEAD role has exceeded prior expectations to such a degree that the USAF believes the future development of a radar-killing version of the F-15 will be unnecessary. Air Combat Command is particularly pleased with the ability of the HTS to interact with off-board sensors such as Rivet Joint.[7] Although the HTS was originally intended as an interim system, planned upgrades should make the F-16 HTS system as capable as the radar-killing F-15 at a far lower cost (Morrocco and Fulghum, 1994).

JTIDS allows pilots to receive and view AWACS data on a color multifunction display in the cockpit (Morrocco, 1994). JTIDS allows a pilot to see the whole battlefield. For instance, instead of being limited to an F-15 radar's 120-degree forward field of view, a JTIDS-equipped F-15C provides its pilot with the ability to see all around his aircraft, including the locations of enemy surface and air threats (Fulghum, 1993e). With the JTIDS-enhanced situational awareness, the 390th Fighter Squadron, the only F-15C unit currently equipped with JTIDS, expects to be able to adopt the line abreast formation

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[6] Since the IDM upgrade was canceled for the F-4G, target information will have to be passed verbally from F-4Gs to other aircraft (Fulghum, 1994b).

[7] The F-16 HTS system is considered proof of concept that with additional refinement, a single-seat aircraft can perform the SEAD role almost as well as a two-seat design. In the future, the electronic warfare officer could be on board an AWACS or Rivet Joint aircraft instead of in the cockpit of a Wild Weasel aircraft (Morrocco and Fulghum, 1994).

instead of flying in trail (Fulghum, 1993e). This allows forward firepower to be maximized and should result in greater lethality and fewer U.S. and Coalition losses.

Cross-C4I Interoperability

During the air campaign, AWACS and JSTARS were networked to provide coalition commanders with a complete picture of enemy movements on and over the battlefield. This sort of capability will certainly be expected of future systems. Moreover, success in the air battle depends heavily on the successful integration of battle control assets such as AWACS, JSTARS, and Rivet Joint (Bowie et al., 1993).

Cross-Service Interoperability

Systems deployed by services should be interoperable with the systems of other military services. A good example of the importance of this class of interoperability problem is provided in Chapter 2 in the discussion of air tasking order generation and distribution problems encountered during Desert Shield and Desert Storm.

Multinational Interoperability

U.S. forces fought alongside the forces of many other nations in Desert Storm. It is likely that similar situations will arise again in the future. Hence, our forces will need to be able to interface as smoothly and rapidly as possible with forces of different nations. Interoperability with some coalition partners was achieved much more easily because of the development of some systems with common technical standards. Developing interoperability with the forces of other nations was more problematic (Wentz, 1992). Thus, this class of interoperability problem should be addressed by an ideal cross-system integration methodology.

Military-Commercial Interoperability

As demonstrated during the Gulf war, the capacity of dedicated military communications systems is dwarfed by the wartime demands of its forces. This necessitated the leasing of commercial capacity for military use during Desert Storm (Wentz, 1992; Campen, 1992d). Care must be taken to insure that this supplementary capacity can be utilized efficiently and effectively in the future. The recent reengineering of military space strategy reflects this reality. For instance, the new proposed military space strategy calls for the initiation

of cooperative, robust technology demonstration projects to ensure compatibility between military and civil space requirements and services, especially in the areas of communications and remote sensing. It would also seek to develop interface standards that would suit both commercial and military needs (Scott, 1994).

Integrated Master Requirements

Cross-system integration should be conducted with an integrated master set of requirements for the entire system. Consequently, an ideal methodology should incorporate some mechanism for master requirements traceability. The formulation of master development plans by the F-16 SPO through meetings with representatives of the LANTIRN, PLSS (Precision Locator Strike System), GPS, AMRAAM, ASPJ (Airborne Self Protection Jammer), SEEK TALK, and JTIDS SPOs was one of the elements integral to the success of the F-16 Multinational Staged Improvement Program (MSIP), which is widely viewed as a great success (Camm, 1993b; Glennan et al., 1993).[8]

Integrated Master Requirements Traceability

If there is a set of integrated master requirements, an ideal methodology should also provide for integrated master requirements traceability.

4.2 THE RATING SCHEME

The rating scheme chosen to evaluate the different methodologies is fairly straightforward. For each criterion, three different ratings are possible: satisfies, partially satisfies, and does not satisfy.

4.3 THE EVALUATIONS

This section contains the evaluations of each of the methodologies described in the previous chapter. The results of the evaluations are shown in two matrices corresponding to the two categories of criteria. Table 4.2 shows how the methodologies rated according

[8] The F-16 MSIP is the development program that has been utilized to move beyond the F-16A/B. The primary product of the F-16 MSIP has been the F-16C/D, an aircraft whose design has evolved over time as new technological capabilities have been incorporated into its design (Camm, 1993b).

Table 4.2: Process Criteria Matrix

	DC-X Rapid Development	GritTech Rapid Development	Ptolemy HW/SW Codesign	RASSP	Cleanroom Engineering
Defined	●	●	●	●	●
Configuration Management	●	●	●	●	●
User Involvement	●	●	○	●	●
Transparent	●	●	●	●	●
Tailorable	●	●	●	●	●
Rapid Development Cycle	●	●	●	●	●
Scalable Methodology	○	○	◐	●	●
Defect-Free	◐	◐	◐	◐	●
Continuous Improvement & Lessons Learned	○	◐	○	●	●

● - Satisfies ◐ - Partially Satisfies ○ - Does Not Satisfy

to the process characteristics criteria. Table 4.3 shows how the methodologies rated according to the system design issues criteria. The reasons behind the ratings are provided in the subsections that follow.

4.3.1 DC-X Rapid Development

The reasons behind the ratings of this methodology are discussed in this section on a criterion-by-criterion basis.

Defined Satisfies. This process follows a defined process.

Table 4.3: System Design Criteria Matrix

	DC-X Rapid Development	GritTech Rapid Development	Ptolemy HW/SW Codesign	RASSP	Cleanroom Engineering
Security	○	○	○	○	○
Robustness	○	○	○	○	○
Manufacturability	○	◐	◐	●	○
Supportability	○	◐	○	◐	◐
Upgradability	○	○	○	◐	◐
Scalable Architecture	○	○	◐	◐	◐
Intrasystem HW/SW Codesign	○	○	◐	◐	○
Cross-System HW/SW Codesign	○	○	○	○	○
Munition-Platform Interoperability	○	○	○	○	○
PGM-C4I Interoperability	○	○	○	○	○
Cross-Platform Interoperability	○	○	○	○	○
Platform-C4I Interoperability	○	○	○	○	○
Cross-C4I Interoperability	○	○	○	○	○
Cross-Service Interoperability	○	○	○	○	○
Multinational Interoperability	○	○	○	○	○
Military-Commercial Interoperability	○	○	○	○	○
Integrated Master Requirements	○	○	○	○	○
Integrated Master Req. Traceability	○	○	○	○	○

● - Satisfies ◐ - Partially Satisfies ○ - Does Not Satisfy

Configuration Management	Satisfies. The process has mechanisms for configuration management.
User Involvement	Satisfies. The process allows simulations, which can be tested by users, to be produced in parallel with the flight software.
Transparent	Satisfies. Designers and managers have a good sense of the status of the project and the rate of progress.
Tailorable	Satisfies. The process is tailorable to the needs of the project.
Rapid Development Cycle	Satisfies. The process is characterized by a rapid development cycle and fully utilizes rapid prototyping.
Scalable Methodology	Does not satisfy. The methodology is not scalable. The process is highly dependent upon a toolset which seems to "break" when applied to large problems.
Defect-Free	Partially satisfies. The process seeks to develop a defect-free product, but does not practice defect prevention.
Continuous Improvement & Lessons Learned	Does not satisfy. This process has no provisions for continuous improvement or documenting lessons learned.

The DC-X rapid development process does not satisfy any of the criteria pertaining to the system design issues since there is no provision in the process for the consideration of these issues.

4.3.2 GritTech Rapid Development Evaluation

The reasons behind the ratings of GritTech's rapid development methodology are discussed in this section on a criterion-by-criterion basis.

