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Understanding Post-Production Change and Its Implication for System Design: A Case Study in Close Air Support During Desert Storm

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Abstract

Complex engineered systems with long life cycles can expect to face operational uncertainty. Systems can either be flexible and change in response to a change in operating environment or can be robust and maintain system performance despite the change in operating environment. There is a wealth of literature surrounding how to design systems to be either flexible or robust, but the literature's understanding of how systems that are already in use can be modified to operate in changing circumstances is incomplete. This paper examines how numerous aircraft were modified post-production to gain new capabilities for close air support in Operation Desert Storm. Through an inductive case study, the authors find that new capabilities can be gained through changes to form and changes to tactics. Additionally, there is an interaction between form and tactical changes that has not been well defined in existing literature.

Introduction

Complex engineered systems (CES) provide critical functions for society, from power generation to mass transportation. For militaries, complex engineered systems like aircraft, missiles, and ground vehicles serve as platforms that enable crucial functions including reconnaissance, strike, and air defense. Increasingly longer and costlier development times for new systems force current systems to stay in service longer than originally planned (United States Government Accountability Office, 2019). Additionally, the constraints on logistics and budget that militaries face has led to systems taking on numerous roles, rather than having purpose-built platforms for every mission type (Wasinger, 2020). Both the need to stay in service longer and to conduct more missions with the same platform has created a need for today's military systems to be changeable.

There is a wealth of literature regarding designing systems to be changeable, but complex engineered systems may not always able to accommodate highly changeable architectures. Additionally, even with changeable product architecture, it can be difficult to plan for what must be changed. This has created a need to understand post-production change, which means changing systems after they have left production in ways not explicitly planned for during the system's design phase. We leverage a natural experiment of close air support (CAS) in Desert Storm, where aircraft were modified to perform the mission, to understand dynamics that enabled post-production change.

Literature Review

Changeability literature is focused on studying how systems can maintain value throughout their life cycle in the face of uncertain operating environments. A great deal of literature in the field is focused on how to design for changeability (Beesemyer et al., 2012; Fricke & Schulz, 2005; Ross et al., 2008). Generally, system designers choose to make flexible systems that can change in response to a change in operating environment to maintain value or to make robust systems that are able to maintain value in a variety of operating environments without having to change the system.

There are many system design properties that have been discussed such as adaptability (Li et al., 2008), scalability (Jogalekar & Woodside, 2000), and modifiability (Ross et al., 2008). These properties are meant to influence how system designers architect their systems (Fricke & Schulz, 2005; Ricci, 2014). For example, a common approach discussed is increasing the modularity of system architecture to enable changeability, but this has implications for the performance of the system as more integrated systems perform better under certain conditions (Hölttä et al., 2005).

Others in the changeability literature have focused on how to measure or quantify the changeability of systems (Rehn et al., 2019). One approach involves calculating the real age of a system after it has been modified (Enos, 2020). Studies in this field have also focused on who implements changes, be it system designers, system users, or other stakeholders (Cox, 2017).

There have been studies that do focus on the enablers of changeability. Many have focused on how margin or excess enable change (Allen et al., 2016; Eckert et al., 2019). Margin and excess refer to the system properties like power generated or weight capacity that exceed initial requirements. Since there is an excess of a property, system designers can leverage that excess to add to the system in some way. Others have focused on how change is enabled from a management perspective. One common enabler is real options in engineering design, which gives system buyers the right but not the obligation to make some change to the system in the future (de Neufville et al., 2006; Sapol & Szajnfarber, 2020).

Still, these studies are generally focused on the design phase and how system design enables change. There is limited work analyzing how complex engineered systems are modified in unexpected ways in the post-production phase (Dwyer, 2020). Long & Ferguson (2017) explore how system margin enables post-production changes to occur. Enos (2022) has taken several DoD platforms and applied his real system age formula to them to understand their useful life after being changed. Mekdeci et al. (2014) discuss how existing systems can change in response to changing contexts. This work builds on existing literature by understanding the enablers of post-production change, such as margin and modularity, and the interactions between them.

