INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

FINDING OPPORTUNITIES FOR COMMONALITY IN COMPLEX SYSTEMS

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ABSTRACT
Many complex systems with similar functionalities are independently developed, entered into service, and must be supported throughout their lifecycles. Costs to support and maintain the systems could be decreased by employing strategies that increase commonality in the systems. We present a process for identifying opportunities and evaluating subsystems for increasing commonality in complex systems. Stakeholders can use our process to improve system management and decrease support costs of systems.

Keywords: commonality, functional decomposition, system architecture, taxonomy, lean

Disclaimer: The views expressed in this paper are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government.

1 INTRODUCTION: OPPORTUNITIES TO INCREASE COMMONALITY

Increased commonality provides several benefits to stakeholders. Having common parts and common interfaces can increase interoperability between systems [2]. In the manufacturing arena, commonality decreases manufacturing complexity [3]:

- Engineering component and design processes are streamlined
- Logistics benefits include less documentation and fewer suppliers to manage
- Material handling can be improved and volume discounts can be passed along the value chain
- Manufacturers may be enticed to make capital investments in tooling that may yield lower maintenance costs, faster set-up times, and better quality components

Other reasons for commonality include improved responsiveness to customer needs such as quicker system deliveries and higher production levels [4].

We found that independently developed unmanned aircraft systems (UAS) with similar missions often have overlapping functions. These overlapping functions are regularly implemented with unique physical instantiations, or form. Figure 1 shows the system architecture results of independent development. In these two systems we show that Systems 1 and 2 have common Function B even though they were developed independently.

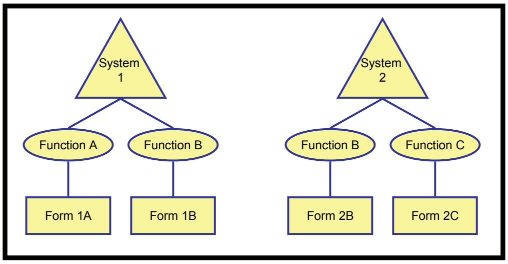


Figure 1 - Independently developed systems

Many reasons exist for these common functions, and they are manifested in the architecture as we show in Figure 2. Lean principles tell us that having multiple sub-systems performing the same function is a source of waste [5, 6]. To eliminate this waste, we can combine the implementation of Function B's related Form 1B and Form 2B into a common module of Form 1B. We need a process to identify the opportunities for commonality.

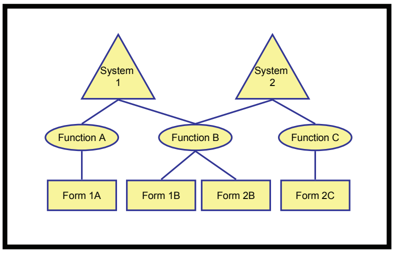


Figure 2 - Independently developed systems implementing common form

This paper provides motivation and a process for identifying potential opportunities for driving physical commonality into systems that were developed without commonality in mind. We developed a process that helps find opportunities for commonality in complex systems. We'll be presenting the method we used to find opportunities to increase commonality across unmanned aircraft systems. The process is executed in the following four major steps:

- a process to align stakeholders' understanding of systems;
- a method to perform black-box architectural functional decompositions;
- an analysis procedure to compare black box system architectures to identify commonality opportunities
- a validation step for stakeholders to confirm the validity of the recommended course of action

The results of the process inform the practitioner of the opportunities for commonality that can then be validated by stakeholders who may have widely varied interests in the system or system performance. We will show the process in detail in section 3.

