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Building a Team for Next Generation Air Dominance

Enabling Mission-Focused Teams through Software-Defined Capabilities

BRYAN CLARK AND DAN PATT

CENTER FOR DEFENSE CONCEPTS AND TECHNOLOGY

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Cover: A F-22 Raptor from the 325th Fighter Wing flies alongside a F-35 Lightning II from the 33rd Fighter Wing over the Emerald Coast. The fifth generation fighter jets flew together in a rare dissimilar formation to salute health care workers, first responders and other essential employees May 15, 2020. (U.S. Air Force photo by 1st Lt Savanah Bray)

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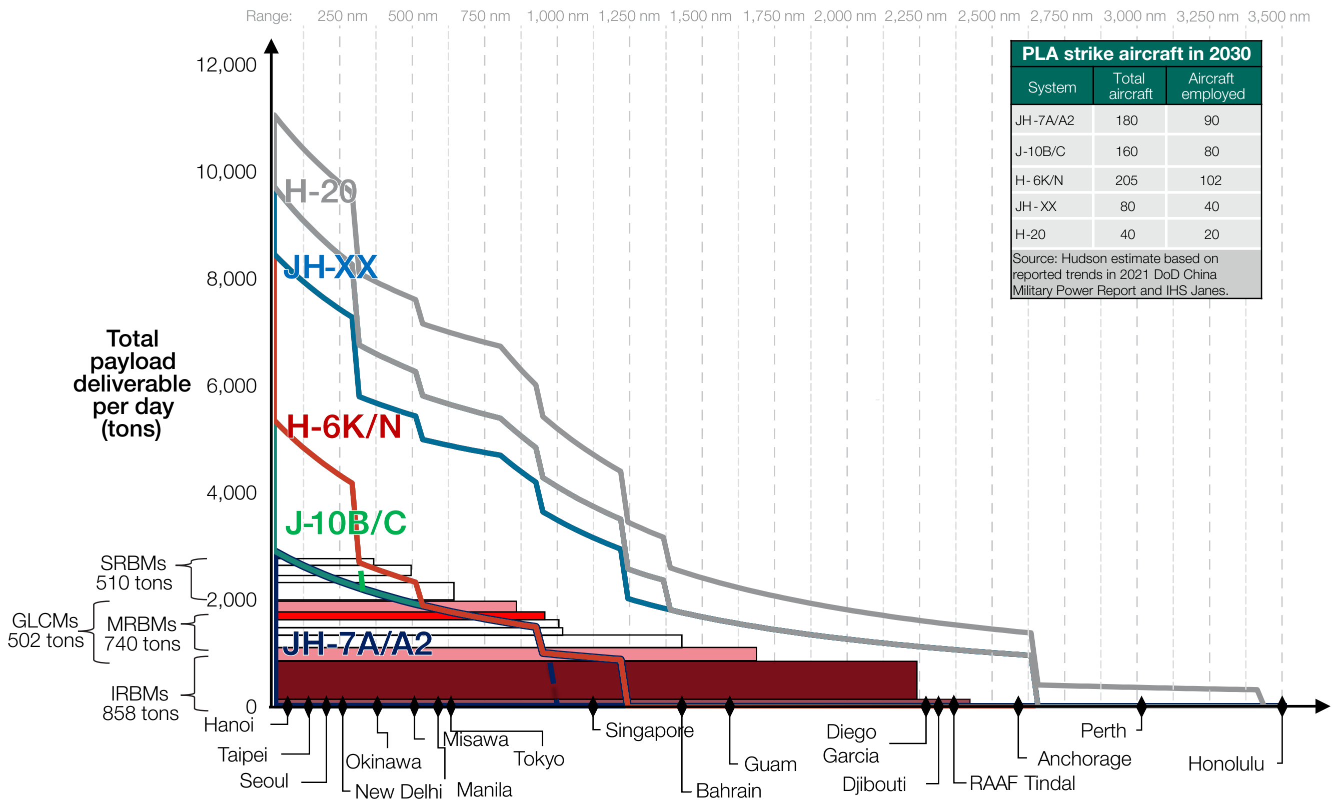
CHAPTER 1. INTRODUCTION

US air and naval forces face contested environments over wider areas than ever before. Opponents fighting near their home territory can use long-range surface-to-surface missiles and air defense systems—enabled by a combination of commercial or military satellites and airborne sensors—to threaten US or allied airfields, ships, and aircraft thousands of miles away, as depicted in Figure 1.[1] By showing they can slow or prevent US intervention in their regions, aggressors like the People's Republic of China (PRC), Russia, and Iran hope they can convince neighbors to accept their demands for access, influence, or territory. And if coercion proves unsuccessful, these revisionist powers could employ long-range precision weapons as part of a military offensive to achieve their objectives.

Although formidable, long-range weapon and sensor complexes like that of the PRC would not be impenetrable. For example, countermeasures and stealth capabilities could degrade the ability of enemy sensors to target and communicate the location of US ships or aircraft, and self-defense systems could prevent small attacks from being successful. As Figure 1 suggests, against the larger strikes likely to be mounted during war, US ships, aircraft, and bases could also be positioned farther from enemy missile batteries to shrink weapon salvos to within US units' defensive capacities.[3] However, reducing their detectability and attacking from longer ranges would reduce the number and intensity of effects US ships or aircraft could generate. Consequently, adversary leaders

Photo: F/A – 18E Super Hornet airplanes preparing to launch from the Nimitz-class aircraft carrier USS Harry S Truman (CVN 75), Mediterranean Sea, May 13, 2018. Image Courtesty Mass Communication Specialist 3rd Class Kaysee Lohman/Released. (Photo by Smith Collection/Gado/Getty Images)

Figure 1: PRC Weapons Capacities and Ranges



PLA strike aircraft in 2030		
System	Total aircraft	Aircraft employed
JH-7A/A2	180	90
J-10B/C	160	80
H-6K/N	205	102
JH-XX	80	40
H-20	40	20
Source: Hudson estimate based on reported trends in 2021 DoD China Military Power Report and IHS Janes.		

Source: The authors based on data and information gathered previously by others.[2]

may have greater confidence in their ability to win a war on acceptable terms.

PRC, Russian, and Iranian anti-access capabilities also enable "gray zone" aggression. Effectively confronting these sub-conventional operations requires small US units or groups that allies and partners in the region would not view as disproportionate or overly provocative.[4] To be credible, however, US forces intent on countering gray-zone aggression should also be survivable enough to avoid being easy targets of a preemptive attack by long-range sensors and weapons. As a result, US force packages generally are too large and well-defended to proportionally counter gray-zone operations, surrendering rungs on the escalation ladder to an opponent.[5]

The intent of the U.S. Air Force's and Navy's Next-Generation Air Dominance (NGAD) programs is to counter the impact of adversary sensor and weapon networks by allowing US air forces to operate against more challenging threats and at longer distances from airfields or aircraft carriers, aims NGAD would accomplish by replacing today's front-line fighters with a combination of manned and unmanned systems centered on a new, sixth-generation manned aircraft.[6] Operationally, the NGAD programs would use unmanned systems to degrade adversary sensors and communications, find enemy forces, and attack targets. Manned NGAD aircraft would manage the actions of unmanned systems and deliver effects when needed because of their greater capacity or ability for more direct operator control.[7]

The services' NGAD plans will present a challenge to the Department of Defense's (DoD) acquisition processes and management structures, which are designed to define, buy, test, and operate discrete platforms or equipment and do not easily accommodate development of recomposable systems of systems (SoS).[8] In light of past SoS failures, including the Army's Future Combat System (FCS) and Navy's Littoral Combat Ship (LCS) program, Navy and Air Force leaders tend to emphasize NGAD's new manned fighters while de-emphasizing the broad family of systems that would also contribute to their respective NGAD programs.[9]

While an aircraft with greater reach and survivability would clearly be useful in the face of improving air defenses and longer range ballistic or cruise missiles, focusing Air Force or Navy NGAD programs on their manned components would be unlikely to deliver more than an incrementally improved version of today's fighters. As counter-air sensors and missiles are easier and less expensive to advance than manned aircraft, whatever edge manned NGAD aircraft might provide would be fleeting and evolving them to stay ahead of adversaries would likely be unaffordable and late-to-need.[10] Sustaining the survivability, reach, and lethality required from the DoD's NGAD program will depend on an array of offboard systems that can independently change and evolve to exploit emerging technologies and avoid presenting opponents with predictable formations and capabilities.

Despite the limited speed of advancement and possible high cost associated with new manned fighters, the Air Force and Navy still need to replace aging F-22s and F/A-18 E/Fs, and automation has not yet matured sufficiently for unmanned aircraft to conduct the full range of air warfare in highly contested environments. The services' NGAD programs will therefore need to develop affordable manned aircraft alongside a recomposable set of organic and offboard sensors, weapons, computer processors, and unmanned vehicles.

To achieve the agility required to counter evolving threats, Navy and Air Force leaders will need to focus their NGAD programs first on software and mission systems and second on manned and unmanned platforms, a departure from historical DoD acquisition practice. NGAD could thus pioneer a new method for military SoS development, which this report describes in the context of the Air Force NGAD program. Prioritizing NGAD's software ecosystem and using it to integrate the program's elements could yield a capability able to respond to an opponent's actions and create surprises that dissuade adversary aggression, which is ultimately the objective of US force development efforts.

CHAPTER 2. NGAD SHOULD BE A TEAM, NOT A FAMILY

The need for the Air Force NGAD program's elements to develop independently—while also being able to combine in novel compositions—suggests that it should more closely resemble a team rather than a family of systems.[11] Families generally are born and develop together, remaining highly integrated over their lives. In contrast, the NGAD team, like its human counterparts, would assemble to execute a series of operations—or plays—and later recombine in new formations to conduct other plays. And, as with human teams, the NGAD program's elements could exhibit emergent behavior, creating new plays based on interactions with each other or with adversary forces.[12]

Developing NGAD to be an evolving team employing previously undefined tactics runs counter to the predominant decision-making processes currently used by the DoD. At the strategic level, American dominance following the Cold War inspired resource and operational planning methods that assumed US capabilities would almost always be qualitatively superior to those of opponents. The DoD could therefore establish relatively static operational concepts, tactics, and material requirements well in advance of a conflict, allowing efficient training and preparation alongside methodical pursuit of next generation equipment. Despite the arrival of innovative peer adversaries, the DoD retains this same basic approach of developing the force around predictions of future need.[13]

At the operational level, US military adaptation is constrained by a lack of organizations and infrastructure required to integrate force packages other than those prepared for deployment by the military services themselves. The Joint All-Domain Command and Con-