Methods

This paper leverages a case study to induce insights about how systems are modified post-production to serve new roles. The case study method is appropriate when there is not abundant empirical data to answer research questions (Eisenhardt, 2021). Cases were selected from a natural experiment where complex engineered systems, military aircraft, were changed post-production for the same mission, CAS, during the same time period, Desert Storm. Data is collected by analyzing a repository of airpower studies on Desert Storm. Insights are drawn from within and cross case examination, and these insights are then tied back to existing literature. This is a widely accepted method to induce theory from empirical case studies (Eisenhardt, 1989).

Research Setting

This paper studies how numerous aircraft were designed and modified to carry out close air support during Operation Desert Storm. Many different types of aircraft performing one mission during a relatively short war provides a natural experiment to examine how changes were made to enable CAS effectiveness, and there has been robust debate about which aircraft are best suited for CAS (Kaaoush, 2016; Macdonald & Schneider, 2016).

CAS is a core mission of air forces around the world and is defined by the U.S. Air Force as “air action by aircraft against hostile targets that are in close proximity to friendly forces and that require detailed integration of each air mission with the fire and movement of those force” (The Curtis E. LeMay Center for Doctrine Development and Education, 2020). The Marine Corps considers CAS to be a subset of its Offensive Air Support (OAS) mission set along with Deep Air Support (DAS). Requirements for OAS are taken from Marine Corps doctrine are described in the section titled “Analysis Approach.”

Data Collection

Changes were identified by analyzing three documents: the DoD’s official report on airpower in Desert Storm (Gulf War Air Power Survey Staff, 1993), the GAO report analyzing the claims of the DoD report (United States General Accounting Office, 1997), and a book written by the Emeritus Chair in Strategy of the Center for Strategic and International Studies that analyzes the war (Cordesman & Wagner, 2013). These documents build off and challenge each other. This is useful in being able to capture a wide spectrum of knowledge, and these documents used to triangulate information to get an accurate understanding of the changes that occurred during the war (Szajnfarber & Gralla, 2017). These documents report the instances of modifications, but other sources are used to supplement and better understand their implementation and effects where necessary.

Case Selection

The DoD identifies six aircraft mission and reports the total number of CAS sorties conducted for each: A-6 (39), A-10 (1,041), AV-8 (1,528), F/A-18 (1,978), F-16 (423), and AC-130 (31) (Gulf War Air Power Survey Staff, 1993). The A-6 and AC-130 are excluded from analysis in this study since they conducted relatively few CAS sorties, which does not provide enough data for analysis. The initial design and conception of the four analyzed aircraft are described in the Analysis section.

Analysis Approach: Functional Comparison

A functional analysis approach was taken to compare modifications against each other. Functions are derived from U.S. doctrine on CAS and serve as a way to categorize changes that occurred. The functions analyzed are effective targeting and marking, effective weaponeering, and flexible control and prompt response, which are described in this section. The unit of analysis for this paper is an attempted capability gain through a modification, be it physical or tactical. Capability gain is defined as a system gaining the ability to perform some task laid out in the definitions of the three functions that it was not able to perform in its base design.

To be able to compare how these aircraft were modified to perform CAS, it is important to understand the requirements of CAS. Marine Corps doctrine lays out requirements, which provides the baseline for our analysis: Air Superiority, Suppression of Enemy Air Defenses, Cooperative Weather, Effective Targeting, Effective Marking, Effective Weaponeering, Capable Platforms/Sensors, Flexible Control, and Prompt Response. It is important to note that these are not firm requirements that systems engineers may employ, as omission of these requirements simply means the mission is less effective, rather than mission failure (U.S. Marine Corps, 2018).

Air superiority and suppression of enemy air defenses are intended to allow CAS operations to occur without overwhelming interference from air-to-air or ground-to-air threats, respectively. They are not considered in this paper since they are conditions for a permissive operating environment rather than being a core part of the CAS mission itself. Permissive weather is a natural phenomenon that innovation and technology for CAS cannot affect, so it is not considered. The requirement for capable platforms and sensors lays out the need for technologically advanced systems that can enable mission success. Since this requirement is simply for technology to be able to make difficult aspects of the mission such as target acquisition easier, it is not considered as its own change category.

Effective targeting refers to the planning stage of a mission where commanders decide what targets will be struck, with what weapons, etc. The services and joint operations use different targeting processes, but generally, they involve assessing which targets to strike, how to strike them, striking them, and assessing the results of the strike (U.S. Marine Corps, 2018).