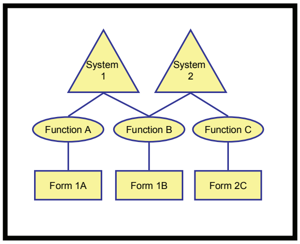


Figure 3 - Independently developed systems implementing common form

2 EXAMPLE PROBLEM AND PROCESS DEMONSTRATION: MULTIPLE SUBSYSTEMS PERFORMING THE SAME FUNCTION

2.1 Background

Many different unmanned aircraft systems (UASs) have been developed and fielded for many users. A recent survey of UASs resulted in 974 different systems in development, production, or service [7]. The list of missions that UASs perform[8] is much smaller than the number of types of UASs in service. For the sample included in our study, we focused on six UASs that are fielded or being developed for the United States Department of Defense. We selected these six systems because of their system complexity, their architecture which includes remote operation, and their operational altitude and loiter capabilities.

Many of these systems provide functionality that is duplicated in other systems. We asked ourselves, "How did these systems get acquired with different subsystems performing similar functions?" We looked at the acquisition strategies for UAS, the physical components of the systems, the prime contractor producing the system, the missions the systems perform and the lead service to find existing commonality at the highest levels (Table 1).

Table 1 - UAS characteristics [2, 7, 9, 10]

UAS	Acquisition Strategy	Contractor	Major Physical Components	Lead Service	Missions	Endurance (hours)
Global Hawk RQ-4	Advanced Concept Technology Demonstrator	Northrop Grumman	UAV, GCS (LRE+ MCE)	Air Force	ISR	32 (A-model) 28 (B-model)
Broad Area Maritime Surveillance RQ-4N	Derivative of Global Hawk initiative by US Navy	Northrop Grumman	UAV, GCS (LRE+ MCE)	Navy	ISR	TBD
Predator R/MQ-1A/B	Advanced Concept Technology Demonstrator	General Atomics	UAV, GCS (LRE+ MCE)	Air Force	ISR Strike	24+
Reaper (Predator B) MQ-9	Derivative of Predator by General Atomics	General Atomics	UAV, GCS (LRE+ MCE)	Air Force	ISR Strike	24+ (Clean configuration)
Sky Warrior MQ-1C	Derivative of Predator by General Atomics	General Atomics	UAV, GCS (LRE+ MCE)	Army	ISR Strike	40
Fire Scout MQ-8	Commercial helicopter derivative	Northrop Grumman	UAV, GCS	Navy/Army	ISR Strike Transport	6+

We chose the domain of unmanned aircraft systems (UASs) for our research sample because of (1) the DoD's increasing overall investments in UASs [2]; (2) the increased numbers of UASs being acquired [2]; (3) the history of the independent development of military weapon systems; (4) the clustering of major UASs contractors.

2.2 Example Problem – Communicating with transponders

One function that the larger unmanned aircraft systems (UAS) perform is identifying themselves to air traffic control (ATC) and other aircraft. This function is common to many UASs and aircraft. The common function of identifying is implemented through the use of transponders installed on each air vehicle. A transponder automatically replies to interrogation requests from ATC and specially-equipped aircraft. The military transponders used in our sample of UASs are also equipped with identification of friend or foe (IFF) functionality that is implemented in transponder modes 4 and 5. This IFF function is well beyond the capabilities of a commercial transponder.

Many different transponders with the same functionality are used in UASs. The processes to acquire and support the multiple transponders cause duplication of development, acquisition, maintenance and operational training, and logistics chains. We surveyed United States offerings of transponders in Jane's Avionics and found four military IFF systems, three military-use combined interrogator-transponders, and eleven transponders for civil use (without modes 4 and 5) which provide the basic functionality of receiving an interrogation from a ground or airborne system and replying with the vehicle's identification and flight information [11].