Defined	Satisfies. The GritTech rapid development group has a defined process.

Configuration Management	Satisfies. The process has mechanisms for configuration management.
User Involvement	Satisfies. User involvement is integral to the success of the incremental software development approach practiced by GritTech.
Transparent	Satisfies. Designers and managers have a good sense of the status of the project and the rate of progress.
Tailorable	Satisfies. The GritTech rapid development process is highly tailorable. Designers have great freedom over tailoring the process to the needs of the project in question.
Rapid Development Cycle	Satisfies. The process is characterized by a rapid development cycle.
Scalable Methodology	Does not satisfy. The methodology relies heavily on informal communication among team members. Since the information flows would break down for large projects, the methodology is not scalable.
Defect-Free	Partially satisfies. The process seeks to develop a defect-free product, but does not practice defect prevention.
Continuous Improvement & Lessons Learned	Partially satisfies. Since activities associated with continuous improvement and documenting lessons learned are conducted at the discretion of the development team, they are not always performed.
Security	Does not satisfy. Security design considerations are not included in the GritTech rapid development methodology.
Robustness	Does not satisfy. Robustness considerations are not included in the GritTech rapid development methodology.

Manufacturability	Partially satisfies. The process can include this consideration, but it can be (and has been) tailored out of the process in the interests of speeding up the development cycle.
Supportability	Partially satisfies. Again, this consideration can be a part of the process, but it can be tailored out of the process.

The GritTech rapid development process does not satisfy any of the remaining system design criteria since the methodology has no provision for the consideration of these issues.

4.3.3 Ptolemy Hardware/Software Codesign Evaluation

The reasons behind the ratings of a Ptolemy-supported hardware/software codesign methodology are discussed in this section on a criterion-by-criterion basis.

Defined	Satisfies. This process follows a defined process.
Configuration Management	Satisfies. The process has mechanisms for configuration management.
User Involvement	Does not satisfy. HW/SW codesign does not involve the user in the design process, partially due to the fact that it relies on other methods to perform requirements capture.
Transparent	Satisfies. Progress is easy to monitor with this methodology.
Tailorable	Satisfies. The process is tailorable depending on the type of codesign problem involved. Different types of problem require the application of different design methodologies.
Rapid Development Cycle	Satisfies. The process is characterized by a rapid development cycle.

Scalable Methodology	Partially satisfies. The methodology is scalable for a large range of design problems, but it is not capable of including the use of high-level languages in the codesign process.
Defect-Free	Partially satisfies. The process seeks to develop a defect-free product, but does not practice defect prevention.
Continuous Improvement & Lessons Learned	Does not satisfy. This methodology does not currently include activities for continuous improvement and documenting lessons learned.
Security	Does not satisfy. Security is not currently considered by Ptolemy-supported codesign.
Robustness	Does not satisfy. Robustness is not currently considered by Ptolemy-supported codesign.
Manufacturability	Partially satisfies. Depending on the specific development project, estimates of the cost to manufacture a design are considered.
Supportability	Does not satisfy. Supportability is not currently considered by Ptolemy-supported codesign.
Upgradability	Does not satisfy. Upgradability is not currently considered by Ptolemy-supported HW/SW codesign.
Scalable Architecture	Partially satisfies. Depending on the specific development project, scalable architectures can be developed.
Intrasystem HW/SW Codesign	Partially Satisfies. The design method is limited to tradeoffs between hardware and low-level software. High-level software is not included in the codesign process.

Ptolemy-supported hardware/software codesign does not satisfy any of the remaining system design criteria since there is no provision for the consideration of these issues.

4.3.4 RASSP Evaluation

RASSP was evaluated even though its work is still in its infancy. This evaluation will help see what future improvements (if any) there may be. The reasons behind the ratings of RASSP development methodology are discussed in this section on a criterion-by-criterion basis.

Defined	Satisfies. This process follows a defined process.
Configuration Management	Satisfies. The process has mechanisms for configuration management.
User Involvement	Satisfies. Users become a part of the development process in the model year design concept.
Transparent	Satisfies. Virtual prototyping and the workflow management features of the RASSP development environment provide a high level of transparency in the development process.
Tailorable	Satisfies. The RASSP process will be tailorable to the needs of the project at hand. Some of the tailoring will come naturally as a result of the design methodologies required to solve the current design problem.
Rapid Development Cycle	Satisfies. The process is characterized by a rapid development cycle.
Scalable Methodology	Satisfies. The methodology is applicable to a broad range of digital systems design.
Defect-Free	Partially satisfies. The process seeks to develop a defect-free product, but does not practice defect prevention.
Continuous Improvement & Lessons Learned	Satisfies. The methodology utilizes continuous improvement and documents the lessons learned from each model year design.

Security	Does not satisfy. Security is not currently considered by the RASSP design methodology.
Robustness	Does not satisfy. Robustness is not currently considered by the RASSP design methodology.
Manufacturability	Satisfies. This is a design consideration of the RASSP design methodology.
Supportability	Partially Satisfies. While RASSP does satisfy this criterion for embedded digital systems, it does not ensure supportability for the range of systems that a cross-system integration methodology would need to address.
Upgradability	Partially Satisfies. The model year concept of design emphasizes the development of upgradable designs. However, while RASSP does satisfy this criterion for embedded digital systems, it does not ensure upgradability for the range of systems that a cross-system integration methodology would need to address.
Scalable Architecture	Partially Satisfies. While RASSP does satisfy this criterion for embedded digital systems, it does not ensure scalable architectures for the range of systems that a cross-system integration methodology would need to address.
Intrasystem HW/SW Codesign	Partially Satisfies. While RASSP does satisfy this criterion for embedded digital systems, the design method is limited to tradeoffs between hardware and low-level software. High-level software is not included in the codesign process.

RASSP design methodology does not satisfy any of the remaining system design criteria since there is no provision in the methodology for the consideration of these issues.

4.3.5 Cleanroom Engineering Evaluation

The reasons behind the ratings of the Cleanroom engineering methodology are discussed in this section on a criterion-by-criterion basis.

Defined	Satisfies. This process follows a defined process.
Configuration Management	Satisfies. The process has mechanisms for configuration management, which is performed by the specification team.
User Involvement	Satisfies. In the least, users are deeply involved in the specification phase of each project spiral.
Transparent	Satisfies. The detailed specifications and top-down design with box structures provide a good sense of project status and progress. Metrics tracked during the project also usually provide an accurate gauge of progress.
Tailorable	Satisfies. Project planning tasks include tailoring the process to the needs of the current project.
Rapid Development Cycle	Satisfies. The process is characterized by high productivity and a rapid development cycle.
Scalable Methodology	Satisfies. Box structure design and functional verification practices are scalable.
Defect-Free	Satisfies. This methodology involves defect prevention.
Continuous Improvement & Lessons Learned	Satisfies. Activities related to continuous improvement and documenting lessons learned are performed in the analysis phase of each project spiral as well as at the end of the development project.
Security	Does not satisfy. Security is not currently considered in Cleanroom engineering.

Robustness	Does not satisfy. Robustness is not currently considered in Cleanroom engineering.
Manufacturability	Does not satisfy. Manufacturability is not currently considered in Cleanroom engineering.
Supportability	Partially Satisfies. Referential transparency and box structure design produce a supportable software design. However, Cleanroom does not ensure the design of supportable hardware.
Upgradability	Partially Satisfies. Referential transparency and box structure design produce an upgradable software design. However, Cleanroom does not ensure the design of upgradable hardware.
Scalable Architecture	Partially Satisfies. Referential transparency and box structure design produce a software design that can be easily extended and enhanced. However, Cleanroom does not ensure the design of scalable hardware architectures.

Cleanroom engineering does not satisfy any of the remaining system design criteria since there is no provision in the process for the consideration of these issues.

4.4 CONCLUSIONS

In terms of process characteristics, only Cleanroom engineering satisfied all the criteria. RASSP also scored very well, but fell just short on the defect-free criterion. The other methodologies all displayed shortcomings on multiple counts (see Table 4.2). Thus, it appears from this standpoint that methodologies exist that have general process characteristics that could provide a good foundation for a cross-system integration methodology.

