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Designing a Maintenance System for Agile Combat Employment: An Agile Engineering Methodology

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Author Note: This capstone research was completed by a team of cadets and faculty advisors from the United States Air Force Academy with backgrounds in systems engineering and mechanical engineering, focused on improving the operational effectiveness of the F-22 Raptor. The team gratefully acknowledges the support of the project sponsors from the 302nd Fighter Squadron, Pratt & Whitney, and the 59th Test and Evaluation Squadron. We also extend our sincere appreciation to our capstone advisor Dr. Feier, systems engineering advisor Captain Welsh, and project lead Lieutenant Colonel Christopher Boyer. These teams and individuals' mentorship, insights, and technical expertise were essential to the successful completion of this project. The views expressed herein are those of the authors and do not reflect the official policy or position of the United States Air Force Academy, the United States Military Academy, the Department of the Air Force and Army, or the Department of War.

Abstract: The emergence of increasingly lethal threats marks an inflection point for the U.S., yet the Department of War (DoW) has kept legacy approaches that remain siloed, diffused, and fragmented. Policy alone will not be sufficient; rather, the implementation of initiatives like Agile Combat Employment (ACE) in the Air Force can improve mission effectiveness. As the USAF moves beyond legacy approaches through agile frameworks, certain systems have been identified as falling short of ACE requirements. Air Force Academy cadets identified the F-22 Raptor as an airframe to enhance capabilities in support of ACE objectives, making it the focus of this research. Through systems engineering methodologies, a limitation in the F-22 oil reservicing process was identified, leading a USAFA capstone team to develop a prototype widget that enhances F-22 ACE capability.

Keywords: Agile Combat Employment, agile, defense modernization, F-22 sustainment, rapid prototyping

1. Introduction

As the DoW adapts to emerging threats, a shift towards an agile systems approach that rapidly fields interoperable systems will be necessary. ACE describes the operational concept of improving mission effectiveness by distributing forces across austere and geographically separated locations to enhance survivability and resiliency (Schroeder, 2025). Agile systems engineering, a concept that supports this operational initiative, emphasizes iterative development to rapidly design systems and reduce acquisition timelines (Roper, 2020). A limiting factor originates from rapid system modernization being paired with lagging maintenance support equipment that is outdated and poorly suited for modern systems (Wells, 2022). Under ACE, this limitation is amplified, as existing equipment is not designed for rapid, flexible use across distributed operations. The Department of the Air Force (DAF) leadership has recognized this limiting factor for long-term strategic success and has introduced the Integrated Capabilities Command (ICC), but action for complex systems cannot wait (Eversden, 2024). To align with the restructuring of the DAF, the ACE initiative needs capabilities that enable aircraft to operate from austere and geographically isolated locations. This research paper presents the ideation and development of a portable oil reservicing device designed to enable the F-22 to achieve these ACE objectives and mitigate the previously addressed limiting factors, particularly outdated maintenance equipment. Developed as part of a systems engineering capstone at USAFA, this paper outlines how a cadet team applied agile engineering methodologies through rapid prototyping and iterative design strategies. This methodology not only delivered a portable oil reservicing device that enables in-field servicing of the F-22's engine in alignment with ACE objectives, but also serves as a case study for the DoW to prioritize an agile approach.

2. Background

2.1 Identifying a Problem: The DoW's Legacy Approach

The legacy Defense Acquisitions Life Cycle is characterized by siloed, diffused, and fragmented processes (Defense Acquisition University, 2022). Programs going over budget and failing to meet timelines commonly occur within this process. The Government Accountability Office has reported that major defense acquisition projects (MDAPs) have accumulated more than $628 billion in cost growth since program initiation, with average delivery timelines increasing by more than two years (Defense Acquisitions Annual Assessment, 2020). Application of the legacy approach results in an average iteration and fielding timeline of approximately sixteen years for the DoW, whereas an emerging adversary can field innovative technology in seven years or less (Lofgren, 2021). Inadequate requirement definitions early in the design and ideation phases of system development create negative effects, notably the inability to iterate effectively. This legacy approach often separates stakeholders, specifically warfighters, from the development phase, which can lead to the system failing to be effective in operational environments (Kwastel, 2025). This status quo has led to aging ground equipment that cannot support today's complex systems, causing the DAF to operate systems that cannot fully achieve the ACE initiative.