Effective marking is the battlefield operation of making targets visible for strike, which has been done by white phosphorus, GPS, lasers, etc. (U.S. Marine Corps, 2018). Marking is especially important for CAS as it helps reduce the likelihood of fratricide. Taken together, effective targeting and marking enable CAS operations to know what targets they are striking. This is especially important with close air support since targets are in close proximity to friendly forces.

Effective weaponeering refers to the need for “effective aircraft and weapon to target match” (U.S. Marine Corps, 2018, p. 15). Plainly, this means that weapons must be available to strike various targets and that aircraft need to be able host these weapons. This is again crucial due to the proximity of friendly forces to the targets. Weapons and the platforms delivering them need to be able to destroy the target without harming friendly forces.

Flexible control refers to the need for effective command, control, and communications (C3) to be leveraged to ensure that troops on the ground are receiving proper and timely CAS (U.S. Marine Corps, 2018). While many changes in this field revolve around communications avionics, different properties of aircraft can also enable different C3 to flow differently. For example, command structures might differ if aircraft are loitering in area to provide continuous CAS versus if they are quickly moving in and out of the battlefield.

Prompt response refers to how quickly CAS can be delivered. This is achieved by forward basing, alert states, and mission classification (U.S. Marine Corps, 2018). Forward basing moves aircraft closer to the battlefield to reduce time to battlefield. Alert states direct aircraft to be ready for takeoff within a certain amount of time and can enable faster response when on high alert. Mission states can be categorized into preplanned or on-call missions, which yield different requirements (U.S. Marine Corps, 2018). Similar to flexible control, properties of aircraft, like their speed and loiter time, may affect how mission planners are able to use different aircraft. Taken together, flexible control and prompt response mean that planners need to get CAS where it is needed in a timely manner.

Analysis

The analysis section will lay out the initial design of the aircraft identified and explain how they were meant to achieve CAS in their base configurations, based on the three functional categories identified. Then, changes that provide capability gain will be discussed. These changes are grouped by the three functional categories.

A-10 Thunderbolt

The A-10 Thunderbolt is the Air Force's first dedicated CAS platform (United States Air Force, 2019). The A-10 is often described as a plane designed around a gun, that gun being a seven barrel, 30-mm Gatling gun that is able to destroy armored ground targets (Smallwood, 1993). The aircraft was designed to be able to handle the intensity of firing the massive gun while maintaining stability and accuracy. Outside of its large cannon, the A-10 is well known for its survivability features. Many of the A-10's system requirements for survivability were derived from studying the failures of aircraft in the Vietnam War (Jacques & Strouble, 2010). Some of the survivability features include self-sealant lined fuel tanks, redundant manual controls, and a titanium casing around the cockpit (Smallwood, 1993). Ultimately, the goal of the A-10 design was to create a slow moving, highly survivable aircraft to support an enormous cannon that could destroy enemy armor with the precision of cannon fire as opposed unguided bombs or precision missiles, which the A-10 is also capable of carrying on its 11 pylons (United States Air Force, 2019).

The A-10 typically serves as a daytime attack aircraft, achieving effective targeting and marking through visual acquisition of targets, aided by aiming references and avionics such as a heads-up display. The biggest upgrade the A-10 received in targeting and marking prior to Desert Storm was the low altitude safety and targeting enhancement system, which provided constantly computed impact points for gravity bombs. Contributing to both targeting and weaponeering, the A-10 also received the Pave Penny pod, which enabled it to use laser-guided munitions (Air Combat Command, 2015). The A-10's massive cannon contributes most to its effective weaponeering capabilities, as does its ability to carry a variety of explosive munitions. System planners can use the A-10 in various ways to achieve flexible control and prompt response. The A-10 is able to loiter at low speeds, meaning it can hover in the battlefield longer than most aircraft.

AV-8B Harrier II

The AV-8B is a McDonnell Douglas (now Boeing) vertical/short take-off and landing (VSTOL) capable aircraft manufactured for the U.S. Marine Corps. It replaced the British developed AV-8, entering service with Marines in 1985 (Naval History and Heritage Command, 2014). It serves as the Marines' primary attack aircraft, and its VSTOL capabilities mean it can be deployed from the smaller carriers and austere bases that the Marines operate out of. The AV-8B was designed to perform a variety of missions like close air support but was not optimized around the role like the A-10. The focus of the Harrier design is its innovative VSTOL capabilities.