Unfortunately, a glance at the system design criteria matrix in Table 4.3 indicates that none of these methodologies are directly applicable to the interoperability problem in

their current form. Very few of the system design issues are addressed by any of these methodologies. Moreover, when these issues are addressed at all, the methodologies usually only partially satisfy the criteria.

Based upon these evaluations, we can make the following conclusions:

- There are methodologies that possess general process characteristics that would provide a good basis for a cross-system integration methodology.
- Very few of the system design issues are addressed by these methodologies.
- None of the complex electronic system development methodologies in their current forms can meet the need for a cross-system integration methodology.

CHAPTER 5

New Problems, New Solutions

Operation Desert Storm demonstrated the power of information-based warfare. Sheer numbers of troops and materiel are no longer the primary determinants of success. On the digital battlefield of the information age, supremacy in the acquisition, analysis, and exploitation of information will be the prime determinant of success. During the Gulf War, nearly all coalition combat and support operations were supported by computerized information and communications systems. Electronic hardware and software systems performed vital functions at all levels of theater operations. Our ability to gather, process, analyze, and disseminate large volumes of information—especially in digital form—enabled our combat forces to conduct operations with unprecedented speed, synchronization, and precision. The air campaign—choreographed by C4I systems such as AWACS and JSTARS and executed with precision by avionics-laden aircraft, many of which carried precision-guided munitions—provided dramatic proof of the advantages that can be gained through the leveraging of information.

Unfortunately, while these technologies have enabled significant advances in military capabilities, the proliferation of advanced information and communication technologies has also created a new class of development problems—interoperability problems. Resolving these problems requires an effective cross-system integration methodology to address this new system integration challenge.

Several methodologies for developing complex electronic systems were evaluated in the previous chapter to determine if any could be employed directly as a cross-system integration methodology. The results indicated that while there are development methodologies that possess the process characteristics of an ideal cross-system integration methodology, very few of the important system design issues are addressed. In fact, not one design consideration related to interoperability is addressed by any of the methodologies. Thus, none of the complex electronic system development methodologies is capable in its current state of adequately addressing the cross-system integration challenge. This finding has major technical and policy implications.

5.1 TACKLING THE INTEROPERABILITY CHALLENGE

To adequately address the complex system integration challenge represented by the interoperability problem, an effective cross-system integration capability must be developed. While none of the methodologies evaluated in the previous chapter is currently adequate for cross-system integration, the process criteria matrix shown in Table 4.2 indicates that a some of them exhibit process characteristics that could provide a good foundation for an effective cross-system integration methodology. Specifically, this foundation could be provided by Cleanroom engineering, the RASSP design methodology, or a combination of the two methodologies.

Cleanroom engineering fully satisfied all the criteria related to process characteristics. However, it only partially satisfied the system design criteria of supportability, upgradability, and scalable architecture since it does not adequately address these aspects of hardware design. The strengths of Cleanroom engineering include a scalable design methodology that exploits the benefits of common services, referential transparency, functional verification, and statistical testing to produce nearly defect-free software. The originators of Cleanroom emphasize that it is applicable to system engineering as well as software engineering. Using box structure design, the system can be designed in a top-down manner. Once the design is completed, the clear boxes can be implemented in hardware or software. Since Cleanroom engineering is practiced primarily by the software engineering community, the process of implementing clear boxes in

software is well understood. The process of implementing clear boxes in electronic hardware is not as mature. Cleanroom engineering does not adequately address digital hardware design issues, nor is it equipped to deal with tradeoffs between hardware and software. For instance, while Cleanroom engineering ensures the development of an upgradable software design, it does not ensure the development of upgradable electronic hardware.

The RASSP design methodology fully satisfied all but one of the criteria related to process characteristics. Moreover, it addressed more system design criteria—manufacturability, supportability, upgradability, scalable architecture, and intrasystem hardware/software codesign—than any other methodology evaluated. It fully satisfied the manufacturability criterion, but only partially satisfied the others since the program is focused on the domain of embedded digital signal processors and may not provide an adequate scope to form a solid foundation for an effective cross-system integration methodology. In addition, since the methodology is still under development, it is not certain that the methodology—especially its system engineering aspects—will be as scalable as hoped.

The third alternative would involve a combination of the Cleanroom and RASSP approaches. This option, suggested by the results of the system design criteria evaluation discussed in Chapter 4, combines the strengths of the two methodologies while addressing the shortcomings of each. A synergistic combination of aspects of Cleanroom engineering and the RASSP design approach could provide a solid foundation for cross-system integration. Cleanroom offers a rigorous approach to system engineering and software development, and RASSP provides design methodologies and tools for hardware/software codesign of embedded digital systems.

Developing a methodology that synergistically combines different aspects of Cleanroom engineering and the RASSP design methodology would not be a trivial undertaking. Many issues would have to be resolved to accomplish this fusion successfully. Some of these issues include:

- Can the Cleanroom principle of separation of development and testing be reconciled with the RASSP approach of rapid prototyping and simulation of hardware/software systems?

- Can the RASSP capabilities of designing hardware that is manufacturable, supportable, upgradable, and scalable be integrated into the Cleanroom process of refining black boxes into clear boxes?
- Are the Cleanroom and RASSP approaches to ensuring supportability, upgradability, and scalability compatible with each other?

Assuming that a synergistic combination of Cleanroom and RASSP methodologies is feasible, the next step in developing a full fledged cross-system integration methodology would be to expand this foundation to include system design considerations for all classes of interoperability problems, security, and robustness. In addition, mechanisms would have to be incorporated to establish and maintain a set of integrated master requirements and to allow for integrated master requirements traceability. Finally, an integrated system engineering environment should be developed to support cross-system integration activities.

All of these technical issues must be resolved to produce an effective cross-system integration capability. However, to insure the development of a sound methodology, it is necessary to determine the context in which cross-system integration will be performed.

5.2 THE CONTEXT OF CROSS-SYSTEM INTEGRATION

For cross-system integration activities to be successful, the methodology and its supporting design environment should be appropriate for the context in which it is to be applied. For instance, a methodology which assumes a stable set of requirements would have great difficulty in accomplishing its task if the requirements are changed frequently. Similarly, if the operating context provides for a stable set of requirements, a methodology designed to be robust to requirements volatility may not be very efficient.

Proliferation of information and communications technologies in the military environment has generated a significant need for adequate interoperability among resources and across services. This need can be addressed by creating an integrated theater system across interconnected command and control assets, platforms, and munitions. At present, the military development community is using a variety of methods to tackle this

integration problem. Analysis of the methods described earlier suggest several policy and technical options.

There are three main approaches to conducting cross-system integration and, hence, developing theater systems:[1]

1. Continue to develop and procure individual systems and then perform cross-system integration after deployment, using increasingly sophisticated decentralized development management approaches.
2. Continue to develop individual systems but try to address interoperability issues early in the development process, using increasingly integrated team approaches, but not modifying the basic development paradigm that keeps portions of interoperable systems independent.
3. Adopt a comprehensive theater system product concept as the dominant development paradigm for most complex systems, defining programs in terms of theater systems (dominated by information and communication technologies) instead of objects (dominated by mechanical specifications).

The first approach essentially maintains the status quo where system integration efforts are primarily focused on platforms. Cross-system integration may alleviate interoperability problems somewhat, but the integrators will have little leverage since the success of their work will depend largely on design decisions made early in the development cycles of the different systems. Integrating disparate systems would likely be a difficult, costly, and time consuming task. It is also likely that the integrated solutions would not be very effective or efficient. In addition, the bottom-up development of a theater system without an integrated plan to guide its development significantly increases the risk that the theater system will not have the appropriate mix of elements.