2.3 Example Process – Communicating with transponders

We first selected our domain of unmanned aircraft systems (UAS) for this study. Next, we surveyed UASs to find common functionality. We found common functionality by decomposing the functions

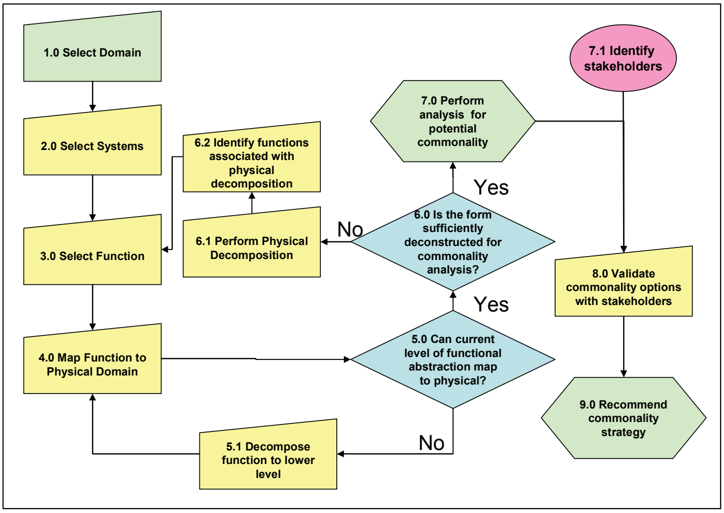


Figure 4 - Method for finding commonality opportunities

of the UAS (see methods section). The top-level function we used in this example is "Communicating." We decomposed communication into several sub-functions. One of these was "Identifying (self)." We determined that the UAS identifies itself to air traffic control (ATC) and other air vehicles and with Mode 5 to systems that have an attack function.

Next, we identified the generalized inputs, controls, outputs, and mechanism (ICOM) of the "Communicating//Identifying (self)" function and captured them in a matrix. Then, we entered the parameters for each of the ICOM fields for the AN/APX-100 and the AN/APX-119 transponders that are in use for UASs in our sample.

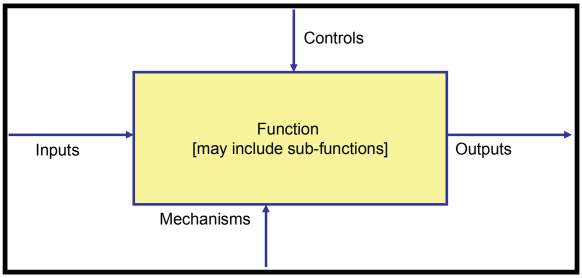


Figure 5 - Function model used to develop ICOM matrix

Generalized ICOM fields for System

[index]	Inputs	Controls	Outputs	Mechanisms
1	Interrogations	Size (mm)	ATC Reply	GPS
2	1030MHz	Length	Mode 1	
3		Width	Mode 2	
4		Height	Mode 3	
5		Weight	Mode A	
6		Volts DC	Mode C	
7		Watts	Mode S	
8		Operating Temp:	IFF	
9			Mode 4	
10			Mode 5	
11			1090 MHz	
12			429 Databus	
13			Ethernet	
14			1553B Databus	
15			RS-232	
16			RS-485	

Comparison Matrix APX-100 v APX-119 (Black=100; Red-119; blank=both)

[index]	Inputs	Controls	Outputs	Mechanisms
1				GPS
2				
3				
4				
5		.03 kg		
6				
7				
8				
9				
10			Mode 5	
11				
12			429 Databus	
13			Ethernet	
14				
15			RS-232	
16			RS-485	

Items in oval are capabilities the APX-119 has and the APX-100 does not have

ICOM Inputs for AN/APX-100 IFF/Mode S (Honeywell Aerospace)

[index]	Inputs	Controls	Outputs	Mechanisms
1	Interrogations	Size (mm)	ATC Reply	GPS
2	1030MHz	136.5	Mode 1	
3		136.5	Mode 2	
4		212.7	Mode 3	
5		4.53 kg	Mode A	
6		Volts DC	Mode C	
7		Watts	Mode S	
8		Operating Temp:	IFF	
9			Mode 4	
10			Mode 5 (future)	
11			1090 MHz	
12				
13				
14			1553B Databus	
15				
16				