2.2 Steps Toward Reform

The DAF has worked to address these concerns, particularly with the ICC and the T-7A Red Hawk and Rapid Dragon programs. The ICC is intended to push the DAF beyond fragmented processes and instead consolidate acquisitions under one command, thereby helping acquire system-of-systems that remain interoperable across domains (Packard, 2024). The ICC would also champion the creation of integrated requirements that are passed down to the acquirers, utilize Model-Based Systems Engineering (MBSE) and digital twins to rapidly prototype (Smith, 2024). Using the T-7A Red Hawk program as an example, its use of digital engineering resulted in an 80% reduction in assembly hours and 50% quality improvement (Albon, 2022). Advanced digital modeling enabled collaboration across engineering, production, and flight teams which reduced the design phase by nine months due to faster problem-solving abilities enabled by an authoritative source of truth (Albon, 2022). The Rapid Dragon program also demonstrated these principles in practice by developing palletized munitions for cargo aircraft, highlighting the emphasis on acquiring adaptable and low-cost weapon delivery systems that serve as modular and scalable solutions (Evans, 2024). These modular and interoperable systems can shorten timelines by enhancing development quality across the DoW. These examples reflect a path to outpace global competitors and guided the development methodology for the F-22 oil reservicing capstone, positioning it as another example of meeting mission demands through agile engineering.

3. Systems Engineering Methodology Applied to Enhance the F-22 Raptor

3.1 Stakeholder Engagement

Across advanced systems in the DAF, the capstone students at USAFA set out to engineer a system that enhances the operational capabilities of the F-22 to meet ACE objectives. To address how the F-22 can become better equipped for ACE, meeting with F-22 stakeholders became the top priority. The engineering team traveled to Nellis Air Force Base during a Red Flag Exercise to conduct operational observations of the F-22 and engage with stakeholders. The engineering team spent two days with F-22 pilots from the 302nd Fighter Squadron, acquisition officers and maintenance personnel from the 59th Test Squadron, and Pratt & Whitney (P&W) engineers. The team identified and studied limitations of the F-22, primarily its current oil reservicing process. The F-119 P&W engine on the F-22 was identified as needing a more efficient oil reservicing method since its current process uses legacy oil carts that are too large, expensive, and unreliable. This outdated maintenance equipment weighs approximately eighty-two pounds and costs over $14,000, significantly hindering the F-22's ability to have its oil reserviced in an austere environment. The team then engaged with industry leaders and engineers from P&W to learn the mechanics of the F-119 engine and its diagnostic readings during full burn rates in an engine test cell facility, and collaborated with maintainers to service the F-22's oil. Thorough stakeholder engagement helped the engineering team determine what the warfighter requires for ACE, which informed the development of system requirements. These requirements are based on developing an agile, portable, and easy-to-use oil reservicing widget that replaces the outdated oil cart.

3.2 Requirement Generation

Following stakeholder engagement, the team worked to solve the legacy approach for reservicing the F-22's oil by defining requirements, shown in Figure 1, tailored towards stakeholders' needs and use cases.

Req. #	Requirement Name	Requirement Description
1	F-22 Oil Reservicing	The widget shall enable oil reservicing of the F-22 in austere environments.
2	Oil Servicing	The widget shall replenish the F-119 engine oil reservoir from caution to operational levels.
2.1	Pressure	The widget shall maintain a minimum delivery pressure of 5 psi.
3	Injection	The system shall connect to the F-22 oil port without leaking oil while operating.
4	Quantity Control	The widget shall show a numeric display indicating the quantity of oil dispensed.
5	Setup and Use	The widget shall be fully operational within 60 seconds of initial deployment.
6	Portability	The widget shall be storable within the F-22's internal storage area.
7	Durability	The widget shall operate under conditions examined in the Environmental Criteria for the F-22 internal storage area.

Figure 1. F-22 Oil Reservicing Widget System Requirement Subset

The team collaborated with warfighters throughout the agile systems process by translating their operational needs into formal mission, stakeholder, and system requirements. Close collaboration between industry and warfighters ensured these operational needs were reflected in concept generation, trade studies, and prototype evaluation. The team subsequently enhanced the F-22's ACE capabilities by defining how a portable widget stored within the F-22 can reservice an F-119 engine while still running. These requirements were then tied to functional elements to explain what a desired system solution must accomplish.

3.3 Functional Architecture

After defining requirements, the engineering team continued the agile engineering process by creating a functional architecture for a desired solution. The functional architecture, as shown in Figure 2, served as a bridge between requirements generation and concept ideation by defining what a system must accomplish when employed.