While the second approach still involves the development of individual systems and integrating them after deployment, it improves on the status quo by addressing

[1] Note that, broadly defined, a "theater system" includes both equipment and personnel. Theater systems would then be the product of more than just development and acquisition activities. Strategic and organizational planning, training, and doctrine would be certainly also be involved. However, in this thesis, we have focused more narrowly on the equipment—electronic hardware and software systems in particular. Thus, "theater system development" refers to the development of the technology component of a theater system.

interoperability considerations early in the development cycle. This "design for interoperability" approach could enable the individual systems to be integrated more easily. This would decrease the amount of time and money required to perform cross-system integration. Moreover, a design for interoperability approach would likely result in more efficient integration solutions. While this bottom-up approach to theater system development would produce better results than the first, it could result in relatively isolated groups of interoperable systems since there is no integrated plan for developing the theater system. Again, the lack of an integrated plan to guide theater system development significantly increases the risk that the theater system will not have the appropriate mix of elements.

The third possible approach is to adopt a development paradigm based ***centrally*** on theater systems, or a derivative. Since the current paradigm regards platforms and other individual systems as the ultimate products, this approach would represent a paradigm shift. To understand the reasons behind the shift, it is useful to compare an automobile with a fighter. An automobile is a system for transporting people from one place to another. It is operated largely as an individual system, interacting with its "theater" only at places like the gas pump, the toll booth, or the traffic light, where it does not require much a priori design integration. It is only loosely coupled with its "theater" and does not require much "interoperability" in its design. Thus, an automobile is an appropriate product concept. A modern fighter, however, rarely operates solo in a theater of operations. In fact, it must be interoperable across many system elements to accomplish many of its missions. Here, a fighter is just one element of a larger whole—a theater system—that is used to conduct military operations. Thus, the theater system, not the fighter, is the ultimate product of development and procurement activities.

Using the automobile as a metaphor for a theater system, it is easy to understand why the cross-system integration task is so challenging when performed within its present context. Imagine having three or four people choose their favorite automobile components and hoping that they will be able to assemble an automobile that runs smoothly and provides the desired functionality.[2] Imagine further the complexity if an automobile were

[2] The number of people involved depends on the relative autonomy of the acquisition activities of the U.S. Marine Corps relative to those of the U.S. Navy.

required to be unpredictably integrated with a wide variety of external data communication environments, many of which had no standards or agreed protocols. The number of fundamental design variables would increase dramatically. Even if the selected parts provide all the required functionality, the task of assembling the automobile is likely to be very difficult and extremely time consuming.

According to a number of military acquisition-related organizations grappling with the "infowar" phenomenon, the theater system is increasingly (and may have always been) the ultimate product of the development and acquisition processes. The essential phase shift that has occurred within the past 10 to 15 years is that the widespread use of information and communication technologies simultaneously increases the number of elements in the theater system and requires that they be coupled more tightly. While focusing on platforms might have been appropriate when electronic contents were small and theater system elements were loosely coupled, high electronic system content and tight coupling indicate that the platform-based integration model is no longer appropriate.

Adopting a theater system product concept shifts the system integration focus from platforms to the theater system. This enables the top-down design of a theater system which would help ensure an appropriate mix of theater system elements. Matching the needs of theater system with present capabilities in a bottom-up fashion would also help identify capabilities that need to be developed. Moreover, by recognizing the critical importance of information technology and interoperability, this approach would provide an integrated plan to guide cross-system integration and design for interoperability activities. The combination of these factors simplifies the cross-system integration task and enables it to be performed effectively and efficiently.

Extending the current development and acquisition model to include cross-system integration, as suggested by the first approach, is inadequate for developing the tightly coupled theater system elements required for warfare in the information age. The second approach represents a marginal improvement over the first, but may produce islands of interoperability rather than an integrated theater system. Only the third approach, adopting the theater system product concept, offers the promise of effective and efficient theater system development.

5.3 CENTRALIZED TOPSIGHT, DECENTRALIZED DEVELOPMENT

Adopting the theater system product concept represents a sea-change in the prevailing defense development and acquisition paradigm. Establishing the theater system as the integration model acknowledges and embraces the integrating power of information technology. Electronic hardware and software form the links that integrate physically disparate systems into a synchronized theater system.

A major implication of the combination of top-down theater system design and bottom-up implementation is that the approach allows decentralized development while providing centralized topsight.[3] It is this topsight—an understanding of the big picture—that should allow the complexity of a theater system to be managed successfully, facilitating effective and efficient cross-system integration. Without topsight, the theater system product concept would not be able to exploit the benefits of an integrated plan to guide the cross-system integration and design for interoperability tasks. Topsight is the key to lean development and integration of theater system elements.

Since the theater system is the focus of integration efforts in this paradigm instead of a platform, product development can be even more decentralized than before. In the context of aircraft, subsystems whose development were traditionally tied to the development of the platform can be decoupled from the airframe. While they are still "integrated" through the logic of the overall theater system product model, upgrades could also be decoupled for development, yet remain "integrated" for interoperability. Decoupled subsystems and upgrades could be driven to completion as quickly as possible with a set of short-cycle rapid development projects. Top-down theater system design allows these subsystem and upgrade development projects to be decoupled from the airframe, rapidly developed, and then re-integrated with the airframe upon completion. Theater system design naturally incorporates cross-system integration issues, and automatically incorporates design for interoperability into the decoupled development programs. Once the systems (subsystems or elements) are developed and reintegrated with

[3] Topsight is a term used by Gelernter (1991) and Arquilla and Ronfeldt (1992) to denote a central understanding of the big picture that enhances the management of complexity.

the airframe, integrating the aircraft with the other existing theater system elements should be nearly automatic.

The decoupled development approach has several benefits. First, development times can be significantly reduced. For electronic systems and software, the decoupled systems can take advantage of fast cycle development methodologies such as Cleanroom engineering and the RASSP design methodology. This should dramatically cut development times while producing high-quality products that are scalable, upgradable, and supportable. Accelerating the development of these systems through decoupling would also place needed capabilities in the hands of the warfighters earlier. Moreover, the fielded systems would be much closer to the state-of-the-art at the time of deployment. Under current development and acquisition practices, the performance of commercially-available systems can surpass the projected performance of a defense system before its development is completed.

Second, decoupled development allows new and existing systems to keep pace with the rate of technological advance. Obsolescence is especially a concern in electronics and software because of the rapid rate of performance improvement of these technologies. Since the products of these decoupled development projects are upgradable and scalable, product capabilities would be much easier to enhance and extend. Decoupled development would also facilitate the application of the model-year design concept, which would further enhance the ability to keep pace with technological advance.

The benefits of decoupled development would extend to airframes as well. Since most new development programs are paced by the development of electronics and software, decoupling these elements should allow an airframe to be developed in less time.

The higher productivity of the decoupled development projects translates into lower development costs, resulting in a more affordable final product once the decoupled subsystems are integrated. In addition, since the subsystems would be upgradable, scalable, and supportable, life cycle costs would also be significantly reduced (Richards, 1994). Further cost savings could be generated through reuse of software and hardware designs and off-the-shelf components. Moreover, applying the principle of common

services during the top-down theater system design process would facilitate substantial cost savings through the identification and exploitation of economies of scope.

In addition to these benefits, the fast cycle decoupled development approach offers the benefits of enhanced robustness to budgetary instability and enhanced risk reduction. The primary vehicle for both of these benefits is speed. Projects that can be completed rapidly are less likely to experience the effects of budgetary instability since there would be fewer opportunities for budgetary changes during development. Maximum robustness would be achieved by projects that could be completed within a single budget cycle. Risk would be reduced in two ways. First, rather than conducting numerous risk assessments and analyses, a real system or prototype would be rapidly developed which would provide more accurate estimates of the risks involved based on actual experience and data. In addition, producing real hardware and software provides a more tangible result than the traditional risk reduction approach of extensive analyses, documentation, and milestone reviews. With all other factors equal, a project that can demonstrate working hardware or software is less likely to experience budget cutbacks than a project that only has reams of analyses and documentation to show for its money.

Thus, the benefits of centralized topsight and decentralized development provided by the theater system product concept enables the lean development of theater systems and theater system elements while simultaneously improving robustness to budgetary instability and reducing development risks.