ICOM Inputs for AN/APX-119 (Raytheon)

[index]	Inputs	Controls	Outputs	Mechanisms
1	Interrogations	Size (mm)	ATC Reply	
2	1030MHz	136.5	Mode 1	
3		136.5	Mode 2	
4		212.7	Mode 3	
5		4.5 kg	Mode A	
6		Volts DC	Mode C	
7		Watts	Mode S	
8		Operating Temp:	IFF	
9			Mode 4	
10			Mode 5	
11			1090 MHz	
12			429 Databus	
13			Ethernet	
14			1553B Databus	
15			RS-232	
16			RS-485	

Figure 6 - Comparison matrices for Identifying (self) function:
Upper Left - generic aggregation of all ICOM parameters for function;;
Lower Left - parameters of APX-100;
Lower Right - Parameters of APX-119;
Upper right - Difference matrix between APX-100 and APX-119

From the data available, we are able to make the following observations about the systems:
The sizes of the systems are the same. They appear to have the same form factors (based on pictures).

- **Inputs**: The inputs of the systems are the same. The transponders receive interrogations from other systems on a defined frequency.
- **Controls**: The controls for this system are the physical characteristics and system constraints. The data show the systems are physically the same. The only difference appears in the weight where the increased precision of the APX-100 system shows the weight to be .03 kg more than the APX-119.
- **Outputs**: Both have the same modes except that the APX-119 reports full Mode 5 functionality and the APX-100 has future plans to add the IFF capability. The APX-119 offers additional interfaces that the APX-100 does not provide.
- **Mechanisms**: The APX-100 reports an interface that allows direct integration with a global positioning satellite (GPS) system.

2.4 Example results – Communicating with transponders

This is the analysis that is required to perform the analysis to determine if the systems ***can*** be made common. These findings are then input into the process with the stakeholders to determine if the systems ***should*** be made common. In this case, the stakeholders will be asked about the requirements for the additional outputs the APX-119 provides and learn about any social issues that may preclude a commonality decision. If the stakeholders agree, then an analysis of alternatives is conducted if further analysis is warranted to make decisions.

3 DETAILED PROCESS FOR FINDING COMMONALITY OPPORTUNITIES

In this section we'll evaluate the unmanned aircraft system's sensing function for potential commonality opportunities. This example will provide additional detail into the process that the example problem (transponder) did not address.

When finding opportunities for commonality across systems, two fundamental questions must be asked:

- Can the function and form be made common?
- Should the function and form be made common?

The first question is based on requirements and technical issues. Do the functional capabilities of the proposed system meet the requirements of the current system? If the capabilities meet the requirements, we proceeded with our next question: Can the form of the proposed system meet the physical requirements and constraints of installing it in the new application? We developed a process to answer these questions and if the answers were both "Yes," then we involve the stakeholders to ask "Should the functions be made common?" [We did not include the stakeholder response in this paper; we focused on the "Should" aspects of the process for this publication.] After a stakeholder response is received about the appropriateness of the functional commonality, the final step is an analysis of alternatives that informs us if the form should be made common. This analysis is beyond the scope of our research because of the well-established expertise in the field.

To answer the questions of "can" and "should" commonality be increased, we developed a process that allows comparing systems across product and organizational boundaries to find areas of potential commonality with the following steps:

- Select domain
- Develop functional taxonomy
- Perform functional decompositions
- Identify common decomposed functions across systems
- Map the function into form
- Compare and analyze form to develop recommendations
- Validate with stakeholders

3.1 Select Domain

While the focus of the method is remaining in the functional domain as long as possible, an early concession to that focus was made to bound the solution space. We selected a physical domain of unmanned aircraft systems (UASs), to ensure the study space would be sufficiently limited for the study. A cross-sectional study of several classes of UASs led us to limit the scope to US military UASs that have a high or medium altitude endurance role. The systems selected can be seen in Table 1.