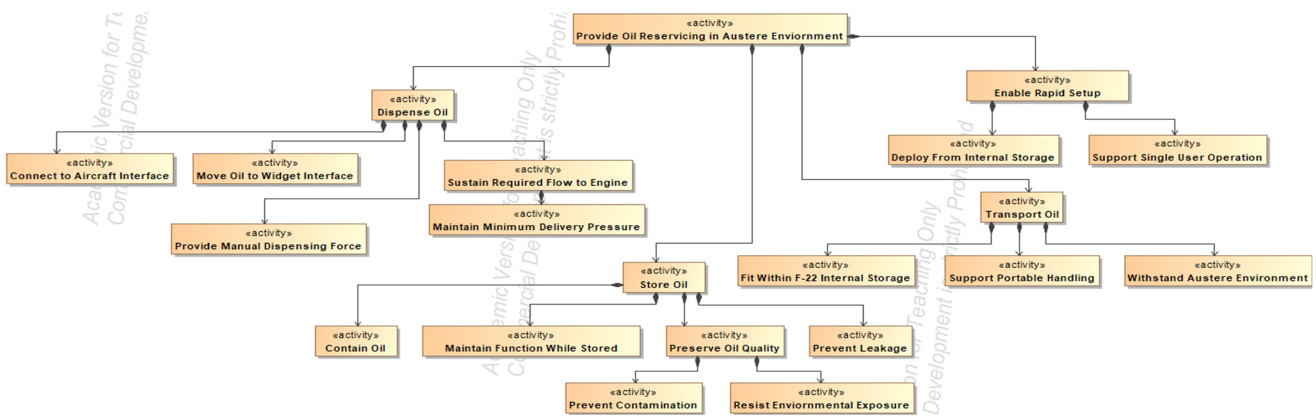

Figure 2. Oil Reservicing Widget Functional Architecture

The top-level function of providing oil reservicing established the operational imperative of accomplishing ACE and outlined the decomposition into four primary functions (dispense oil, store oil, transport oil, and user employment) to help achieve the top-level function. Decomposing these functional elements highlighted the value of architecting with Systems Modeling Language (SysML) in Catia Magic because its solution-independent structure enabled iterative prototyping and flexibility in decision-making without needing the redefinition of system objectives. This process informed the direction of concept generation, ensuring all designs remained aligned with the system's operational purpose and stakeholder needs.

3.4 Concept Generation

Using the operational requirements and a functional architecture as a foundation, the agile systems process for widget development began with an iterative ideation sprint. Ideation techniques such as the 6-3-5 brainwriting, mind mapping, and morphological analysis resulted in thirteen ideated designs. The 6-3-5 Brainwriting generated a solution that would dispense oil into the F-119 engine similar to how a tube-of-toothpaste dispenses its contents. The team developed this solution with an understanding of how the DoW is seeking to increase the use of commercial off-the-shelf solutions (COTS) for system design

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(Wells, 2022). Given COTS' purpose of maintaining speed and agility by utilizing easily available technologies for military purposes, the team focused on quick, inexpensive, and simple solutions (Wells, 2022). The team expanded these concepts in a mind-mapping exercise to break down five COTS-based concepts for the widget: the IV bag, toothpaste/roller, caulking, flexible bladder, and pressurization. These concepts were generated based on their connection to key functional requirements, including pressure delivery, portability, and ease of use. As shown in Figure 3, these five abstract ideations generate specific concepts and potential COTS they require.