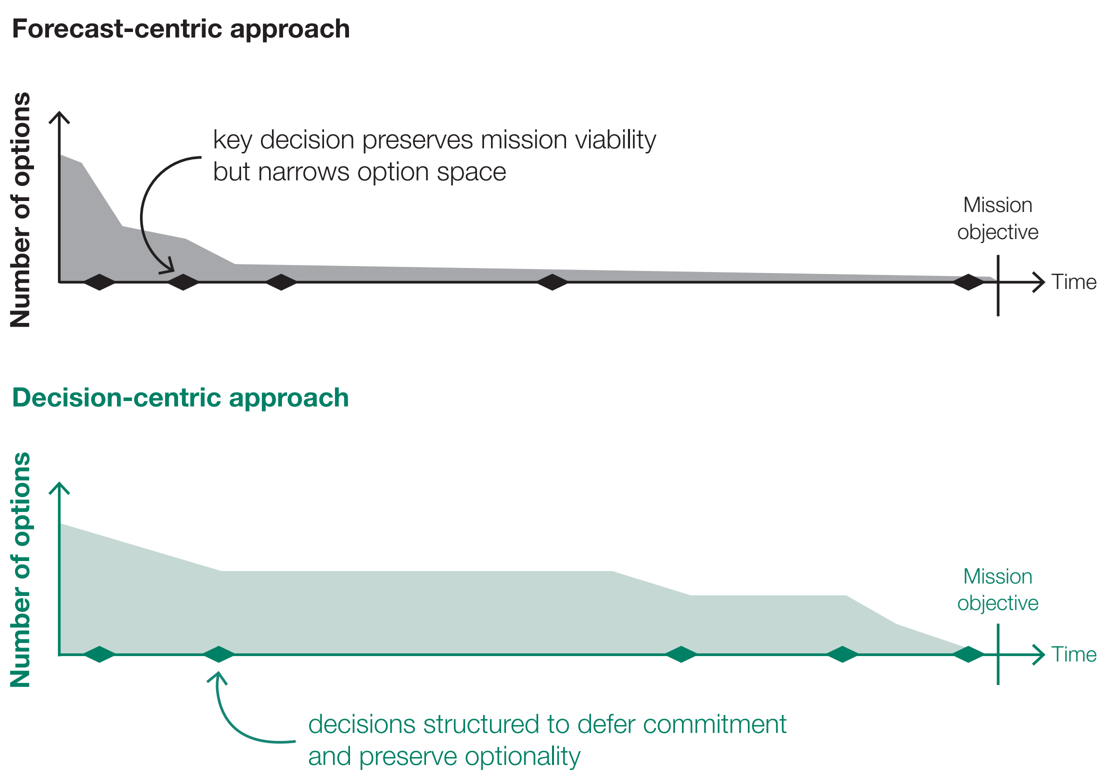
Photo: An F-22 Raptor and two A-10 Thunderbolt IIs fly overhead before landing at Ämari Air Base, Estonia, Sept. 4, 2015 as part of a brief forward deployment. (U.S. Air Force photo/ Tech. Sgt. Ryan Crane) trol (JADC2) initiative is intended to address this gap but, due to its reliance on universal standards and a top-down management approach, is unlikely to deliver a DoD-wide solution within this decade.[14] JADC2 is producing some examples of joint integration at the tactical level through experiments led by the military services as part of the Navy's Project Overmatch, the Army's Project Convergence, and the Air Force's Advanced Battle Management System (ABMS). These successes, however, highlight the tactical constraint on US military courses of action (COA)—a lack of interoperability and decision support tools for commanders in the field.[15]

When it was the dominant global military, the DoD could afford to depend on static doctrine and slowly evolving systems. Against peer adversaries like the PRC, however, military superiority will increasingly need to emerge from operational innovation rather than a qualitative technological edge. And with the leveling of military technologies demonstrated by recent conflicts in Nagorno-Karabakh and Ukraine, US forces may need creativity to gain an advantage against even regional opponents such as Iran or North Korea.[16]

Overcoming Disadvantages through Optionality

Using the DoD's post-Cold War planning approach to develop NGAD would require accurate predictions of the threats and scenarios US forces would likely face and the operational concepts they would employ. When the US military and its weapons systems were dominant, relying on such forecasts was

Figure 2: Forecast-Centric vs. Decision-Centric Acquisition Approaches



Source: Authors.

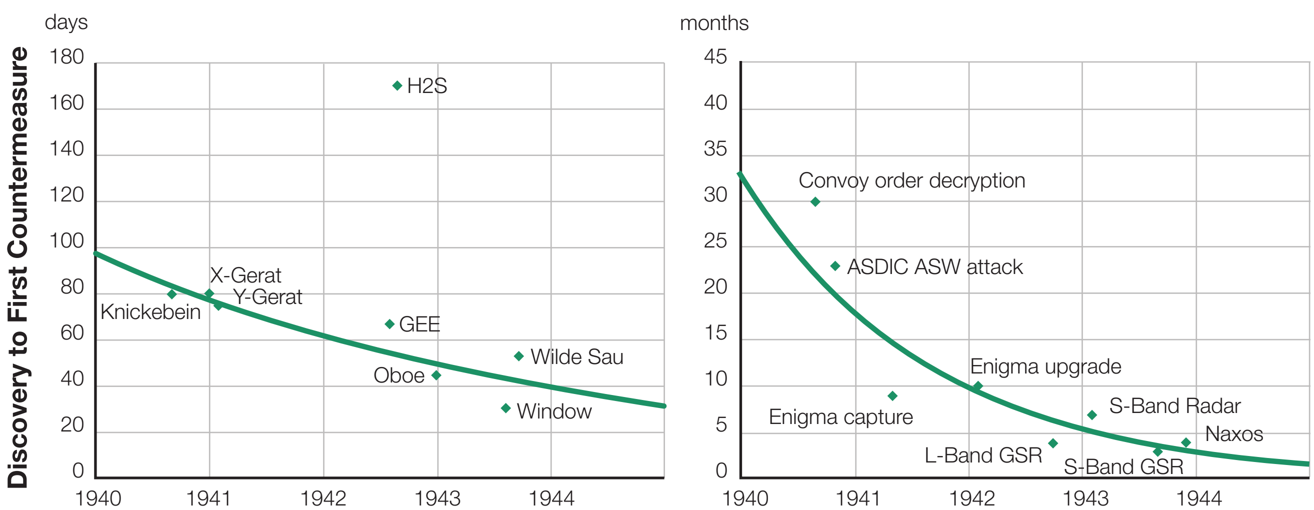
not unreasonable because opponents would only be able to challenge US forces through a narrow range of scenarios and capabilities.

However, peer adversaries like the PRC can challenge US and allied militaries using a diverse array of threats. The US reliance on a forecast-centric approach eases China's planning burden and reduces its uncertainty, undermining US efforts to deter aggression. As shown in Figure 2, the DoD should instead pursue programs that afford commanders more options compared to opponents and thereby provide a decision-making advantage. In such a decision-centric acquisition process, systems would be built in ways that allow them to more easily change their configuration and incorporate new technologies. Although a decision-centric acquisition approach would likely be less efficient than building a well-defined and tightly integrated SoS, the resulting adaptability and resilience of the program would more than compensate for the cost in terms of efficiency.

To succeed in likely future operating environments NGAD should embrace a decision-centric approach incorporating a flexible team of manned aircraft, unmanned vehicles, and mission systems. By itself, a manned aircraft—even a sixth-generation one—would be challenged to remain untargeted in enemy airspace while generating useful effects due to its payload or capacity limitations, outer mold line, and emissions. In highly contested environments, offboard unmanned vehicles could help sense the environment and attack targets, but the NGAD SoS composition cannot be static, or it would result in a predictable set of characteristics that adversaries could quickly counter. Commanders therefore require the ability to change tactics and system configurations up to the time of mission execution.

In addition to being operationally valuable, adaptability is important over the course of a campaign or war. Historically, military competitions have turned on the ability of one combatant to introduce new capabilities and concepts more quickly than an

Figure 3: Time to Introduce Operational or Technical Innovations During the World War II Bombing Campaign Over Germany (Left-Hand Plot) and the Battle of the Atlantic (Right-Hand Plot)



Source: Stillion and Clark.[17]

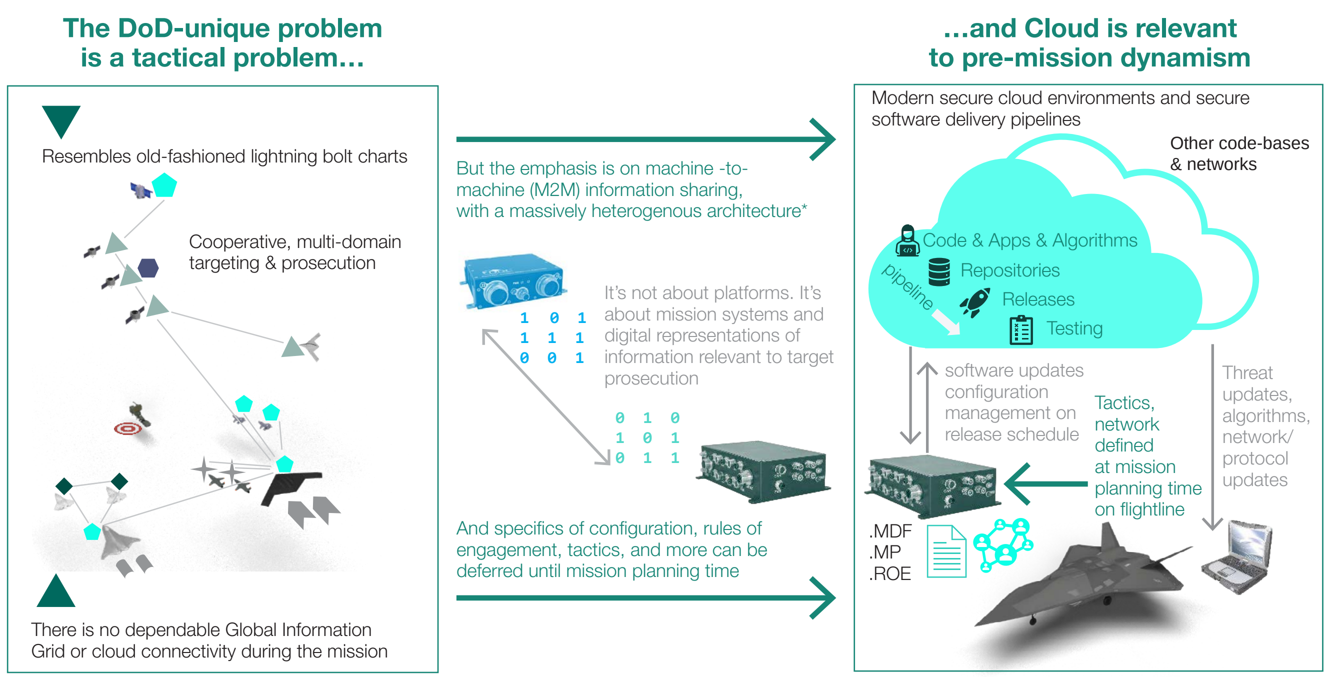
opponent. The left side of Figure 3 shows, for example, the competition of the US and German militaries in air navigation and air defense, respectively, during the bombing campaign over Germany. The right side of Figure 3 shows the US and German forces' implementation of new anti-submarine warfare techniques and systems compared to advances in submarine evasion technologies. In both competitions, the time between the development of measure and countermeasure shrank during the war, suggesting that the ability of one side to field operational and technical innovations more quickly than the other constituted an advantage.

NGAD as an Optionality Engine

The above discussion suggests adaptability will be a more important attribute of NGAD than traditional performance measures such as speed, range, or survivability. Inside highly contested areas where the kinematics of anti-air missiles far exceed levels human operators can endure, greater speed and maneuverability are of reduced value. And, although longer range and greater survivability compared to current fighters would be helpful in pushing closer to targets protected by overlapping air defense complexes, tailored and scalable multi-vehicle force packages would be more effective at sensing and engaging targets over long distances in high threat areas compared to the small number of manned multimission aircraft US commanders could afford to deploy on a single operation.

The ability to build force packages from a wide variety of manned and unmanned systems will also address a limitation of approaches like "Loyal Wingman" that expands the capacity of a manned

Figure 4: The Transition from a Pre-Configured Family of Systems to an NGAD Ecosystem



*I.e. mission systems and internal logic processors are non-uniform and not designed with a requirement to interoperate

Source: Authors.

ship or aircraft by coupling it with an unmanned platform.[18] Under this model, the unmanned vehicles would require approximately equal range, speed, and survivability to their manned counterparts, resulting in them having similar costs per pound of payload.[19] In the approach proposed here for NGAD, unmanned vehicles would not be coupled with the manned NGAD aircraft and would instead team with it when needed. Unmanned systems in the NGAD team could be deployed by the manned NGAD aircraft, by other aircraft or ships, or from remote shore facilities, which would allow the unmanned vehicles to have shorter ranges and lower speeds. Because they could be smaller and less expensive, unmanned systems participating in NGAD could also be more expendable than their manned teammates.