For this example, we remained in the domain of unmanned aircraft systems.

3.2 Develop functional taxonomy

The role of this step in the method is multi-purpose. The first purpose begins by identifying the highest-level of functions that the domain of UASs performs. The intent is to identify the continuum of all functions of the domain. After these high-level functions (also known as capabilities or missions) are identified, the functions are decomposed into lower-level abstractions to better understand the complex, high-level functions. The second purpose behind developing the functional taxonomy is to build a common dictionary. A common dictionary is important when comparing functions across organizational and cultural boundaries so that terms of reference are universally understood.

We divided the functional taxonomy into two parts which we named following Lean conventions as Value-added and Support functions. We defined Value-added functions as the elements that directly provide actionable information or interaction to the warfighter. These are the direct functions the system performs to execute missions. The Support functions are enabling roles the system must perform to operate. The warfighter does not interact directly with these functions and could be considered "black boxes" [12] by the system beneficiary. The black box functions include preparing for flight, moving (and flying), powering the system, recovering the system and maintaining for the next mission, and the internal communications required to control the air vehicle, coordinating airspace and monitoring the health and status of the UAV and its sensors.

The functional taxonomy provides the framework to build into the functional decompositions. For this example we used the functional taxonomy we developed for UAS in Figure 7.

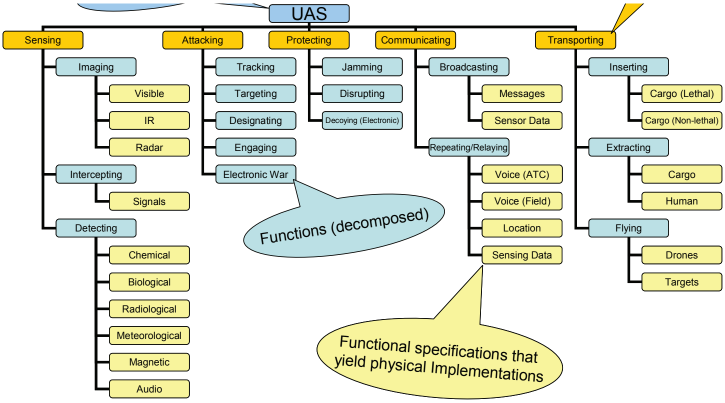


Figure 7 -UAS Taxonomy for value-added functions

3.3 Perform Functional Decompositions

Functional decompositions are performed by engineers to both simplify the functions of the system and allow rapid development by employing parallel design processes. Simplifying complex functional systems deconstructs the complex functions of the system into smaller chunks that can be better understood and facilitate fully documenting the functionality and the interfaces. The decomposition process is often used to both simplify allow parallel design processes[13]. We use the functional decomposition to improve the understanding of the systems and allow comparison of the decomposed functions as an entry point into developing units of analysis at appropriate levels of abstraction.
The functional decomposition for our sensing example began as analyzing the function of sensing visible light. The product from sensing the visible light would be seen as real time video. By entering into Figure 7, we can identify the functional decomposition as SENSING//IMAGING//VISIBLE.

3.4 Identify common decomposed functions across systems

This step is performed by first identifying all the functions of interest for each system. The functions present in each system are then compared. Intersections between functions in separate systems reveal the areas of commonality between two or more systems. After learning there was potential functional overlap in the area we started with the basic black box model [12] to perform function modeling.
We expanded the scope of the model and used the integrated definition language, or IDEF. We used the IDEF0 variant for the functional modeling. The IDEF0 model consists of an activity represented as a box and then has inputs, controls, outputs, and mechanisms (ICOM) connections [14].
The IDEF0 interfaces are defined in Table 2.