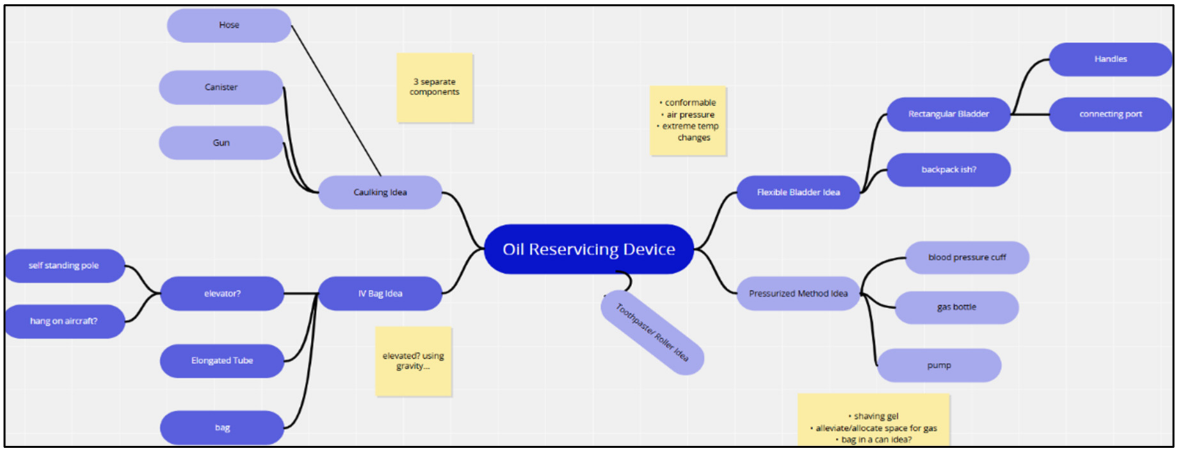

Figure 3. Mind Map Ideation of Widget

While executing this sprint, the team constantly iterated their concepts within a feedback loop that connected to the widget's functional architecture and requirement definitions. This led the team to produce concepts that focused on customer needs tailored to warfighter requirements through novelty and ease of use, highlighting how agile principles enabled rapid system development. After these concepts were evaluated, a trade study was utilized to discern which concept maximized functional requirements.

3.5 Prototype Selection Through Down Selection

The ideation process prioritized the traceability of system design to stakeholders' needs; therefore, five concepts were selected as candidate solutions for assessment in a trade study, as shown in Figure 4.

	Concept 1	Concept 7	Concept 8	Concept 10	Concept 11
Requirements	Presurized Bottle	Manual Bag Compression	Foot on Bag Compression	Electric pump	Toothpaste Tubing Roller
Speed (Setup Time and Completion) <= 2 min service	+	+	+	+	+
Weight <= 20 lbs	+	+	+	+	+
Usability <= 4 steps	+	+	+	+	+
Stored Oil Volume 4 <= x <= 8	-	+	+	+	+
Storability <= 472.19 in^3	+	+	+	+	+
Durability	-	+	+	-	+
Cost <= $15	+	+	+	-	+
Accuracy <= .1 Quart	+	-	-	+	+
Single User	+	+	+	+	+
Pressure >= 5 Psi	+	+	+	+	+
No Tools	+	+	+	+	+
Minimal Complexity	-	+	+	+	+
Number of +	9	10	10	9	11
Number of -	-2	-1	-1	-2	0
Net Score	7	9	9	7	11
Improve/Combine?	None	None	None	None	None

Figure 4. Trade Study Down Selection

The green cells represent concepts that satisfy the requirements and customer needs, and vice versa for the red cells. The criteria for each concept were tied to the warfighter's priorities, with simplicity, portability, and effectiveness receiving the highest importance. These selections were based on prioritizing a user-centered design, particularly for a multi-capable airman (MCA) such as a pilot. As shown, the "toothpaste tubing roller" concept scored highest in the trade study because of its ease of use, low cost, and ability to meet system requirements. Each of these considerations and elements of design are connected to how the DoW and warfighters should seek to develop systems that achieve ACE and foster an agile engineering framework due to the need for rapid iteration, low-cost development, and modular design. This allowed the team to confidently select this design for rapid prototyping.

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3.6 Physical Architecture and Prototype Development

After a six-month concept development phase, the team advanced to prototype development. To keep both the warfighter and industry involved in the agile engineering process, the team presented their ideations and concept selection to F-22 stakeholders during a critical design review (CDR). The stakeholders approved the team's design for prototyping as it met their requirements and operational needs. The team then selected a prototyping strategy using rapid and low-cost methods with iterative refinement, focusing on high-risk components identified from a Failure Mode and Effects Analysis (FMEA). Within one month of concept selection, the team developed their initial design as shown in Figure 5.