The growing need for adaptability thus drives NGAD toward being a collection of digitally connected mission systems hosted on a combination of manned and unmanned vehicles. Previous DoD efforts to coordinate the fielding of multiple interdependent systems such as LCS and FCS were plagued by the varied development timelines and communication capabilities of their constituent systems. The NGAD program will need to employ an acquisition approach explicitly designed to support changing system compositions from development through fielding and operations.[20]

NGAD's ability to use diverse combinations of manned and unmanned platforms would enable it to counter enemy anti-air threats. However, fully exploiting the option space available with NGAD would require US forces to implement new tactics in concert with new systems or compositions. NGAD will resemble a software-defined team in which tactics, force packages, and networks could change up to and during mission execution rather than a relatively static SoS or family of systems.

The dynamism NGAD would require in tactics and composition would also necessitate a reversal of the traditional paradigm used in military SoS development, which—to use terms drawn from computer science—is akin to "compile-then-compose," where compilation entails translation of the programming language used by humans into executable files a computer can employ and then verification the program works. In DoD SoS development, mission systems or vehicles are developed and built independently, or "compiled," and then composed into defined force packages such as an E-3 airborne warning and control system (AWACS) aircraft with F-15 fighters. Issues with the compile-then-compose model arise when SoS elements change or when interfaces do not perform as expected, such as when Link-16 systems prove incompatible with each other due to version control discrepancies.[21]

The range of SoS configurations possible under DoD's existing requirements approach is limited by the need to define specifications for each interaction between SoS elements during development and acquisition. Because military services build their crewing and training plans around the range of available unit compositions and system characteristics, the diversity of tactics is therefore also constrained. For example, the U.S. Air Force is pursuing greater recomposability through programs such as Skyborg and is collaborating with the Royal Australian Air Force on its Loyal Wingman concept.[22] These SoS approaches would use unmanned air systems (UAS) to carry weapons, conduct electromagnetic warfare (EW), or act as sensors for manned aircraft. Although they modestly increase the diversity of possible force packages and COAs, these concepts are being implemented in each program through the synchronized development and acquisition of manned and unmanned platforms, which will constrain the variety of possible configurations and tactics available to a future commander.

In contrast to traditional DoD SoS development, a dynamic team like that needed from the NGAD program would "compose-then-compile." Under this approach, shown in Figure 5, aircraft and mission systems would be loosely coupled during development with the ability to adjust the configuration of their software-defined command, control, and communications (C3) capabilities during mission planning. In this model, the specific composition of mission system, airframes, support systems, and even hardware board versions might remain unknown until the mission planning cycle began. When an operation is imminent, mission configuration software would be defined and configured ("compiled") for the entire force package, thus ensuring interoperability between elements. Mission configuration software would also be used to digitally verify the complex interactions between elements.

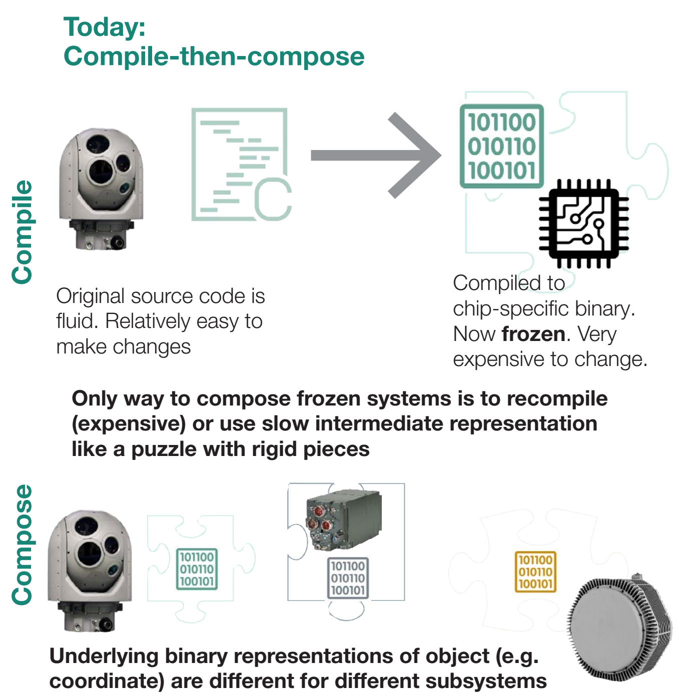
A shift to "compose-then-compile" became possible only recently due to the prevalence of digital systems and engineering—driven in part by commercial technology development.[23] Unlike the Cold War generation of analog aircraft, NGAD program elements will communicate and share data via interfaces which, along with the mission systems and vehicles themselves, are controlled by software—even if overseen by a human operator. Recomposability in NGAD would therefore depend on machine-to-machine (M2M) communications like that in modern software-defined networking for enterprise applications.[24] And, as in commercial use cases, cloud computing could host the pipeline for software delivery, maintaining version control as well as providing a shared development environment for diverse capability contributors.

The DoD's compile-then-compose approach is assumed to be a low-risk path to SoS development because it allows software to be fully tested before a system is fielded and integrated with other SoS elements. However, the combinatorial complexity of software makes comprehensive pre-configuration testing an illusion. A more effective method would be to rely on digital verification tools that could be employed after a force package is composed for a mission as part of the compose-then-compile process.

Implementing Compose-then-Compile

Compared to the relatively static force compositions possible through coordinated acquisition, compiling the software-de-

Figure 5: Evolving SoS Approaches to Exploit M2M Communications



Source: Authors.

fined networking and tactics associated with a particular NGAD composition at the time of mission execution would allow commanders to better tailor force packages for specific targets and tasks. As shown in Figure 6, the ability to compile force packages in mission time would also enable greater elasticity in force compositions after a mission is underway as well as more efficient use of a given set of mission systems and manned or unmanned vehicles.

Rather than centering on combinations of platforms as in today's SoS, the focus of NGAD force composition during COA development would be the mission systems carried by platforms, as shown in Figures 6 and 7. Just prior to mission execution, NGAD's distributed C2 system would decompose each platform's functions by mission system and develop a COA that best exploits the available elements to accomplish the objective. The COA would prescribe tactics, assign functions to each mission system on each platform, identify the network configuration to be used, and define the appropriate autonomy approach—or the relationship between human operators and robotic systems.

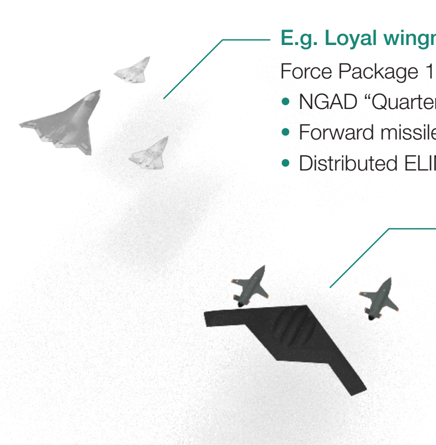
Although the vehicles and mission systems participating in NGAD could rely on substantial amounts of hardware to receive or transmit information, relocate, and generate effects, like most of today's military systems they would all be managed and operated via computers. The challenge of configuring and allocating resources among NGAD elements would therefore be similar to a distributed computing problem.[25] In this model and as shown in Figure 8, COA development would include the interrelationships between elements with respect to communication, data sharing, decision-making, and resource allocation.

This NGAD construct would also represent a heterogeneous computing environment. Developing unmanned aircraft in concert with their manned counterparts as in the Loyal Wingman program is intended, in part, to allow them to use a unified computing architecture. However, co-developing a set of unmanned

Figure 6: Comparing Fixed and Dynamic Resource Allocation in COA Development

Avoid Rigid, Fixed Role & Functional Allocations

- Difficult to coordinate during acquisition process
- Limits future combat options –new operational concepts, surprise



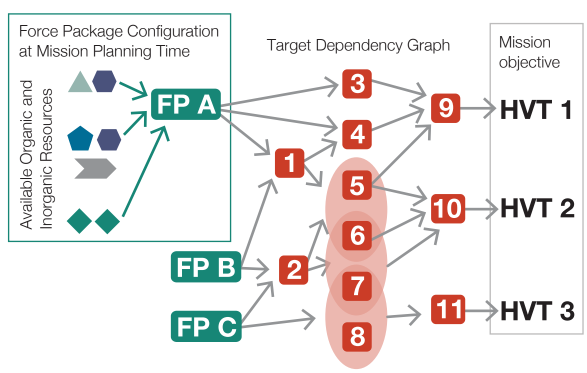
E.g. Loyal wingman

Force Package 1
- NGAD "Quarterback"
- Forward missile trucks
- Distributed ELINT

E.g. Unmanned Escort

Force Package 2
- LRS "homebase"
- sensing escorts

Dynamic resource autonomy model



Preserve elasticity in mission planning via basket of techniques
- Planning to kill boxes not specific locations
- Multi-function arrays allow backup communications paths
- Autonomy configuration and rules of engagement

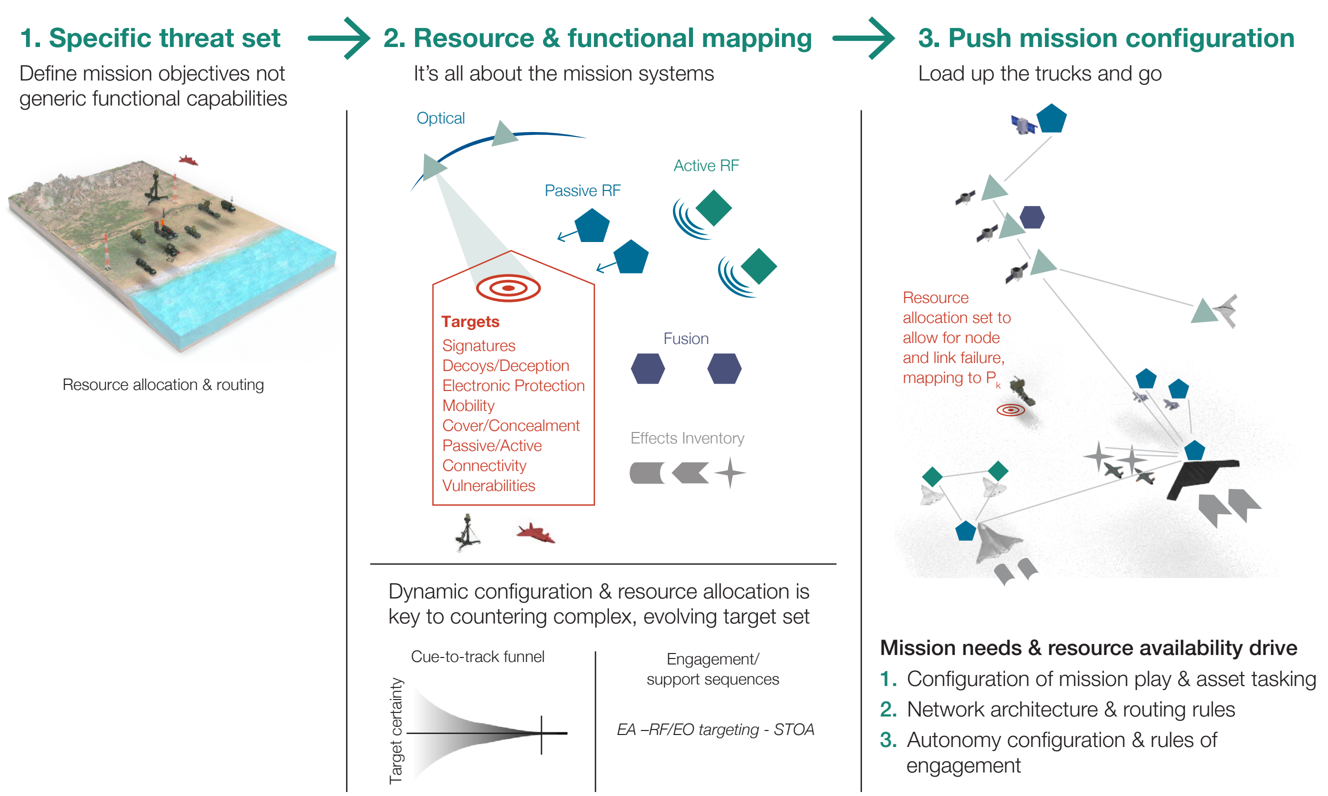
Source: Authors.

and manned aircraft could significantly constrain the ability of other vehicles or systems to participate in force packages, thereby creating more predictability for opponents and affording less operational innovation for US commanders. To enable more diverse combinations of units, the compose-then-compile paradigm would assume that the exact combination of participating computing nodes would be unknown months or even years in advance. Instead, force package composition, autonomy relationships, network configuration, and other parameters would be compiled and distributed as part of mission planning. Mission planning would also use virtual and constructive techniques to define tactics, bound within the set of COAs approved by operators based on their experience and training.