Table 2 - Interface and descriptions for IDEF0 activity models

Interface	Description
Input	transformed or consumed by the function to produce outputs
Control	specify conditions required by the function to produce correct outputs
Output	data or objects produced by the function
Mechanism	means that support the execution of the function

We performed this step by matching each of the systems in our sample (Table 1) with the SENSING//IMAGING//VISIBLE function to find functional commonality between the systems. We found that we needed to change our level of abstraction. As we looked into the systems that provided SENSING//IMAGING//VISIBLE, we discovered they were coupled with the infra-red (IR) sensing systems so we changed our unit of analysis to SENSING//IMAGING to cover both visible and IR sensing. The associated results are categorized in the IDEF0 and aggregated for all the systems in the ICOM matrix (Figure 8).

3.5 Map the function into form

The next step is mapping the system function into the form that implements the function. This allows us to see how the function is implemented and acquired. In the Department of Defense acquisition system, functional capabilities are procured and then implemented through the purchase of physical end items. These end items may implement a part of a function, a complete function, or multiple functions. These end items are the levels that systems are managed by item managers and systems are repaired, transported, and operated. This is the level of physical commonality.

For the SENSING//IMAGING function in our sample of UASs, the function is implemented with a "sensor ball" that is attached to the air vehicle. The sensor balls that have been commonly purchased are the AAS-52 and AAS-44. These systems provide IR and visible light full motion video, spot tracking, target ranging, and laser designating [1]. We captured the forms and interfaces of these two systems ICOM matrices. Then, we compared them by determining the differences between the two matrix representations.

Table 3 - AAS-52/44 and difference matrices

ICOM Inputs for System AAS-52 Functionality

[index]	Inputs	Controls	Outputs	Mechanisms
1	IR	900W	Laser designa	ambient light
2	Color	125	Sensor data	IR signature
3		Length	Spot tracker	
4		17.5	Target ranging	
5		Width	IR	
6		18.7	IR/TV wide	
7		360 deg	IR/TV m/w	
8		=60/-105	IR/TV med	
9			IR/TV narrow	
10			TV ultra narrow	

ICOM Inputs for AAS-44 Functionality

[index]	Inputs	Controls	Outputs	Mechanisms
1	IR	200W	Laser designa	ambient light
2	Color	114	Sensor data	IR signature
3		Length	Spot tracker	
4		16.65	Target ranging	
5		Width	IR	
6		14.8	IR/TV wide	
7		360	NA	
8		NA	IR/TV med	
9			IR/TV narrow	
10			none	

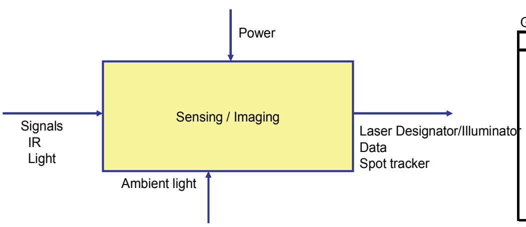
Difference Matrix (AAS-52 "minus" AAS-44)

[index]	Inputs	Controls	Outputs	Mechanisms
1		700W		
2		9		
3		Length		
4		0.85		
5		Width		
6		1.9		
7			IR/TV m/w	
8				
9				
10			TV ultra narrow	

3.6 Compare and analyze for to develop recommendations

We have implemented this step by identifying each of the physical flows (physical, energy, signal, [15] required to operate the system. In this case of the AAS-52 and AAS-44 (see Figure 9), the difference matrix revealed the AAS-52 is slightly larger in length and width and uses 700W more power than the AAS-44. In addition, the AAS-52 has an additional two modes: IR/TV medium/wide and TV ultra-narrow.