For targeting and marking, the Harrier's nose is mounted with an avionics suite that "has a TV/laser target seeker and tracker" (Gulf War Air Power Survey Staff, 1993, p. 60). The Harrier hosts a 25-mm cannon and can use traditional gravity bombs (Cordesman & Wagner, 2013). The Harrier lacked the ability to use laser-guided weapons during Desert Storm. In regard to flexible control and prompt response, the Harrier's VSTOL capabilities gives planners options to be closer to the battlefield as ships and austere runways could be setup closer to the battlefield than traditional bases. Being closer to the battlefield increases security threats but also enables quicker time to the field.

F/A-18 Hornet

The F/A-18 Hornet was manufactured for both the Navy and Marine Crops. The F/A-18's original design came out of the competition for what would become the F-16. Congress directed the Navy to consider the two prototypes from that competition, the YF-16 and YF-17, for their needs. Eventually the YF-17's revamped design, more fit for carrier operations than it had been when it was first submitted for the Air Force, won out and became the F/A-18 (Naval History and

Heritage Command, 2014). The unique designation F/A refers to the fact that it was designed to serve both air-to-air and air-to-ground missions and can be changed to either its fighter or attack configuration with external equipment (U.S. Naval Academy, n.d.).

The F/A-18s had a forward-looking infrared radar (FLIR) targeting and navigation system that enabled day and nighttime marking and targeting. The system provided thermal displays of the battlefield in real time at night, which along with night vision goggles and digital maps, enabled F/A-18s to conduct nighttime operations with largely the same procedures used for daytime operations. During the day, F/A-18s would visually acquire targets, often with the aid of binoculars, which is similar to the A-10's daytime operations (Gulf War Air Power Survey Staff, 1993). F/A-18s host a 20-mm cannon and can carry a variety of gravity and guided munitions, being one of the most versatile platforms in terms of the types of weapons it can host. This also gives planners flexibility in planning as the F/A-18 was able to engage air-to-air and air-to-ground in the same sortie (Gulf War Air Power Survey Staff, 1993).

F-16 Fighting Falcon

The F-16 came out of the Air Force Lightweight Fighter technology demonstration, with the eventual winner of the follow-on program being General Dynamics (now Lockheed Martin) (Bjorkman, 2014). The F-16 is a multi-role aircraft, designed to be able to perform air-to-ground missions while still keeping its fighter capabilities in air-to-air combat. The F-16 is fast and highly maneuverable, capable of carrying both unguided and precision weapons and still lighter than previous generation aircraft (Gulf War Air Power Survey Staff, 1993).

The F-16s deployed in Desert Storm were primarily daytime only aircraft and acquired targets visually. The F-16 hosts a 20-mm cannon and can carry gravity and guided weaponry, but the F-16 primarily used gravity and guided bombs against ground targets rather than its cannon (Gulf War Air Power Survey Staff, 1993). F-16 is a very versatile aircraft, similar to many other multi-role fighter aircraft and provides planners with flexibility similar to the F/A-18.

Changes to Enable Effective Targeting & Marking

For platforms carrying out CAS to be effective, they "need accurate weapon systems and sensor equipment to aid in target acquisition/designation in day and night operations" (U.S. Marine Corps, 2018, p. 16). A key success in Desert Storm was the ability to conduct aerial operations during nighttime. Table 1, Bombing Capabilities by Platform, modified from the DoD report, shows the system modifications that enabled nighttime visual bombing for the F-16, A-10, and F/A-18 (Gulf War Air Power Survey Staff, 1993). As described previously, the F-16 and A-10 traditionally acquire targets visually, so nighttime operations were not explicitly designed for.