This same conceptual approach to managing large-scale operations of critical distributed information systems is employed in core enterprise networks or other modern information systems. Since having identical hardware and software in every component of a large-scale system such as a 5G network is impossible, operators instead use a network management system that keeps track of components and periodically pushes new configurations and updates to maintain compatibility.[26]

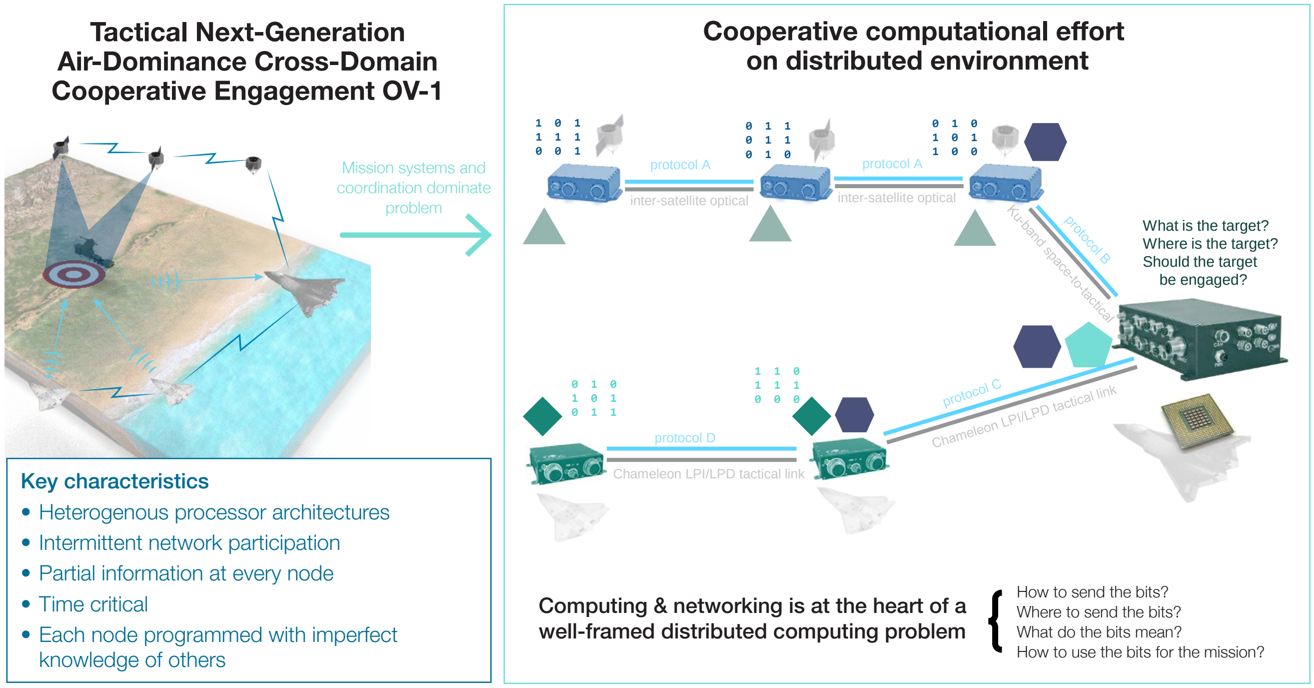
The need for heterogeneous distributed architectures will only grow as operating environments become more contested. For example, participating units will need to change the operating characteristics they present to the network when damaged or lost due

Figure 7: Preferred COA Development and Implementation Process



Source: Authors.

Figure 8: NGAD Viewed as a Distributed Computing Problem



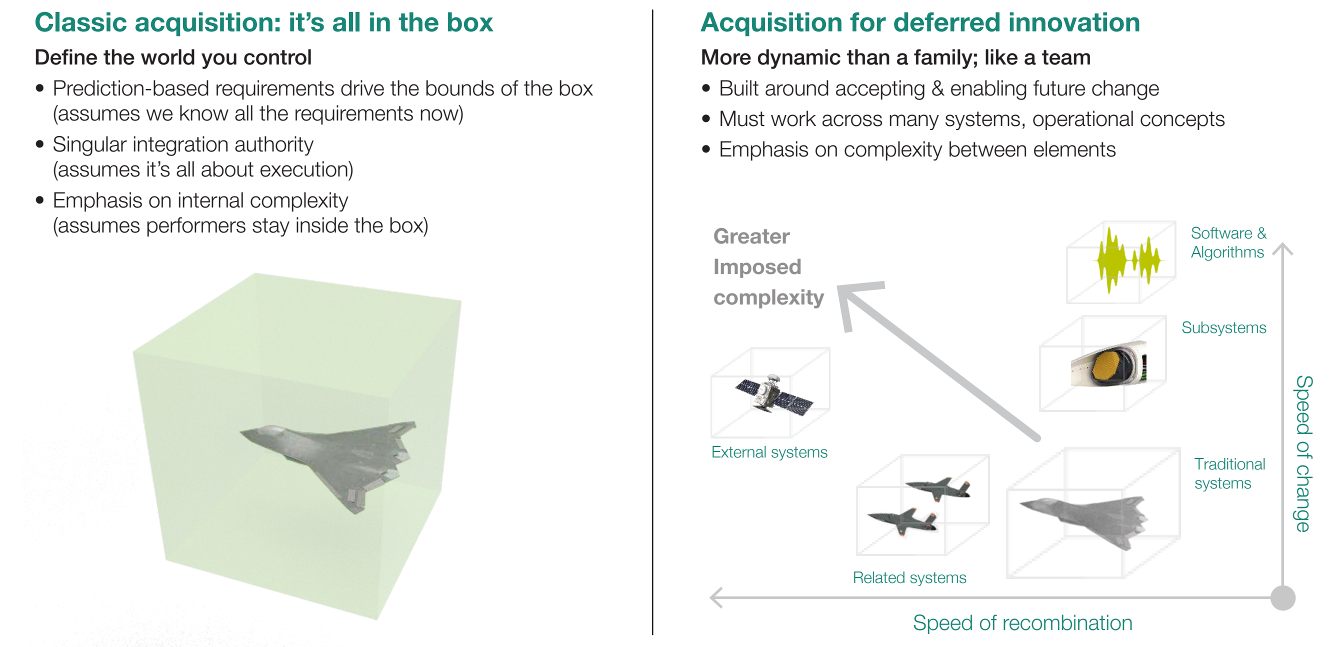
Source: Authors.

to enemy action. Units may need to join and leave the network more frequently during a mission to degrade enemy sensing and understanding, engage targets, or sustain communications within and external to the force package. And, as threats intensify, a more distributed force will likely be necessary to reduce the threat to manned aircraft and generate effects over wider areas.

The need to treat NGAD primarily as a heterogeneous, distributed computing problem should reverse the DoD's traditional development process, whose primary focus is the hardware system being developed or procured and which views networking and computing as supporting elements only. In contrast, an alternative perspective on NGAD shown in Figure 9 starts with the computing and network structure and develops participating systems to work within that ecosystem.

Additionally, viewing NGAD as a team rather than a family would enable elements to materialize and change over different timelines. For example, NGAD's manned aircraft would emerge from the traditional acquisition process over a decade or more. Its subsystems—radars, mission computers, and countermeasures, for instance—would be co-developed but could be changed and updated at a relatively higher tempo than the aircraft itself or its parts. Related systems such as unmanned aircraft, air-launched effects (ALE), and weapons would be fielded independently over short timelines of months to years.[27] External systems like satellite constellations would develop asynchronously from NGAD through independent processes. Most importantly, software and algorithms needed to integrate the NGAD elements would continuously evolve through combined development and operations (DevOps).[28] In this model, it might be possible to evolve com-

Figure 9: Alternative Views of NGAD Acquisition



Source: Authors.

munications waveforms, sensing modalities, cooperative tactics, and electronic warfare modes over a timeframe of weeks or even between sorties based on threat evolution.

Focusing the NGAD program on relationships and connective software between its elements rather than hardware platforms and systems reflects a commercial approach conceptually, although the components and algorithms employed would largely be unique to the military. This approach would stand in stark contrast to the DoD's traditional acquisition processes, which carefully attempt to define a program's bounds early in its development to ease management and budgeting. Assembling a flexible team of NGAD systems would demand a shift from focusing on large multimission platforms to instead first identifying the software-based ecosystem that would integrate NGAD elements and then building hardware and applications within it. This approach is like that employed today by thousands of commercial technology companies working in operating systems from iOS to Linux and using shared development environments that include testing and tools such as shared code repositories and continuous integration.[29]

CHAPTER 3. BUILDING THE NGAD ECOSYSTEM

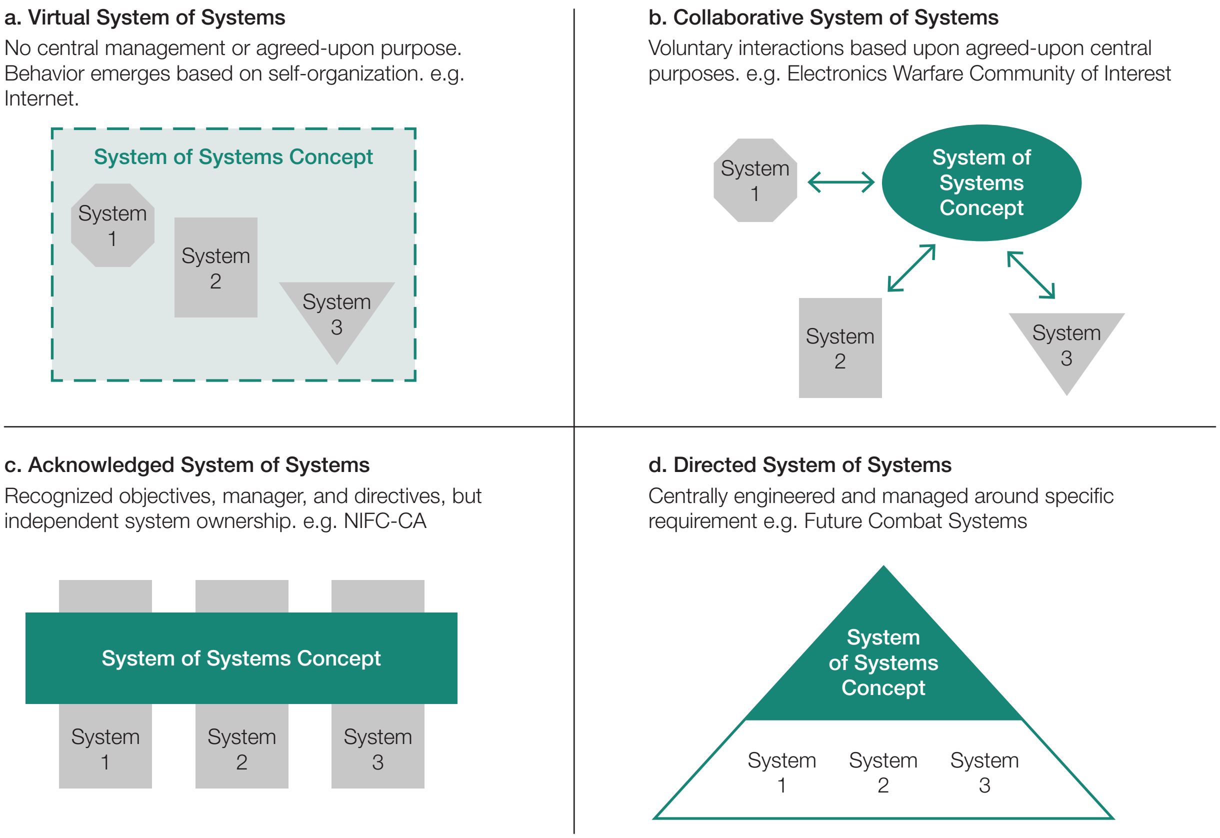
NGAD would be a type of SoS in which future aircraft interact with new and existing mission systems and weapons, space-based capabilities, advanced automation, and human battle managers and pilots. But, in contrast to current DoD SoS structures and like other teams, the NGAD program would need to be agile and recomposable over both mission timeframes and the service lives of its component elements. Foreseeing every mission-system, force-package, and sensing-capability combination that would be useful in and relevant to a given future air-dominance mission is simply not possible. Therefore, to create a team capable of being operationally relevant and surprising future opponents, NGAD would need to incorporate features from each of the four existing types of DoD SoSs: virtual, collaborative, acknowledged, and directed.[30] These are depicted in Figure 10 and described in detail below.