To summarize, centralized topsight and decentralized development provide the following benefits:

- Decoupled development of subsystems and upgrades
- Natural incorporation of cross-system integration issues in theater system design
- Smooth integration of theater system elements
- Rapid development of needed capabilities
- State-of-the-art operational systems
- Greater affordability

- Enhanced robustness to budgetary instability
- Reduced development risk

5.4 MULTIPLE THEATER SYSTEMS

During our efforts to preserve military capabilities in the face of the defense drawdowns, we must not become too focused on preserving and enhancing capabilities needed for a particular type of conflict. Theater systems must be designed for each class of operations in which our national military strategy envisions the use of military capabilities. This could include peacekeeping, conducting humanitarian missions, defeating regional aggression in two concurrent major regional conflicts, and countering insurgencies. Each of these types of operations begets its own operational strategy and, hence, its own theater system design. We must design our theater systems to fit reality rather than fit reality into a particular theater system.

Designing each of these theater systems in a top-down manner would enable the identification of common services among theater systems as well as within each theater system. This could facilitate the realization of remarkable economies of scope. We may also discover that we could fulfill our missions with a smaller force structure than ever thought possible.

5.5 IMPLEMENTATION ISSUES

Although analyzing and recommending solutions to implementation issues is a task that is beyond the scope of this thesis, it would not be complete without a discussion of some of the issues involved. There are numerous implementation issues that need to be resolved for the theater system product concept approach to work. These issues can be summarized by two broad questions:

- Who should design theater systems?
- How can theater systems be designed?

Who should design theater systems?

This is a difficult question to answer. Industry possesses the technical knowledge required to develop theater system components. However, few companies, if any, possess technical knowledge in all of the required disciplines. Hence, it may not be appropriate for industry to design and integrate theater systems. On the other hand, while the government possesses the knowledge of desired theater system capabilities, it lacks the technical knowledge required for implementation. One option could be to form a government-industry partnership to design theater systems. This could produce designs that would benefit from operational and technical knowledge. Alternatively, theater systems could be designed jointly by the services in a Joint Theater System Center. This center could operate under the Joint Requirements Oversight Council, which oversees wargaming and seeks ways to improve military coordination among the services. Clearly, only a few of the relevant factors have been discussed here. There are many other questions to consider before a decision can be made.

How can theater systems be designed?

The methods and tools to support theater system design need to be developed. These include the methodology for theater system design and an integrated design environment to support it. Box structure design offers one possible method for designing theater systems since its underlying mathematical foundations permit the scale-up of analysis and design to systems of arbitrary size. Moreover, the use of black boxes to specify behavior in an implementation-free manner provides the designer with great freedom in devising a means to implement the required functionality. An integrated design environment that usefully supports theater system design must also be developed.

Wargaming technology must also be improved. Ironically, although wargaming has been enhanced through the use of computers, the military use of information technology has rendered much of wargaming obsolete since it is primarily focused on modeling attacks and defenses with conventional force structures. Wargaming is not adequate to model information-based warfare (Cava, 1993). In fact, current wargaming tools are not capable of satisfactorily modeling the effects of changes in C4I support (Bowie et al., 1993). Limited wargaming capabilities can prejudice our theater system

designs toward force structures that can be modeled. Improvements in wargaming are necessary so that we may design our force structures to fit reality as opposed to trying to fit reality to our force structure (Steele, 1993).

5.6 CONCLUSIONS AND RECOMMENDATIONS

This thesis is the start of a study of how to address the new integration challenge—to ensure the interoperability of systems through rapid cross-system integration while producing a theater system that is flexible, rapidly deployable, upgradable, evolvable, and maintainable. This problem is very complex, but there are concepts and methodologies—some of which are unconventional—that point the way to a solution. New problems require new solutions. The information revolution is producing remarkable advances in military capability and is transforming warfare in the process. The development and acquisition of defense systems must adapt to this new reality.

5.6.1 Conclusions

- The ability to acquire, analyze, disseminate, and exploit battlefield information is critical to military success.
- The proliferation of information and communications systems in all aspects of theater operations has created an interoperability problem.
- To address the classes of interoperability problems, a cross-system integration methodology is needed.
- Although there are complex electronic system development methods that meet some of the criteria of a good cross-system integration method, none of the methods studied can adequately perform cross-system integration in their current form.
- Cleanroom engineering and the RASSP design methodology rated the best in terms of process characteristics, but satisfy only a fraction of the relevant system design criteria.

- Cleanroom engineering and the RASSP design methodology could be combined to form a foundation for cross-system integration.
- The current model of developing disparate systems and focusing system integration efforts on platforms is not suited to the development of the tightly coupled theater system elements required for warfare in the information age.
- A theater system is the product of defense development and acquisition activities. Consequently, theater systems should be the focus of system integration activities. Platforms are elements of theater systems.
- The theater system product concept enables lean development of theater system elements and, hence, theater systems.

5.6.2 Recommendations

- Combine Cleanroom engineering and RASSP design practices synergistically to form a core from which to develop a cross-system integration methodology. Cleanroom engineering offers a rigorous methodology for system and software engineering that can scale-up to permit the design of systems of arbitrary size. The RASSP design methodology offers a scalable approach to designing embedded hardware/software systems.
- Adopt the theater system product concept. This continues to permit decentralized development of theater system elements, but provides an integrated design of a theater system to guide development and cross-system integration activities. Cross-system integration activities are essentially absorbed into theater system design. The actual integration would be much simpler than performing cross-system integration within the context of the current development and acquisition framework. Designing theater systems top-down also enables the identification and exploitation of common services for economies of scope.
- Decouple development of subsystems and upgrades from the platforms. The centralized topsight of the theater system product concept is provided by the top-down theater system design. This topsight enables subsystem and upgrade

development work to be decoupled from the platform. Fast cycle methods like Cleanroom engineering or the RASSP design methodology can be applied to rapidly develop these subsystems and upgrades. For electronics and software, the benefits are systems which are state-of-the-art at the time of deployment, upgradable, scalable, supportable, and more affordable. Needed capabilities are fielded faster. Airframes can also be developed faster. Decoupled rapid development also provides for improved robustness to budgetary instability and risk reduction.

- Design theater systems for the different classes of military operations. This should help develop a force structure that fits reality. Designing multiple theater systems also provides greater opportunities to exploit common services and take advantage of economies of scope that exist among theater systems.
- Specify functional requirements, not implementations (i.e., specify black box behaviors of subsystems). This provides designers with maximum flexibility in devising a solution to provide the required functionality.
- Develop an integrated design environment to support theater system design and cross-system integration.
- Develop a comprehensive wargaming toolset to simulate theater systems and the benefits of C4I systems and the effects of degradations of C4I capabilities. This technology does not currently exist and is required to support theater system definition activities.
- Resolve issues pertaining to who should design theater systems.

APPENDIX A

Cleanroom Engineering Extras

This appendix contains more detailed discussions of three aspects of Cleanroom engineering. Box structure design is discussed first. The following section discusses functional verification. The last section provides a more detailed description of the statistical testing practices of Cleanroom engineering.