Table 1: Bombing Capabilities by Platform

	Visual Bombing During Day	Visual Bombing During Night	Radar	Air-to-Air Swing Role	Comments
F-16C	X	LANTIRN-equipped aircraft	X	X	LANTIRN pods available for only two squadrons
A-10	X	X			Precision accuracy with 30-mm GAU-8 cannon; limited night capability with IIR AGM-65
F/A-18	X		X	X	Highly capable air-to-air attack aircraft

USAF General Bill Creech recognized that being able to operate at night was crucial for the United States. In 1981, Gen. Creech testified to Congress that flying at night would enable the United States to deliver more firepower 24/7, take away the cover of darkness from foes, and provide air support to ground troops engaged in nighttime combat (Slife, 2004). The Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) was developed by Martin Marietta (now Lockheed Martin) to help fill this need. LANTIRN development was initiated in the 1980s and was delivered to the Air Force just before the start of the Gulf War, being installed on F-15s and F-16s (Lockheed Martin, n.d.). The system "consists of a navigation pod and a targeting pod integrated and mounted externally beneath the aircraft" (Air Combat Command, 2005). The pods can be used together or individually. The pod was designed to be very modular and was optimized around the aircraft's aerodynamic profile. It was a crucial part of the Block 40/42 upgrades that were part of a larger program to evolve from the F-16A to the F-16C (Camm, 1993). F-16s with the LANTIRN system only received the navigation pod, as the targeting pods were reserved for F-15s (United States General Accounting Office, 1997). The navigation pod uses infrared sensors to show the terrain in the heads-up display (Camm, 1993). The LANTIRN system provided the F-16 with the ability to operate at night and was crucial in denying the Iraqi army the cover of night, but there are limitations to its ability to operate in adverse weather.

While the DoD and contractors boasted about the system's performance, the GAO found that "its ability to find and designate targets through clouds, haze, smoke, dust, and humidity ranged from limited to no capability at all" (United States General Accounting Office, 1997, p. 26). Issues with targeting went unresolved throughout the war and throughout the program's duration. Despite the challenges of flying without the already insufficient targeting pods, F-16s were able to achieve nighttime bombing accuracy by flying at lower altitudes, as permitted by LANTIRN (Gulf War Air Power Survey Staff, 1993). In the case of LANTIRN, the technical change of adding a modular pod to the body of the aircraft enabled operational changes in the ability to effectively operate at night.

USAF Lieutenant Colonel Rick McDow and others realized that A-10 would likely also be called in to perform nighttime CAS since the Army was training for nighttime operations. A-10s achieved nighttime capabilities through less technically sophisticated means than the F-16. His group practiced using flares to illuminate targets on the ground, a tactic that dated back to World War II (Smallwood, 1993). Eventually, A-10 pilots realized they could fly "at night using the infrared video of the AGM-65D Maverick missile as a 'poor man's FLIR'" (Gulf War Air Power Survey Staff, 1993, p. 54). The infrared Mavericks contained a camera in the head that would feed to a small television in the cockpit (Cordesman & Wagner, 2013).

This technique was actually strongly advised against in USAF Weapons School, as looking through a camera during the daytime led to predictable flight patterns, giving air defense systems an easy target (Smallwood, 1993). The A-10 pilots, however, found relative security at night as their dark jets were hard to detect since much of the Iraqi radar capability had been crippled. Additionally, A-10 pilots had learned that their aircraft could not be heard on the ground about 5,000 feet. To maintain the cover of darkness, A-10 pilots had to fly with their lights off which made simple tasks like reading a map more difficult, and the A-10 autopilot system could not be engaged at night, taking focus away from the pilots (Smallwood, 1993). These and other challenges associated with flying at night were eventually overcome with patience and practice by the pilots. The A-10s were able to effectively deliver firepower at night and the cover of darkness they were able to utilize made flying at night extraordinarily safe (Smallwood, 1993).

Changes to Enable Effective Weaponeering

In the original conception of the F-16, it was supposed to be a lightweight, affordable air-to-air platform, a far cry from its multi-role air-to-ground capable status in Desert Storm. This was discussed in 1977 hearings on military posture, with USAF General Slay remarking that the F-16 can do CAS but is not optimized to do so like the A-10 (United States Congress House Committee on Armed Services, 1977). While the F-16 was capable but not optimized, logistic and budget concerns around retaining a CAS-oriented aircraft led the Air Force to explore the option of making the F-16 better at CAS so that the A-10 could be replaced. The initiatives to create a CAS oriented F-16 were called the A-16 or F/A-16, and these initiatives led to many technologies being test bedded (United States General Accounting Office, 1989). One technology that made its way to Desert Storm was a 30-mm gun pod marketed as GEPOD 30 and called GPU-5/A during operations. These pods were part of the Pave Claw initiative, part of the larger A-16 or F/A-16 efforts (Smith, 2021).