A *virtual SoS* lacks a central management authority and a centrally agreed-upon purpose. It is the least cohesive form of SoS, which facilitates the addition of new participants. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain itself. And, because it does not integrate its component systems, it also offers the least potential performance improvement over individual systems.

The US economy is an example of a virtual SoSs.[31] A broad operational concept establishes basic procedures and rules, but a virtual SoS generally does not define technical specifications,

Photo: The littoral combat ships USS Independence (LCS 2), left, and USS Coronado (LCS 4) are underway in the Pacific Ocean. (U.S. Navy photos by Chief Mass Communication Specialist Keith DeVinney/Released).

Figure 10: Taxonomy of Systems of System Types



Source: Authors.

intended participants, or specific objectives. The ability of multiple independent systems to cooperate with one another in a virtual SoS enables them to achieve greater effect than each could independently, but the capabilities of the participating systems used in combination are largely unknown when each system is being developed. NGAD would need to reflect the flexibility of a virtual SoS but would also depend on the ability of the constituent elements to share data and tightly coordinate their actions as in other types of SoSs.

In a *collaborative SoS*, the component systems interact voluntarily to fulfill agreed-upon central purposes. Its operational concept describes the SoS's broad goals and the procedural and technical processes for participation but does not specify its intended components. An example of a collaborative system is the internet, where protocols for participating are established in advance and component elements can change.

Military tactical data networks could also be characterized as collaborative SoSs.[32] They can be used for a wide range of missions; participants can enter or leave as needed or desired; and the size, scope, and component systems in the SoS change over time and with each new operation. However, networks like CDL or Link-16 operate according to strict standards, and messaging formats are highly prescribed. As a result, SoSs built around most of the DoD's current networks are constrained in the number and diversity of components that can be incorporated. An NGAD program would need to capture the interoperability and potential for data sharing of a collaborative SoS but without the constraints associated with the DoD's current network architectures.

The *acknowledged SoS* is the most common type pursued today in the DoD. Acknowledged SoSs have recognized objectives, a designated manager, and dedicated resources. However, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Interoperability between component systems in the acknowledged SoS is achieved and sustained by individual program managers, who must collaborate with each other and with the SoS manager to ensure their respective requirements remain in alignment.

An acknowledged SoS has the advantage that the component systems are independently developed and so can also operate outside the subject SoS. Although in modern military operations this normally means that component systems can operate as part of another SoS, they may sometimes operate independently outside any SoS. The disadvantage of this approach is that the component systems are not optimized to exploit the capabilities that other systems that are also part of the SoS bring, likely resulting in higher costs and decreases in overall capability.

In contrast to virtual or collaborative SoSs, an acknowledged SoS has a defined set of component systems that may change over time as systems are replaced or new applications are identified for the SoS. An acknowledged SoS's operational concept describes its objectives, how its component systems interact with one another, and the resulting requirements for those systems. An example of an acknowledged SoS is Navy Integrated Fire Control-Counter Air (NIFC-CA), which uses the Cooperative Engagement Capability and Tactical Targeting Networking Technology datalinks to integrate Aegis ships and E-2D Hawkeye early warning aircraft. Accessing the E-2D's radar allows surface combatants to engage air threats using SM-6 surface-to-air missiles well beyond the launching ship's radar horizon.[33]

A significant challenge with an acknowledged SoS is the time to field a useful combination of independently developed systems. The Navy's NIFC-CA capability took more than 20 years to emerge, and the DoD cannot wait multiple decades for NGAD to yield a minimally viable product. Therefore, development of NGAD would likely require more coordination between its architectural and physical elements compared to NIFC-CA.

Lastly, a *directed SoS* is built and managed to fulfill defined purposes with a specific set of systems. Under a directed SoS approach, each element can be refined to exploit characteristics of other participants in the SoS. A directed SoS is centrally managed during development and in operation to continue to fulfill the purposes for which it was constructed as well as any new ones the system owners wish to address. The component systems maintain some ability to operate independently, but their normal operational mode is subordinate to the centrally managed purpose.

An example of a directed SoS is a multi-mission platform such as a fighter aircraft or a combatant ship. In each platform, the system integrator identifies the component systems, e.g., sensors, weapons, and propulsion equipment, to be incorporated into the platform and manages their development until the platform is fielded. A lack of duplication of its component systems benefits the platform's overall capability, and program managers can gain cost efficiencies by ensuring that their platform's component systems leverage each other's capabilities.

A directed SoS offers the potential of dramatically improved performance or unique capabilities, but at the cost of flexibility. To sustain the tight integration necessary between elements of the directed SoS, its configuration must be well-defined and only changeable slowly over time.

As pursued by the DoD today, NGAD is most frequently envisioned as a directed SoS, with all the attendant limitations and constraints imposed by that classification. However, to achieve the flexibility and performance required for future air dominance, the NGAD team will need to combine the synchronization possible with a directed SoS, the flexibility of a virtual SoS, and the programmatic agility of collaborative or acknowledged SoSs.

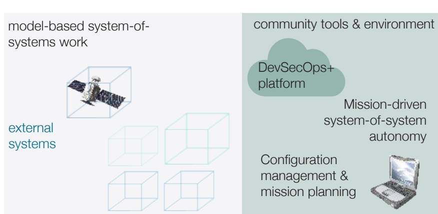
Flipping the Traditional Acquisition Process by Starting with Software

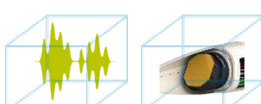
To realize the combination of SoS synchronization and compositional flexibility needed in NGAD, the DoD should move away from a platform-centric or directed SoS approach and should instead focus the program's efforts primarily on development of a software-based ecosystem capable of incorporating a changing combination of mission systems, applications, and platforms.[34] Like a collaborative or acknowledged SoS, the NGAD ecosystem must enable participants to share data and direction, support mission planning and decision-making by human operators, orchestrate the actions of NGAD elements, and afford the interoperability required to recompose NGAD elements over mission time and across the program's lifecycle.

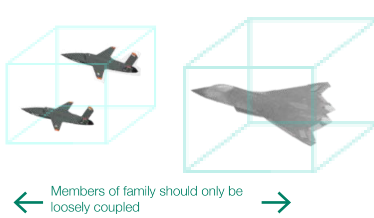
Starting NGAD development at the ecosystem level as shown in Figure 11 is counterintuitive and the reverse of most DoD acquisition projects. Manned aircraft and weapons take years or decades to develop, encouraging technologists and acquisition professionals to initiate an air warfare program by first defining

Figure 11: Process for Defining NGAD Technical Characteristics

mission → drives → mission systems → drives → platform







	Level	Key Considerations	Key Time Constants
mission	Ecosystem Level	• C3 structure • Software & collaboration environment • Cooperative mission autonomy • Mission planning • Network management	Days-Months
mission systems	Mission Systems Level	• Threats • Modalities • Aperture compatibility • Processing capacity • Modularity and upgradability • Software-definition	Months-Years
platform	Platform Level	• Vehicle performance –signature, range, payload • Automated vehicle guidance, navigation, and flight control • Aperture integration • Primary communications integration Compute architecture for flight critical functions • Open architecture provisioning (spare compute, exposed interfaces)	Years-Decades

Source: Authors.

platform requirements and then following with the mission systems and networks needed by the platform to operate.

By beginning its development with its software ecosystem, a NGAD program could avoid constraints imposed by the hardware associated with its initial platforms. For example, a specific fighter aircraft like the F-22 is limited in the number and type of electromagnetic apertures it can incorporate; the space, weight, power, and cooling (SWAP-C) available for mission systems; and the size and shape of payloads it can carry internally and externally. Building an SoS around the F-22 would necessarily constrain its initial C3 construct in terms of such characteristics as communications bandwidth, processing power, data sharing, distributed computing, and sensor modality and capacity. The modest degree of change possible in the F-22 itself and its payloads would constrain future options.

Reversing the traditional acquisition process to start with the software ecosystem is consistent with commercial technology development. The forms in which such enterprise software packages as Salesforce Customer Resource Management and commercial operating systems like Apple iOS were first deployed provided the minimum needed functionality for initial platforms like the iPhone but also incorporated procedural or protocol-based interoperability that allowed for a variety of future applications and hardware. The C3 systems and attributes were then evolved using a DevOps process to introduce additional functionality or incorporate a more diverse array of user equipment such as iPads and Apple Watches.

Modularity Enables an Ecosystem-Centric Approach

Initiating NGAD development with its software ecosystem creates program-management challenges. The initial C3 construct, mission planning tools, and decision support programs need to work with NGAD's inaugural collection of platforms and systems and then accommodate continued evolution of both the ecosystem and its participants to embrace new technologies or address emerging threats. As noted in Figure 11, however, the program's ecosystem and component mission systems or platforms will likely evolve at different rates. Managers will therefore need to build the beginning C3 constructs or mission planning software without fully knowing the characteristics of the NGAD's initial participants, and, at the same time, platform developers will have to construct weapons and systems over years to work with an ecosystem that could change over days or months.

The solution to these NGAD program-management challenges is modularity. In a modular development process, ecosystem developers—like their commercial counterparts working on iOS or Android—need only establish the appropriate application program interfaces (APIs) to participate in the ecosystem. APIs are not simply static specifications for characteristics such as frequency, data format, or bandwidth; rather, they describe processes by which participants interact with one another, communicate, and share data that are often agnostic as to specific signal or attributes. Developers build and test their components' software with the ecosystem's APIs in development environments such as Apple XCode for iOS or Chrome DevTools for Google Chrome and publish working instantiations of the ecosystem incorporating their components.[35] In a more heterogeneous example, the 3GPP standards for 5G communications are built and maintained in this way.[36]

The use of APIs eases the coordination burden on developers creating the ecosystem and manufacturers of mission systems or platforms. Mission system builders only need to ensure that their sensors, radios, decision support tools, and countermeasures incorporate the appropriate APIs that allow them to interact with the ecosystem. And, because modern aircraft, UASs, or weapons interact with the ecosystem through their digital mission systems, the underlying platform itself does not need to be directly interoperable with the ecosystem.

The key to decoupling platforms from mission systems and from the ecosystem is employment of open architectures.

Figure 12: Examples of Modular Acquisition

Acoustic Rapid COTS Insertion (A-RCI)

Structured around a continuousthread of technology insertions based on commercial processing hardware and evolving algorithms.