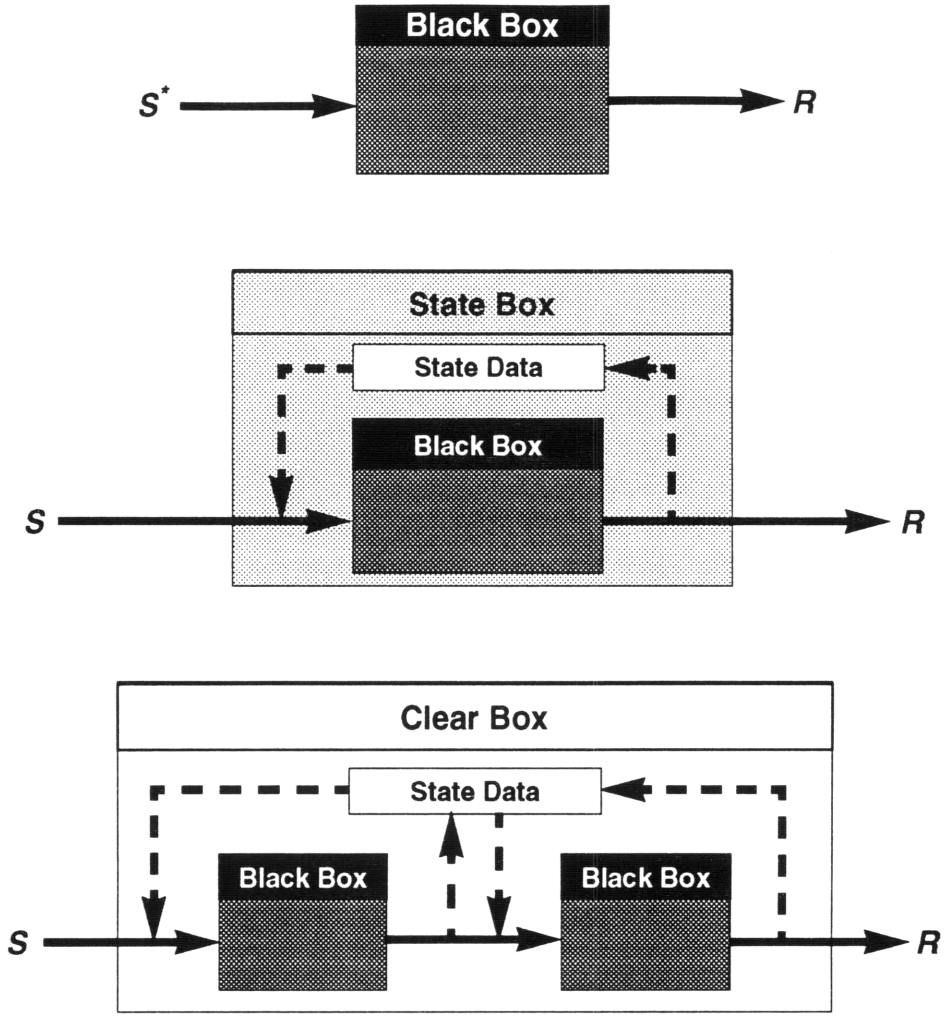
A.1 BOX STRUCTURE DESIGN

This section provides a more detailed discussion of box structure design methods. The different box structures—black boxes, state boxes, and clear boxes—are described first. The guiding principles of box structure design are discussed next. Finally, the box structure design algorithm is described. As a reminder, diagrams of the three box structures are shown again in Figure A.1.

A black box provides an implementation-free, object-oriented description of software. This box structure only describes the software's external behavior in terms of a mathematical function that maps a stimulus history, S^*, to a response, R. Since the black box view excludes all details of internal structures and operations, it also provides a description of the user's view of system behavior.

A state box provides a data-oriented view that begins to define implementation details by modifying the black box to represent responses in terms of the current stimulus,

Figure A.1: Box Structure Diagrams



Note: The clear box structure is shown with a sequence process structure.

S, and state data that contains the stimulus histories. To form a state box, a black box is expanded by adding state data and state machine transitions to black box transitions. Thus, the state box contains a black box that accepts the external stimulus and the internal state data as its stimulus and produces both the external response and the new internal state which replaces the old state as its response. State box behavior can be described in the transition formula

$$(\text{Stimulus, Old State}) \rightarrow (\text{Response, New State})$$

A clear box provides a process-oriented view that completes the implementation details by modifying the state box view to represent responses in terms of the current stimulus, state data, and invocations of lower level black boxes. To form a clear box, a state box is expanded by adding procedure structures and delegating parts of the process to component black boxes. The processing can be defined in terms of three possible sequential structures—sequence, alternation, and iteration—and a concurrent structure.

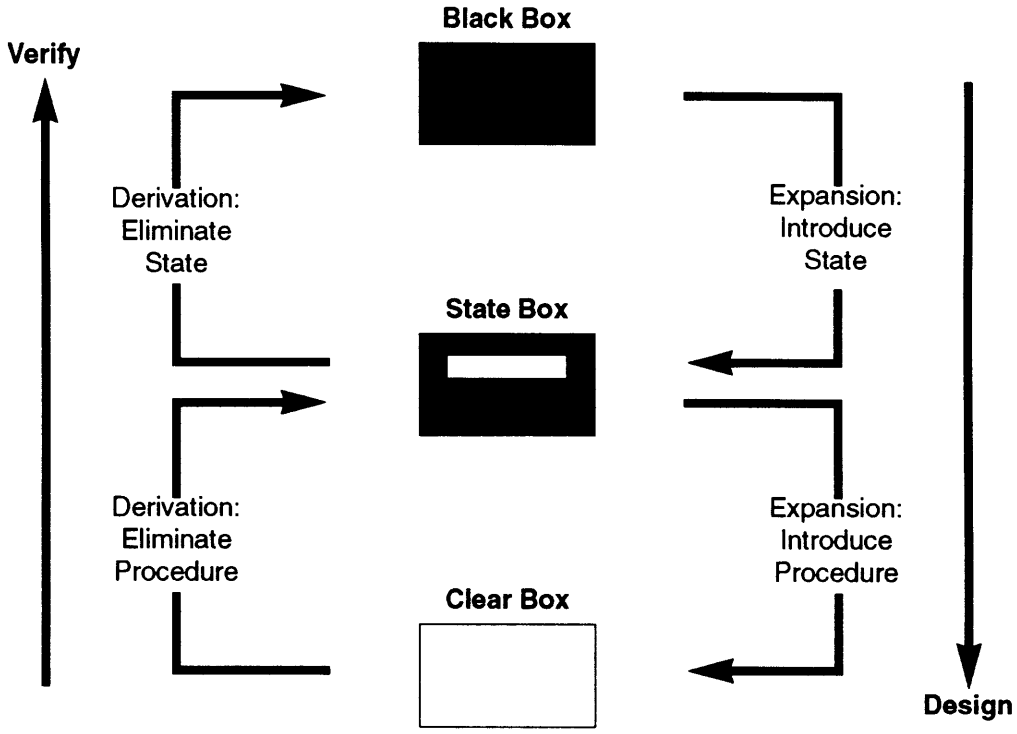
The relationships among the black box, state box, and clear box descriptions of a system or subsystem precisely define the tasks of *expansion* and *derivation*. Whereas it is an expansion task to design a state box from a black box or to design a clear box from a state box, it is a derivation task to abstract a black box from a state box or to abstract a state box from a clear box. An expansion does not produce a unique product since there are many state boxes that behave like a given black box and many clear boxes that behave like a given state box. A derivation, however, produces a unique product since there is only one black box that behaves like a given state box and only one state box that behaves like a given clear box (Mills et al., 1987). Expansion and derivation are the basis for box structure design and verification, as shown in Figure A.2.

The effective use of box structure design methods for the development of systems is guided by the application of six basic box structure principles: referential transparency, transaction closure, state migration, common services, correct design trail, and efficient verification.

Referential Transparency. This condition occurs when a black box is encapsulated by the clear box at the next higher level of the usage hierarchy. Each object is logically independent of the rest of the system and can be designed to satisfy a well defined "local" behavior specification. Referential transparency simplifies development and produces designs that are easy to enhance.

Transaction Closure. The transactions of a system or subsystem should be sufficient for acquiring and preserving all its state data, and its state data should be sufficient for completing all its transactions. The principle of transaction closure defines a systematic, iterative specification process to ensure that a sound and **complete** set of transactions is identified to achieve the required system behavior. The result is that the required stimuli,

Figure A.2: Box Structure Expansion and Derivation



data, and transactions are available at each stage of the design to generate the desired behavior.

State Migration. State data is identified and stored in the data abstraction at the lowest level in the box structure hierarchy that includes all references to that data. The result is that state data can easily be transferred to the lowest feasible level.

Common Services. A common service is a data abstraction which is described in a separate box structure hierarchy, and used in other box-structured systems. System parts with multiple uses are defined as common services for reusability. In the same way, predefined common services, such as database management systems and reuse objects, are incorporated into the design in a natural manner. The results are smaller systems and designs which accommodate reuse objects.