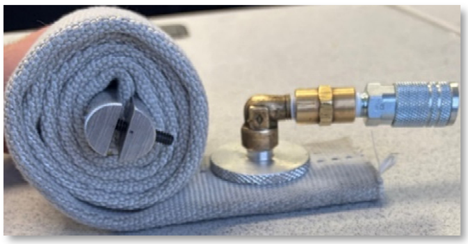

Figure 5. Initial Design

Figure 6. Iterated Design

Figure 7. Final Prototype

This design is a flexible hose assembly that internally stores jet oil. When the hose is rolled up using an aluminum cylinder attached to one end, it dispenses oil through a vacuum seal as intended by the tube-of-toothpaste concept. This design proved inefficient when evaluated in the operational use case of an MCA dispensing liquid from the widget into an F-119 engine mock-up. Test analysis showed that the metal roller did not provide sufficient leverage, and the vacuum seal requiring too many interfaces, which caused leakage. Using an agile and iterative prototyping sprint, digital engineering methods enabled the team to iterate a new design in two weeks. The iterated design, shown in Figure 6, integrates a quick-disconnect interface that connects directly to the F-119 engine and maintains the foundational tube-of-toothpaste design, as the concept design and trade study stages verified that it met functional and user requirements. The machined aluminum roller with outer grips was updated to improve manual torque generation, allowing the user to apply sufficient rotational force to dispense oil without external tools. The use of SolidWorks Computer Aided Design (CAD) modeling and rapid 3-D prototyping enabled the team to rapidly iterate updated interfaces whenever a part or measurement within the system architecture required modification. Further improvements led to a final prototype, shown in Figure 7, that required minor changes due to modularity. The modular 10-AN adapters enabled additions of an in-line filter, pressure gauge, and a direct connection to the quick-disconnect interface. While physical components remained consistent, the 3-D printed interface evolved into a milled-out piece of aluminum, which improved system durability, performance, and lowered manufacturing costs. The agile engineering process resulted in a prototype that minimized complexity, served customer and warfighter needs, and efficiently dispensed oil.

4. Results

The agile engineering approach was based on close collaboration with warfighters and industry, early requirement definitions, rapid prototyping, and digital engineering. This process led to successful tests of the widget being employed on F-22 engines and stored within the aircraft during a mission, successfully demonstrating how agile engineering methodologies can produce rapid and effective solutions for the warfighter. The final prototype, now called the Compact Oil Based Refill Apparatus (COBRA) and shown in Figure 7, supported updates to oil reservicing training orders to allow oil servicing while engines are operating, based on successful operational implementation on the F-22. Operational use case testing confirmed that the COBRA can enhance ACE capabilities for the F-22, fit within its internal storage, and withstand pressure differentials and high gravity forces. It also demonstrated the ability to dispense oil with a force greater than five psi and that an F-22 pilot or MCA can learn to operate the system within thirty minutes of training, eliminating the need for a career field maintainer to execute this task. Optical emission spectrometry testing also confirmed the use of Nitrile as the COBRA's interior liner because it did not contaminate the oil, therefore meeting containment requirements. The COBRA's modularity also proved that the use of COTS, such as the 10-AN fittings, can integrate other parts into the system like a pressure gauge, adapters, and hoses, showing its capability of being an iteration-based design. The total cost of one COBRA was also minimized to $1,687, representing approximately an 88% decrease compared to the original oil cart ($14,000). The cost minimization came by using COTS, 3-D printed materials, digital engineering, and early system architecture. The demonstrated capability of the COBRA led to operational implementation on the flight line and ongoing efforts toward achieving patent-pending status, successfully meeting ACE objectives and warfighter needs. After following an agile engineering approach, the COBRA's system lifecycle reflects similar agile development principles seen with the T-7 and Rapid Dragon programs, serving as a case study for the DoW in future system development.

5. Conclusion and Future Work

The rapid development of the COBRA proved to be a valuable case study, similar to the T-7A and Rapid Dragon programs, which provide evidence of how legacy systems within the DoW must adapt to incorporate agile engineering methodologies. These examples show that MDAPs would greatly benefit from implementing digital engineering, closer interaction with warfighters and industry partners, rapid prototyping, and modular design approaches. Transitioning to this agile approach will help the DoW engineer systems that mitigate cost overruns and schedule delays, become more mission effective, and develop integrated systems within a system-of-systems environment. Based on the COBRA's success, it is recommended that the DoW transition away from outdated engineering methods with an agile approach to deliver mission-effective systems.

Although the COBRA's success validates the recommendation for new strategies to address emerging threats, certain design methods could be improved in future work. The COBRA project would have benefited from creating a complete digital twin for stakeholders that outlines its connection to the F-119 engine. Outlining its complete architecture would function as an authoritative source of truth, enabling program managers and engineers to enhance communication, iterate faster, and ensure the system remains compatible within a larger system-of-systems architecture. This would help a program reduce development timelines, cut costs, and boost system effectiveness within a multi-domain environment. Finally, future research should explore further applications of the COBRA to enhance ACE capabilities for other fighter platforms. If the agile approach utilized throughout the COBRA's development continues to demonstrate success, the DoW could develop systems with smaller teams, budgets, and timelines; however, applying these methodologies to more complex systems will require additional coordination across stakeholders and engineering disciplines.

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