Integrator prime style structure:

- Platform integration prime (LM-MS)
- Re-competed every 3 years
- Prime makes interfaces available, subcontracts computing hardware

A-RCI runs across multiple submarine platform classes (Virginia, LA, Seawolf) providing an open and evolving tech stack. Community simulation/test environment provided.

Requirementsownership managed at program office level (NAVSEA) which separately contracts for algorithm development.

MQ-9 Program

Prototype (YMQ-9) delivered for evaluation in 2002. Leads to MS B (ACAT II) in 2004. (fully vertically integrated solution from prime) Extensive evaluationled to many refinements of concept. Seven iteratively refined versionsdelivered by 2007. Multiblock APB USAF begins acquisition planning in 2010

Separate prime contracts:

- GA -air vehicle
- Raytheon -sensor systems
- Ground Station -separately competed to standard

Key community standards:

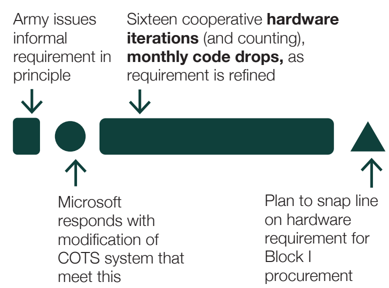
- Universal armaments interface

Requirementsownership managed at program office level –short chain to leadership

IOC: 2015, FRP 2017

Integrated Visual Augmentation System IVAS

Started as an MTA –with no approved formal requirement or acquisition strategy.



Cooperative operational experimentation and testing to discover requirements, iterative development

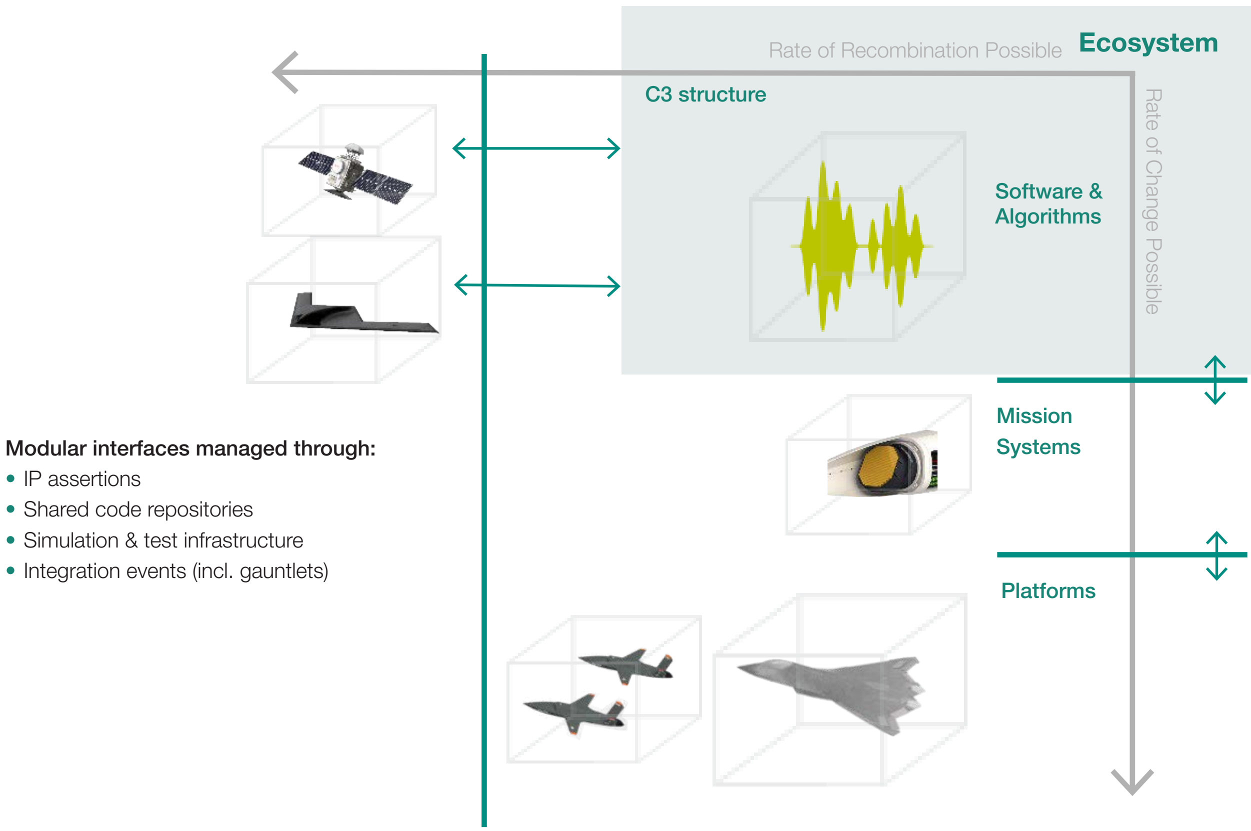
Source: Authors.

The Modular Open Systems Approach (MOSA) embodied in frameworks like the Air Force's Common Open Architecture Radar Programs (COARP) or Open Mission Systems (OMS) and the Army's Future Airborne Capability Environment (FACE) are mandated by law to enable separation of the platform control, guidance, and safety systems from the software associated with the platform's mission systems.[37] However, NGAD will need to not only leverage these approaches to modularity but also employ a compose-then-compile model that avoids the version incompatibility issues that plague current open architecture efforts.

Figure 12 shows two examples of how modularity and open systems have enabled DoD programs to decouple their platforms from their mission systems and, by extension, from their broader ecosystems. By enabling the program office to separately contract and manage development and acquisition of software algorithms, mission system hardware, platform hardware, and networks, each of these programs has evolved over years or decades.

Under the Navy's Acoustic Rapid Commercial-Off-The Shelf Insertion (A-RCI) program, software running on submarine sonar and fire control systems is procured separately from the system hardware and both the software and the combat systems are also developed independently of the submarine. As a result, although multiple submarine classes carry the same combat and sonar system, the BSY-1 for instance, individual submarines may be running different versions of the BSY-1 software depending on where they are in the A-RCI refresh cycle.[38]

Figure 13: Relationships between Elements of an NGAD Ecosystem



Source: Authors.

Like the submarine and A-RCI program, the MQ-9 Reaper UAS carries a changing variety of sensors, weapons, processors, and radios that are developed and built by different vendors and purchased separately from the MQ-9 airframe. The software running on each mission system changes based on the vendor's refresh cycle, but mission systems always integrate with the aircraft's operating system through common interface protocols under an open systems approach.[39]

A key aspect of these programs' modularity is their establishment of boundaries that allow for the varying speeds of innovation between the software algorithms running inside mission systems, the mission system's hardware, the platform, and the overarching C3 and mission planning ecosystem. A-RCI, for instance, adapts sonar or fire control algorithms on an annual basis and evolves independently of the decadal tech-refresh cycles employed for submarines or combat-systems hardware.

A-RCI and the MQ-9 benefit from being contained within existing ecosystems of the submarine or the UAS. As an SoS intended to operate in highly contested areas, NGAD will need to establish its own ecosystem that can also interact with other ecosystems or external systems, as shown in Figure 13. NGAD can set boundaries that allow for the differing rates of evolution possible within each SoS element type. For example, platforms like aircraft and UASs change most slowly and interact with the overall ecosystem via mission systems such as sensors and radios that change over shorter timeframes. The fastest evolving elements will be software programs running on NGAD's distributed computing architecture.

By establishing open and dependable interfaces between platforms, their mission systems, and the ecosystem, NGAD could enable each element to evolve at its own pace given the relevant technological and programmatic limitations. Moreover, interfaces with the NGAD ecosystem's C3 structure could be used to integrate with systems or platforms from outside the ecosystem in order to expand the range of COA options available to commanders.

In addition to providing a framework for technical management, modularity also informs the acquisition approach of open systems. The Integrated Vision Augmentation system shown in Figure 12 began with loose requirements and a period of exploratory development such as that permitted by the Middle Tier of Acquisition[40] and only established firm requirements after completion of prototyping and operational experimentation. In a flexible SoS like NGAD, the functionality, employment concepts, and team composition are expected to evolve even after initial operational capability and in ways that cannot be predicted in an initial weapons system specification or requirements document.

Shifting NGAD development to begin with the program's ecosystem of C3 structures, mission planning tools, and network management systems will increase the likelihood that future commanders will have greater flexibility and survivability compared to today's force. Based on previous military and commercial projects, building a successful ecosystem will depend on defining interfaces, exploiting modularity, and employing open systems approaches. Although messier and harder to manage than building hardware, developing an ecosystem is the only way to achieve the composability needed for NGAD to gain a decision-making advantage.

CHAPTER 4. USING COMPOSABILITY FOR ADVANTAGE

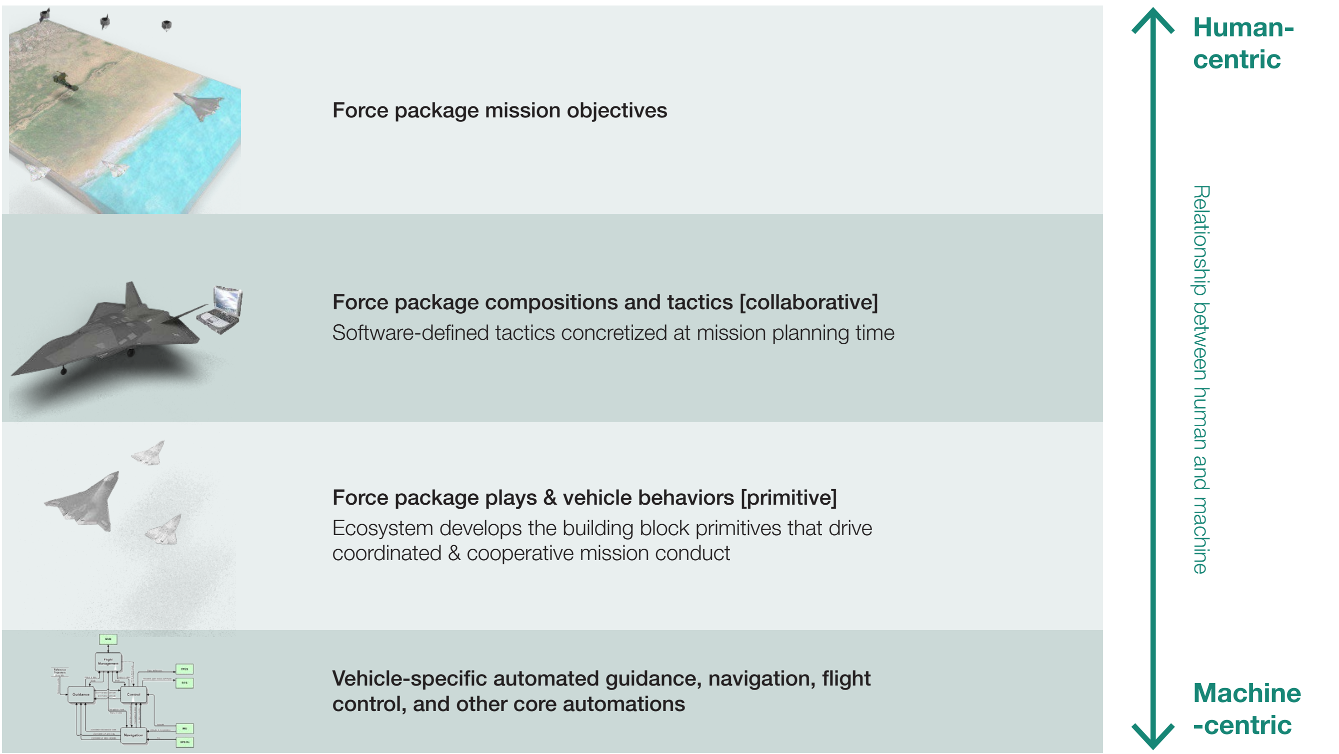
A modular, multi-layer approach to acquisition would enable the NGAD program to incorporate a changing array of platforms and systems over its lifetime, thereby improving its adaptability and continued relevance. Operationally, NGAD's recomposability would provide commanders with more options and create complexity for opponents. Harnessing that composability, however, would require the DoD to adopt a new framework within which to define autonomy, develop COAs, and plan operations.