30-mm gun pods were attached to select Air National Guard F-16s (Gulf War Air Power Survey Staff, 1993). The gun itself was a pared-down version of the A-10's gun that was meant to be used for gun pod attachments. During the planning phase of the 30-mm pods, the goal was to provide the "flexibility to destroy heavy armor that cannot be effectively destroyed by 20 mm guns" so that the Air Force could "supplement armored vehicle killing capability of A-10" (United States Congress House Committee on Armed Services, 1980, p. 1740). In essence, the goal of the pod was to lend the A-10's unique gunpower to the F-16.

The gun pods are meant to be highly modular for the aircraft they are bolted on to as they contain their own power supply and ammunition. For the F-16, the pod was mounted on to the center of the aircraft and came with a software package to enable targeting with the pod. The modified F-16s were given to a squadron that previously flew A-10s (Werrell, 2003). During Desert Storm, the vibration from firing made the pods inaccurate and unstable. Since the pod carried such an enormous gun, the "structure of the modified F-16s could not withstand the vibrations" from firing the GPU-5/A (Smith, 2021, p. 45). While the GPU-5/A seemed like a promising way to enable the F-16 to perform CAS just like the A-10, the modification was abandoned after one day of use in Desert Storm.

Much has been said about how Desert Storm showcased the United States' capability in laser-guided and other precision weapons, including the Maverick missile, which has been discussed in relation to its usage on the A-10, the primary carrier of the Maverick during Desert Storm (Gulf War Air Power Survey Staff, 1993). The Maverick provided precision strike capability for CAS, but the extent of this capability is questionable since only 8% of the weapons fired in Desert Storm were guided (United States General Accounting Office, 1997). Additionally, all platforms that were firing Maverick missiles were able to use unguided weaponry to strike targets as well. Since Desert Storm lacked many of the close quarters combat situations that other missions like Operation Anaconda required, there was not an absolute need for guided weaponry for CAS. Mavericks merely enhance the accuracy of strikes carried out. Other platforms like the F/A-18 dropped flares and rockets to mark targets for CAS, but the use of flares and rockets to mark targets is neither innovative nor a contribution to effective weaponeering (Gulf War Air Power Survey Staff, 1993). While many new weapons were fielded, only the GPU-5/A and Maverick were identified as having contributed new capabilities for the CAS mission.

Changes to Enable Flexible Control and Prompt Response

Prior to Desert Storm , U.S. forces had been thinking about what a war in the region might look like. U.S. planners had considered that CAS would be needed if Kuwait was invaded by ground, and they wanted to make sure that there was a plan in place to provide it. USAF General Horner developed the Push CAS model April 1990 to ensure that ground forces' CAS needs were being met while not wasting resources by having aircraft be on high alert on a runway (Gulf War Air Power Survey Staff, 1993). Push CAS is a tactic that involves sending aircraft out to positions to be on-call for CAS, and allowing them to engage in DAS if CAS calls do not come in (Gulf War Air Power Survey Staff, 1993). This created a steady flow of CAS resources into the battlefield, while reducing overall inefficiency of being on alert or on station with no mission. When CAS requirements were low, all four analyzed aircraft went on to perform other missions.

No form changes were identified that enabled prompt response, but tactical decisions were made that compensated for the lack of form change in this category. Even with Push CAS in place, there was a need for CAS to be readily available in places it might not be expected. Urgent CAS calls necessitated prompt response, and the Marine Corps' Harrier was well suited for this need. The AV-8B Harrier was based closest to the Kuwaiti border and was the most forward-based aircraft of the entire war (Naval Air Systems Command, 2012). Being able to more easily shift around where the aircraft was based "allowed the aircraft to minimize its limitations in range-payload, reduce its need for refueling, and increase its sortie rate" (Cordesman & Wagner, 2013, p. 431). In this instance, military planners were able to use tactics like forward basing to overcome the AV-8B's flying limitations. It is important to note that the ability to fly the Harrier from such positions is because of its designed VSTOL capabilities.