Correct Design Trail. It is important to insure consistency in the entire design trail when correcting an error. If the changes to a previous design document are trivial, the

corrections can be performed right away without stopping the current design process. However, if the necessary changes are major, the design process should be stopped until all the corrections to the previous design documents are made.

Efficient Verification. It is only necessary to verify what is changed from one refinement to the next since all elements of the design are referentially transparent. In addition, if the design refinements are conducted in small steps instead of large leaps, each refinement can be shown to be correct by direct assertion.[1] Otherwise, verification might require the use of rigorous proofs which are significantly more time intensive than the direct assertion approach.

The box structure design algorithm begins with defining and verifying the black box function for the system. This task is usually accomplished by the specification team who delivers it to the development team. Once the black box has been defined and verified, the design is refined by expanding the black box into a state box. Before the state box is expanded into a clear box, a black box is derived from the state box by eliminating references to state data in the state box functions and comparing it to the original black box. If the two black boxes are equivalent, then the state box design is verified as correct. Otherwise, the state box design must be corrected.

After the state box refinement has been verified, the design is refined once more by expanding the state box into a clear box. Again, the clear box design must be verified by deriving a state box from the clear box by eliminating references to procedure and the internal black boxes it encapsulates and comparing it with the original state box. If the state boxes are the same, the design process can continue. Otherwise, clear box design must be iterated until a design can be verified successfully.

Following verification of the refinement, this same process is repeated for each of the internal black boxes in a stepwise refinement process that ends when all the remaining internal black boxes represent either single commands of the destination language or subsystems that have been implemented in a previous increment. This top-down design process produces a box structure hierarchy, such as the one shown in Figure A.3.

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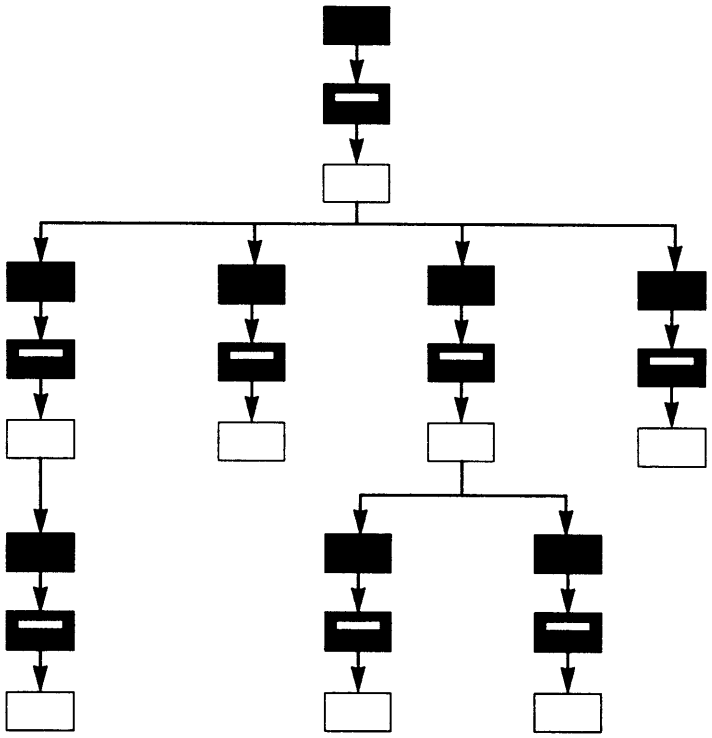
[1] Refining designs in small steps typically creates simple software designs that are typically correct. Refining designs in large leaps can increase the chance that errors will be introduced into the design.

Figure A.3: Box Structure Hierarchy



After the top-down box structure design is completed, the clear boxes can be implemented. Depending on the nature of the system under development, the actual clear box implementation could be accomplished through an integration of hardware, software, and human behavior (SET, 1993). For software development, clear boxes are translated into code through stepwise refinement. The implementation must be verified as correct and consistent with the clear box design. The software code is verified by demonstrating the equivalence of the program and the design represented by the clear box refinement. While system design proceeds in a top-down fashion, the implementation of the design is accomplished in a bottom-up fashion. Designing top-down and then coding bottom-up allows the developers to exploit fully the principle of common services during the design phase and generalize the common services as much as possible during the coding phase.

A.2 FUNCTIONAL VERIFICATION

In Cleanroom engineering, functional verification is used instead of unit debugging. Once a clear box has been refined into code, the development team uses functional verification to help structure a proof that the refinement correctly implements the clear box design. If multiple steps were taken to refine the clear box design to code, the current refinement would be verified against the last refinement. The principle of referential transparency allows these smaller proofs to be easily accumulated into a proof for a large program. Unlike the unit debugging practices that are traditionally used, functional verification is scalable. Experience demonstrates that people are able to master these ideas with little difficulty and construct proofs for very large software systems (Cobb and Mills, 1990).

These functional verifications typically yield surprising improvements in design, even for the best software engineers. As a result, the developed software can be smaller and faster than previously thought possible, delivering more functionality per instruction. In addition, using functional verification allows quality to be designed into the software. According to Cobb and Mills (1990), functional verification leaves only two to five defects per thousand lines of code to be fixed in later phases of the life cycle whereas debugging leaves 10 to 30 defects per thousand lines of code. In contrast to functional verification, debugging attempts to test quality into the product. However, since more than 15 percent of the corrections merely introduce newer, deeper errors, testing quality into software is not possible (SET, 1993).[2]

Functional verification and testing seem to exhibit a high degree of synergy. Functional verification eliminates defects that tend to be difficult to detect with testing. The defects that remain after inspections and functional verification are generally the type that can be easily detected with testing. The combination of inspections, functional verification, and testing can eliminate more than 99 percent of all defects (Head, 1994). Table A.1 summarizes the defect removal performance for a range of different defect detection strategies.

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[2] DeMarco (1982) contains an excellent analysis which demonstrates the validity of this point. Testing seems to be capable of eliminating half of the software defects. However, this factor of two improvement is overwhelmed by the extreme variability in the quality of software being produced today.

Table A.1: Defect Removal Percentages of Different Strategies

Detection Strategy	% Defects Removed
Testing	50%
Inspections	60%
Inspections + Testing	85%
Inspections + Functional Verification	90%
Inspections + Functional Verification + Testing	>99%

Source: Head (1994).

A.3 STATISTICAL TESTING

Cleanroom engineering makes use of statistical usage testing to certify the reliability of the developed software in terms of its MTTF (Mean Time To Failure). The application of rigorous statistical theory allows both quality control of the software being developed and process control over the development of the software.

The testing approach used in Cleanroom projects differs from the prevailing approach of coverage testing. The goal of Cleanroom testing is to maximize the expected MTTF of the software under development. Since coverage testing is just as likely to discover rare execution failures as it is to discover frequent execution failures, an alternative strategy that focuses on detecting frequent failures is needed. This need is satisfied by usage testing since its utilization of a statistical usage profile allows the formulation of tests that are representative of expected usage. In fact, for the purposes of increasing the MTTF of software, usage testing has been determined to be 21 times more effective than coverage testing (Cobb and Mills, 1990). Usage testing also typically takes less time than coverage testing.

The usage profile is represented by a Markov model specifying the probability of moving from each usage state to all other usage states. The model describes every possible state that a system can be in, identifies all the different actions that the user could take in each state, and assigns probabilities to each possible action in each state. The usage profile can be expressed in a state transition diagram or a matrix.

The requirement specifications and usage profile, which are developed by the specification team, are used by the certification team to develop a set of random test cases which are representative of the expected usage. After the current increment is coded and delivered to the certification team, the current increment is integrated with previous increments, if any, and the test scenarios are executed. The error history is evaluated with a mathematical model designed to predict how many more defects the user might encounter in a certain period of time with a certain number of uses (Head, 1994). As soon as the reliability model indicates that the developed software meets or exceeds the desired quality level with a sufficiently small degree of uncertainty, testing is considered complete, and the product can be safely released.[3]

Software must be minimally reliable for statistical testing to be valid. Applying statistical testing to software developed with typical defect densities would cause the statistical reliability models to blow up. If the model does not blow up, its predictions are usually extremely unfavorable (Head, 1994). According to Cobb and Mills (1990), defect densities of five defects per thousand lines of code or less can be tolerated without invalidating the application of statistical MTTF estimation.[4]

[3] Currit et al. (1986) describes several statistical models for certifying the reliability of software.