Autonomy as a Relationship

Increasing the reach, survivability, and adaptability of NGAD will depend on unmanned vehicles and automated mission systems, as well as the computer-aided decision support tools that help commanders build COAs. Accessing the wider range of options and flexibility possible with unmanned or automated systems will only be possible, however, if the DoD allows these systems greater independence. Today, unmanned vehicles like the MQ-4A Global Hawk or MQ-4C

Photo: Airmen from the 432nd Aircraft Maintenance Squadron stand side-by-side in front of an MQ-9 Reaper during their day shift at Creech Air Force Base, Nevada, Aug. 19, 2020. The Airmen and civilian contractors of the 432nd AMXS work around the clock, despite the COVID-19 pandemic, to maintain the MQ-9's mission readiness. (U.S. Air Force photo by Staff Sgt. Omari Bernard)

Figure 14: A Construct for Autonomy in NGAD



Source: Authors.

Triton fly programmed tracks, deviating according to preplanned responses if they lose communications, to avoid weather or traffic, or to investigate sensor readings.[41] Smaller, less multifunctional UASs such as missiles or Miniature Air-Launched Decoys (MALD) operate automatically but do so only within highly circumscribed tactics, techniques, and procedures (TTP).[42]

One of the reasons for the limited operating envelope of unmanned systems is the lack a consistent autonomy construct in DoD acquisition. The term “autonomy” connotes a condition in which a system can operate without outside intervention or support. Very few platforms or systems in the DoD operate with complete autonomy, as even submarines or stealth bombers periodically require offboard sensing or logistics support. On the other end of the spectrum, the MQ-9B Reaper is continuously operated remotely by an offboard pilot and sensor manager.[43]

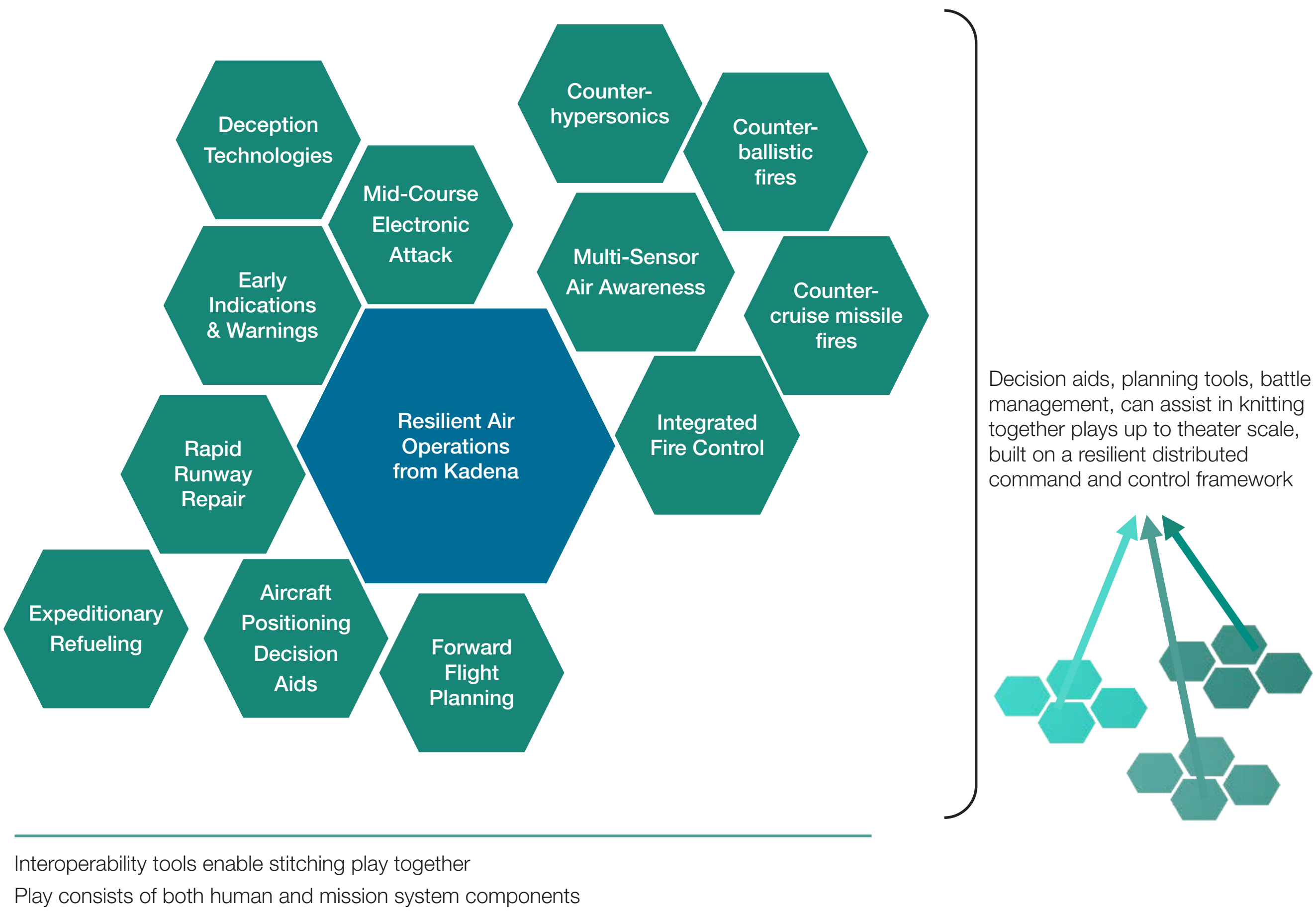
In terms of unmanned vehicles and mission systems, a machine’s autonomy is a function of the amount of intervention by human operators it requires to complete its mission.[44] Thus, autonomy could be viewed as a relationship between humans and machines. As shown in Figure 14, each phase of NGAD’s operations would involve operators working with computer-based systems; as activities move from high-level goal setting to more discrete tasks, the balance of agency shifts away from humans and toward machines.

For NGAD, commanders would identify missions and objectives to be pursued, which operators would then compose into force packages and tactics in collaboration with computer-aided decision-support tools just before or during each mission.[45] The resulting COA, or "play," would be pushed to the NGAD ecosystem for compilation into vehicle behaviors and mission system operations. NGAD's distributed computing environment would develop the specific actions needed by its platforms, payloads, and mission systems to accomplish the play, including identifying steps where the operator would have to intervene to augment the automatic operation of systems, such as authorizing weapons employment or deciding how to proceed when two potential branches of a play are available.

Building Plays through Human-Machine Teaming

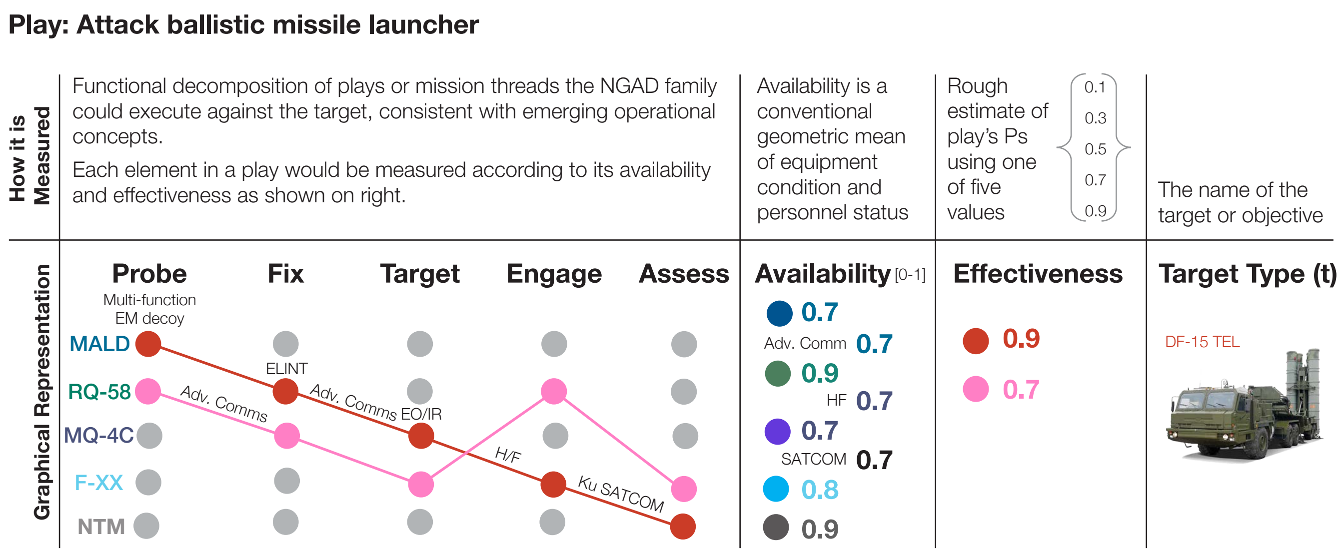
Combatant commanders and their supporting joint force commanders will develop plays to address operational problems that must be solved to succeed in scenarios against such opponents as China or Russia. For example, sustaining air operations from Kadena Air Base in Okinawa would be

Figure 15: Missions Associated with Resilient Air Operations from Kadena



Source: Authors.

Figure 16: Example Plays for Attacking PLA Ballistic Missile Launchers



Source: Authors.[47]

important in almost any scenario involving the United States and China in the Western Pacific. Although a perfect defense of Kadena is unlikely during such a conflict because of its proximity to China, sustaining even a small number of sorties would provide Indo-Pacific Command options to counter PRC aggression and create complexity and uncertainty for PLA planning.[46]

As shown in Figure 15, operations from Kadena could be sustained through a combination of missions that defend against attacks, strike Chinese weapons and platforms before launch, and restore air operations after engagements. Each mission could be conducted by multiple plays. Figure 16 shows two plays that include potential NGAD elements such as the future F-XX fighter and RQ-58 UAS. The information in Figure 16 would come from operators' composition efforts using virtual and constructive modeling and simulation tools to evaluate the different force configurations and concepts of operation that could be employed to conduct the mission. During mission planning, the virtualization of functions for compilation would aid the comparison process by identifying which force packages would be easier or harder to assemble and employ.

Starting NGAD at ecosystem rather than platform level would increase the program's ability to support a wider variety of plays. Fully exploiting that inherent composability, however, would rely on understanding and operationalizing the relationship between the human operator and the machines.