Other changes that helped improve flexible control and prompt response did occur, but they did not provide new capabilities. Rather, many form changes in this area were improvements on existing capabilities. More capable radars and sensors made the coalition more effective but did not yield any capabilities that did not exist before. Despite the relative lack of capability gain in this area, there were many issues with communications. Coalition forces often used Soviet technology that was similar to what Iraq was fielding, so the coalition painted symbols and put lights on tanks that could be confused for Iraqi vehicles (Powell, 1991). Still, these efforts proved to marginally successful as Desert Storm saw numerous incidents of friendly fire. After the war, many tactics and technologies were developed around ensuring better communication and control of CAS missions while still ensuring prompt response time (Powell, 1991). Since these changes occurred after the war, they are out of scope of this paper.

Discussion & Conclusions

This paper analyzed how different aircraft were modified for CAS to understand what enables post-production change and how the changes are actually implemented. Changes involved both the physical modification of the aircraft and tactical innovation surrounding its use. Both of these types of changes yielded capability gains. Consistent with findings of previous authors, margin and modularity both proved useful in enabling post-production change, but not all dynamics behind post-production are well understood in the literature.

Implications for Changeability

When analyzing the changes that led to new capabilities for aircraft performing CAS, it is clear that tactical innovation can provide changeability for systems in a similar the way physical changes to form can. A change to form is not always needed to achieve the desired functional gain. For enabling nighttime operations, the F-16 and A-10 show this paradigm quite well. The F-16 was able to fly at night by equipping the LANTIRN pod, a technological advancement in aircraft navigation. The A-10 was able to achieve its nighttime capabilities first by flying in pairs and dropping flares, and then by the A-10 pilots' use of the camera on the Maverick missile. The innovation with F-16 was largely the addition of a modular pod enabling nighttime operations, while the A-10 had to use conventional tactics to achieve nighttime capabilities.

While the Maverick is technologically advanced in its own right, it required tactical innovation to be used to conduct nighttime operations. Official USAF instruction was to explicitly *not* use the Maverick's camera for navigation, but by understanding how tactical changes could be made to leverage the capability, A-10 pilots were able to challenge conventional wisdom.

This is an important insight for maintaining system life-cycle value. Functional gains can be made by innovating how systems are used. This is also shown in how flexible control and prompt response were achieved. In those cases, post-production changes to form did not occur, but military planners were able to leverage the aircrafts' inherent system properties to achieve effective CAS in ways that had not been done before the war.

The GPU-5/A is an example of why a change to form is considered risky. The system was designed to be modular, but the interfaces and system interactions were not carefully considered. This is a well understood problem in the systems engineering literature, but the GPU-5/A shows why changeable architecture is not a silver bullet for enabling post-production change. The GPU-5/A was not able to transfer the A-10's capabilities to the F-16 as intended, but the F-16 was able to perform CAS by leveraging its own strengths.

Largely, this case study reveals that margin and modularity are useful tools in enabling post-production change. Having hardpoints on aircrafts gives the system flexibility in terms of what is being changed. Specific changes were not planned when the hardpoints were installed, but they provided an interface for modules like the LANTIRN or the GPU-5/A to be integrated with the system. This is not a new concept in changeability literature, but few authors have made the connection between the physical form of the system and the operational context. This data reveals the need to look at the physical system in its operational context. Changeability literature largely focuses on the physical system, but many of the capability gains happened through tactical changes or through a combination of form change and tactical innovation. While these are not new concepts separately, they have not been well connected together. Form change and tactical change are not entirely independent from one another, as the A-10 would not be able to achieve the level of success it did at night without the Maverick's IR camera.

Future Work

This paper presents preliminary results of a larger study focused on inducing the dynamics and enablers of post-production change. There are a limited number of cases analyzed in the scope of this paper, which limits the degree of theory that can be induced from these cases. Future work will build deeper case histories in this research setting. Additionally, future work will also analyze the C-130 as a foil to this experiment. The C-130 has been modified numerous times to serve new missions, including CAS. Where this paper analyzes how numerous aircraft were modified for the one mission, the C-130 research will analyze how one aircraft was modified for numerous missions. Future work will enable more robust insights to be made

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