[4] The reader may recall that this figure of 5 defects/KLOC was mentioned earlier during a description of the Cleanroom principle of defect prevention. Apparently, discarding software with high defect densities is done not only to motivate designers to develop defect-free software but for statistical reasons as well.

APPENDIX B

Recommendations for Further Study

The subject of this thesis is an important topic that is too wide-reaching to be studied adequately in a single master's thesis. In the course of researching this thesis, a number of interesting possibilities for further study were identified. Some of these topics are important subjects related to cross-system integration and the theater system product concept that were beyond the scope of this thesis. Other suggestions include further study of some of the methodologies that were selected for evaluation in this thesis. Some topics are interesting ideas that were encountered during the research process that may have potential for application in the aerospace industry.

B.1 CROSS-SYSTEM INTEGRATION AND THEATER SYSTEMS

There are many interesting subjects for further study related to cross-system integration and the theater system product concept. This section contains just a sample of the topics related to implementing the theater system product concept. While these topics were beyond the scope of this thesis, two important questions were identified:

- Who should design theater systems?
- How should theater systems be designed?

There are a myriad of interesting subjects for further study encompassed by these two seemingly innocent questions. The first concerns determining the optimal mix of government and industry participation in the theater system design process and defining the mechanisms for that participation.

Another interesting topic concerns the organizational aspects of performing theater system design. The transforming effect of information technology is already being felt in the business world. Clearly, an appropriate organizational structure will need to be devised to handle the task of designing theater systems.

This question is closely coupled to the second which concerns the actual methodology for designing theater systems. Clearly, more work is necessary to develop a good cross-system integration methodology. This is a must if we are to successfully address the interoperability problem.

Also included under the second question is the issue of how to develop an integrated design environment to support the design of theater systems. In the near term, one subject that definitely requires further study is how to develop a comprehensive wargaming technology. This is needed to allow the benefits of C4I systems and the effects of degraded C4I capabilities to be modeled explicitly in wargaming simulations. Otherwise, we may limit our ability to design innovative theater systems.

B.2 FURTHER STUDY OF SELECTED METHODOLOGIES

While none of the methodologies are directly applicable to the cross-system integration function, many of them could produce significant improvements in the development of theater system components. The following is a list of recommended actions for this purpose:

- Maintain contact with the ARPA/Tri-Service RASSP program. Draw upon the findings and the development work being conducted under its auspices. Monitor the progress of benchmarking activities and the evolution of the design process. At minimum, the Initiative would benefit from increased insight into the benefits and problems associated with integrated electronic design environments and collaborative design.

- Maintain contact with the ARPA STARS (Software Technology for Adaptable, Reliable Systems) program. Currently, this ARPA program is conducting multiple technology and process demonstration projects, some of which involve the Cleanroom engineering methodology described in this thesis. The Initiative would benefit from the insights generated by these demonstration projects as well as the wealth of software development data that will be produced and collected for analysis.
- Conduct an F-22 avionics development case study. It appears from several phone interviews conducted with former and current members of the avionics integrated product team that there were a number of substantial improvements over past programs in the development of avionics and software for the F-22. Among the innovations is a systems/software engineering environment that allows the designer to simulate the avionics system from high-level Ada code down to gate-level hardware functionality. Preliminary research indicates that a derivative of hardware/software codesign has been used. Other interesting aspects include the use of common hardware modules and the application of data fusion to integrate information and display it to the pilot in a more understandable form rather than requiring integration to take place "between the headphones".

B.3 OTHER INTERESTING TOPICS

B.3.1 Architectural Innovation and Transformation

New technologies are usually applied initially as substitutes for old technologies to enhance performance or increase the efficiency of a product, process, or system. Typically, the new technologies are substituted without changing the overall framework or architecture of the product, process, or system. Some technologies, however, can also be *transformational.* Transformational technologies disrupt old ways of thinking and operating and provide the capability to do things differently with greater effectiveness and efficiency, leading to the creation of radically different frameworks and architectures as a result. It is this architectural innovation that unlocks the true potential of the technology.

The transformational effect of information technologies is already being felt in several aspects of society, including the conduct of modern warfare. In the future, many institutions are expected to evolve from traditional hierarchical structures to new flexible models of organization resembling networks.[1] These transformational effects are expected to influence the structure of military organizations as well (Arquilla and Ronfeldt, 1992; Krepinevich, 1994). What new doctrines, organizations, and force structures will arise as a result of the current military-technological revolution? What form will the "sunrise" systems take? Will future defense systems function like distributed networks with sensors being separated from smaller weapons platforms, as some experts predict? What elements of today's military are destined to become "sunset" systems? These issues must be studied to ensure that our military does not follow the path of the British Army during the 1920s and 1930s, which failed to effect the organizational changes necessary to develop its own *blitzkrieg* capability even though it had developed the necessary enabling cutting-edge technologies (Krepinevich, 1994).

B.3.2 Set-Based Design

As documented by Ward et al. (1994), Toyota's product development process, which is seemingly incongruent with widely accepted models of concurrent engineering, provides a second Toyota paradox. Contrary to conventional wisdom on concurrent engineering, delaying decisions and making many prototypes can make better cars faster and cheaper (Ward et al., 1994). Toyota's multidisciplinary development teams are neither co-located nor dedicated to a single project. Instead of trying to freeze specifications as rapidly as possible, Toyota engineers and managers deliberately delay decisions and provide deliberately ambiguous information to their suppliers. Moreover, instead of seeking to minimize the number of prototypes, Toyota and its suppliers produce a seemingly excessive number of prototypes (Ward et al., 1994).

The key to understanding this development approach is "set-based design". While more traditional processes utilize an iterative "point-to-point" design approach, in which the state of the design moves from one point to another in the "design space", the Toyota

[1] The literature on the transformational effect of information technologies is vast. Examples include Arquilla and Ronfeldt (1992), Bankes and Builder (1992), Malone and Rockart (1991), Ronfeldt (1991), Sproull and Keisler (1991), and Toffler (1990).

development approach uses a set of specifications to achieve a solution. Using set-based design, engineers and managers can test and evaluate numerous prototypes, which allows a more robust exploration of the design space and enables them to devise a combination of specifications to produce the most robust car or truck. Moreover, if problems are encountered during development, a set of possible alternatives exists (McElroy, 1994).

This research provides a number of interesting topics for further study. Could a set-based concurrent engineering approach be applicable in the aerospace industry? How would a set-based approach be implemented? What changes would be necessary to successfully implement a set-based development approach?

B.3.3 Robust Technology Development

Robust technology development during the research and development phase can simplify and accelerate the product development process. Developed by Dr. Genichi Taguchi, the originator of quality engineering, Technology Development reduces the risks involved in introducing new technologies into a product and can significantly reduce the amount of time devoted to "tweaking" in a product development process (Ealey, 1994; Clausing, 1994). Technology Development ensures that a technology is capable of overcoming downstream forces that can introduce variability in the end product (Ealey, 1994).

According to Dr. Taguchi, ensuring "origin quality" through Technology Development is the most powerful application of quality engineering, providing the greatest leverage for saving cost and time in the product development process (Ealey, 1994).[2] Since less funding is being allocated for developing and procuring new defense systems, the quality of the output of research and development activities has become even more important. It is important for our technology development programs to engage in robust Technology Development so that designers can merely "tune" the technologies to yield the desired outcome when it is desired to incorporate the technologies in a new product. For instance, since JAST (Joint Advanced Strike Technology) seeks to develop "bins of technology", a robust Technology Development approach would certainly benefit future aircraft development programs seeking to employ JAST-developed technologies.

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[2] Taguchi's Technology Development has already been applied successfully for several years at Nissan's Reliability Engineering Center. An example of its application can be found in Ealey (1994).

Clearly, the potential benefits and barriers to the application of Taguchi's Technology Development concepts during research and development activities merit further study.

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