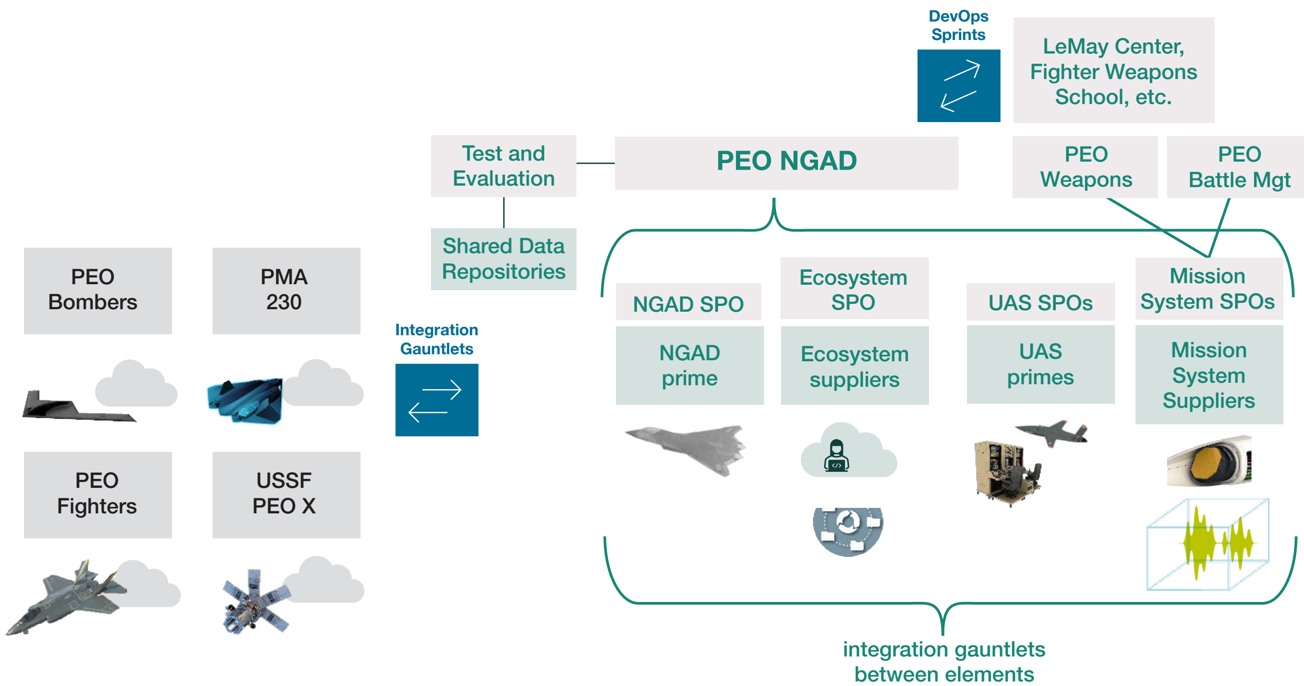
CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

The compose-then-compile approach described above would allow US commanders to adapt NGAD teams in mission time, thereby providing resilience in the face of adversary action and imposing complexity on enemy planning. But enabling compose-then-compile would require that the DoD reverse its normal acquisition priorities, first developing and acquiring NGAD's software-defined ecosystem and then proceeding through its mission systems, weapons, and platforms employing an open systems approach and modularity.

Accommodating the different tempos of innovation possible in hardware compared to software would also require that NGAD program management loosely couple ecosystem, mission system, and platform development. NGAD-related elements should not be executed by unrelated groups but should also not be tightly organized under a single office. Thus, this study recommends that NGAD components at the ecosystem, mission system, and platform levels be developed by different offices overseen by a common executive,

Photo: A F–22 Raptor flies in this undated image provided by Lockheed Martin. The First raptor will join the 27th Fighter Squadron at Langley Air Force Base in Virginia October 27, 2004 after leaving Lockheed's plant in Marietta, Georgia. (Photo by Lockheed Martin via Getty Images)

Figure 17: Proposed Acquisition Structure for Air Force NGAD Program



Source: Authors.

and Figure 17 shows an example of this proposed arrangement for the Air Force.

The proposed construct shown in Figure 17 would reallocate program management responsibilities across Air Force program executive officers (PEOs) to reflect the view of NGAD as a team rather than as an SoS organized around its manned platforms.[48] The current Air Force PEO structure places manned NGAD aircraft, future unmanned aircraft, and existing fighters such as the F-16 and A-10 under the PEO for fighters and advanced aircraft—a construct that reinforces the idea of NGAD's unmanned systems being coupled to its manned platforms. Moreover, PEO Fighters and Advanced Aircraft does not have responsibility for or oversight of the C3 structures or decision support tools that would form the NGAD ecosystem.[49]

The proposed PEO structure would separate NGAD's manned aircraft and UASs from PEO Fighters and Advanced Aircraft and place their system program offices (SPOs) under a new PEO NGAD. Sustainment of existing aircraft like the F-16, F-22, and A-10 would remain under a restored PEO Fighters. Other expendable or attritable UASs that could join the NGAD team—derivatives of Golden Horde or X-61 Gremlins for example—would also be moved from PEO Weapons to UAS SPOs under PEO NGAD. The resulting structure would intentionally place most smaller Air Force UASs under PEO NGAD and leave only such larger UASs as MQ-9 or MQ-4 under their currently existing program management. This approach would allow UAS SPOs to use the software development environment provided by the NGAD ecosystem to exploit the variety of use cases and diversity of mission systems possible with attritable and expendable UASs.

Under PEO NGAD, SPOs would lead the development of NGAD manned aircraft, UASs, and mission systems. Most importantly, the PEO NGAD would establish an SPO to manage development and operation of the software ecosystem that connects and orchestrates NGAD system interactions. This approach would enable flexibility in the configuration of NGAD between missions and over the program's lifespan by avoiding the monolithic prime contract structures common today, in which a prime contractor acts as the lead integrator for a family-of-systems and its associated C3 and mission planning software.

A potential problem with the proposed approach is that UASs could operate with a variety of manned Air Force and Navy aircraft outside of NGAD, including the B-21 Raider and FA-XX, and the NGAD team as a whole would need to work with such external systems as Space Force satellites. To address that concern PEO NGAD would lead regular development gauntlets to ensure continued interoperability between programs being developed under NGAD and existing systems or programs being pursued by other services. As in commercial technology development, a gauntlet would consist of experiments where participating systems were forced to work together in a variety of relevant use cases.[50] Some gauntlets would be strictly virtual, using the NGAD ecosystem to assess the interoperability and effectiveness of potential force compositions. Others would be both virtual and physical, allowing program managers and executives to evaluate logistics, protection, and orchestration challenges between the NGAD team and outside programs.

To support a DevOps approach, PEO NGAD would also conduct periodic sprints in which operators from doctrine and tactics development commands such as the Air University Curtis LeMay Center or Air Force Fighter Weapons School explore possible COAs in potential future scenarios using digital models of flight computers, radios, sensors, and countermeasures alongside the ecosystem's network software and mission planning tools. Insights from sprints would guide the evolution of NGAD elements and the ecosystem.

PEO NGAD Should Focus on Interfaces and Integration

The primary role of PEO NGAD would be portfolio management, which would entail prioritizing levels of investment and effort across elements of the NGAD ecosystem and defining and owning interfaces between platforms and mission systems and between mission systems and the NGAD C3 architecture. PEO NGAD would oversee integration, but not lead it. Like Apple—which does not integrate, for example, Sony headsets with iPhones—PEO NGAD would rely on system vendors and their associated SPOs to ensure that systems work with each other using approved interfaces, which would be validated through integration gauntlets. By allowing each program to be funded and developed independently and at a tempo consistent with its technological advancement, priority, and operational need, this approach would achieve loose coupling between NGAD elements.

To gain control of interfaces within the NGAD ecosystem and with external systems, PEO NGAD should assert the government's intellectual property rights, which existing laws and regulations already require.[51] However, the responsibility for establishing and maintaining interfaces today is often delegated to prime contractors, who then act as program integrators. The reason for delegating integration responsibilities is usually the substantial engineering needed to make mission systems, platforms, and C3 architectures work together due to the lack of well-defined software or hardware interfaces. By focusing primarily on interfaces, PEO NGAD should be better able to achieve the open and reliable interface performance reflected in commercial products. Additionally, these interfaces should be delivered in their native digital form, as required by law, and housed and maintained as part of the NGAD ecosystem.

The loose coupling afforded by PEO NGAD's focus on interfaces would also provide a useful management tool to promote interoperability and incentivize contractor results. Often the most significant shortfall in a new program is not the performance of the system itself; rather, it is the ability of the program to synchronize and integrate its efforts with other systems and platforms. The multi-year timelines required to insert a new feature into F-35 operational flight program upgrades are an excellent example of this. Loose coupling would enable PEO NGAD to spur contractor performance by requiring frequent demonstrations of interoperability, including during gauntlets, as a condition for progress payments and moves to the next milestone while the program is in development. In contrast, many programs today wait to demonstrate interoperability until the program is nearly complete.

To support DevOps sprints and interoperability gauntlets, PEO NGAD would need to own a shared repository of software code and training data associated with simulated environments and models of NGAD systems and platforms provided by SPOs and their vendors. This horizontal infrastructure would be essential to enabling individual NGAD elements to develop independently. To execute gauntlets and sprints PEO NGAD will need a test and evaluation office associated with Air Force Test and Evaluation Command.

Program Management Principles

PEO NGAD's structure and priorities are intended to reflect a set of program-management principles the DoD should follow to achieve NGAD teams that are flexible and highly recomposable. Overall, these principles center on the need to manage software ecosystems, mission systems, and platforms differently from one another, rather than as parts of a monolithic whole.

Heterogeneity in the NGAD Team and its Software-Development Processes

Allowing programs and systems to evolve independently while remaining interoperable would be best achieved by avoiding reliance on homogenous software development pipelines or cloud environments across SPOs and PEOs. Although applying the same software-development process to disparate programs is efficient, doing so for systems that are intentionally heterogeneous—those comprising a NGAD team for instance—could introduce unnecessary complexity since different programs could be more efficiently supported by differing coding and computing approaches. Moreover, common software development approaches could introduce shared vulnerabilities should a cloud environment or pipeline be exploited or flawed.

Deferred Concretization

Conventional acquisition under the DoD's Joint Capability Integration and Development System fixes requirements ahead of experimentation and capability exploration and well before system composition and compilation. While it allows efficient allocation of resources, this forecast-centric planning approach can lead to overly detailed or erroneous contracts, neglected opportunities for technology insertion, and fielding of obsolescent systems.[52]

To allow a wider variety of elements to be incorporated into the NGAD ecosystem, the program should delay software concretization as long as possible—after force packages are composed in advance of a mission and preferably not until their compilation. Because vehicle designs must be concretized during development, SPOs should establish needs for NGAD aircraft, weapons, and UAVs using short statements of intended outcomes rather than highly-specified requirements. As each element matures and integration gauntlets give rise to better understanding of its relationships to other NGAD elements, these statements can be adjusted.

Employment of Segmented Program Baselines

A conventional acquisition baseline creates a single monolithic delivery schedule regardless of the underlying system-of-systems architecture. With hardware and software in a NGAD maturing or concretizing at differing speeds and toward different endpoints, one schedule would not allow effective program management. Therefore, NGAD SPOs and PEO NGAD should instead employ a segmented baseline that establishes one delivery schedule and set of programmatic estimates for physical air vehicles but uses agile work statements to deliver mission systems and the supporting software ecosystem.

Reliance on Modular Contracts

As with requirements and schedules, contract management should also differ between NGAD's platforms, mission systems, and software ecosystem. Due to their early cost commitment and high transaction costs for changes, hardware programs like NGAD manned aircraft or larger UAVs would likely require detailed contract specifications and multiple layers of management controls.

Other than air platforms, NGAD SPOs should use multiple award contract vehicles such as closed IDIQs to develop and evolve mission systems and the NGAD software ecosystem. Further, mission system hardware and software should be contracted separately to account for their differing rates of evolution. Software for mission systems and the NGAD ecosystem should be funded for continuous development through the DoD's software acquisition path using software appropriations or should be purchased iteratively using IDIQ-type contracts like the Navy's A-RCI submarine combat system software.[53] Mission system hardware could be developed and purchased using multiple award contract vehicles to account for their longer refresh cycles.

An Opportunity to Overhaul DoD Acquisition

The Pentagon has struggled to exploit the adaptability and flexibility afforded by software-defined capabilities despite the prevalence of mobile communications, APIs, DevOps software pipelines, and cloud computing. NGAD presents an opportunity to put some of these concepts into action for military operations by reframing the program as a team operating within a software-based ecosystem rather than as a family of hardware systems.

By building out the horizontal infrastructure that hosts C3 structures, software development pipelines, network management systems, and mission planning tools, the DoD could create a capability that would afford commanders greater optionality and impose complexity on opponents in ways that hardware programs are unable to do alone. Only by exploiting the versatility of software is the US military likely to overcome the home field advantages of opponents like the PRC and so deter aggression.

ENDNOTES

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