From our analysis through the ICOM difference matrix (included in Table 3). We determined that the



Generalized ICOM fields for Sensing / Imaging Functionality

[index]	Inputs	Controls	Outputs	Mechanisms
1	IR	Power	Laser designa	ambient light
2	Visible Light	Weight	Sensor data	IR signature
3		Length	Spot tracker	
4		Diameter	Target ranging	
5		Width	IR	
6		Height	IR/TV wide	
7		Field of view	IR/TV m/w	
8		elevation	IR/TV med	
9			IR/TV narrow	
10			TV ultra narrow	

Figure 8 - IDEF0 for Sensing/Imaging and associated ICOM matrix

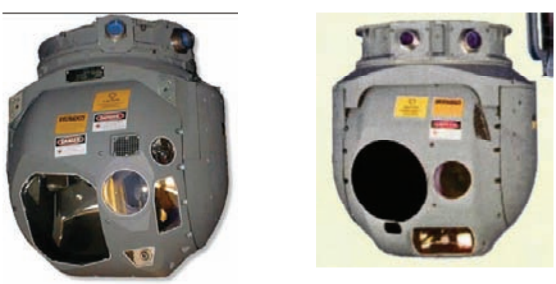


Figure 9 - AAS-52 & AAS-44 Sensor Balls [1]

AAS-52 could be a possible candidate to replace the AAS-44 in UAS or other air vehicle operations. Further analysis is required to ensure the physical tolerances will be compatible when installed into the next higher assembly. We are also concerned about the difference in power consumption. We would need to inspect the power budget of the air vehicle before committing to an upgrade for the additional functionality.

3.7 Validate with stakeholders

The stakeholders for UAVs have many varied interests that include cost savings, improved system and enterprise performance, reduced logistics management, better reliability, lowered system handling costs, improved manufacturing processes, improved system security and more. Some of the goals of stakeholders are in conflict with each other and must be considered and balanced.

- What characteristics of systems provide opportunities for commonality?
- How do stakeholders' interests affect decisions for commonality?

We did not receive validation comments back from our stakeholders in time for the publication deadline. We will be reporting our findings through the validation step in future publications.

3.8 Other comparisons performed

In addition to the transponder system we compared in the first example and the sensor ball compared above, we analyzed several other systems with varying results.

Ground control system generators: these generators provide power to the ground control stations when the power grid is unavailable. The size and weight constraints did not appear to cause any issues that would preclude commonality. However, we could not make a definitive recommendation because a power budget for the control stations was not made available for our research.

Communication radios: We found that ARC-210 radios with various configurations were used in multiple UASs. The ARC-210 radio system is considered to be a product family by Rockwell-Collins and offers many variants in common sizes. Radios seemed to be a good candidate for commonalty because of common interfaces and form factors.

Landing gear: An analysis of the landing gear systems revealed they are an unlikely candidate for commonality between Global Hawk and Predator. The stresses that the landing gear struts and wheels must bear vary greatly with the operational take-off and landing speeds and the weights of the air vehicles. Other air vehicles may be better candidates for landing gear commonality, but we did not discover those opportunities. We did learn that there is commonality between the Global Hawk and the Lear Jet 45 landing gear and the Global Hawk wheels are the same at the F-16 wheel assemblies.

Communicating Beyond Line of Site: We discovered that a major component that enables the remote operations to have a high level of commonality. The satellite link that receives signals from the UAS and translates them to the terrestrial network has great similarity between the Global Hawk's Tactical Field Terminal (TFT) and the Predator's Predator Primary Satellite Line (PPSL).

4 RELATED WORK

We were greatly influenced by the works in the areas of UASs and system architecture of Nehme on developing an operator functional taxonomy [9]. We used the operator functional taxonomy as a starting point when we developed the system functional taxonomy. The work on commonality in developing systems [16] influenced concepts on commonality, cousin, and unique parts. We applied his work to drive commonality into existing systems instead of studying the time-series decay of commonality in product families.

While several metrics have been developed to measure system architectures, modularity, and commonality [17-20], relationships between modularity indices and applications of commonality could help design for life-cycle supportability.

5 CONCLUSIONS AND FURTHER WORK

5.1 Method strengths and weaknesses

Our method's strengths include embracing the stakeholders concerns early in the acquisition process to avoid later rework from course changes. We bring stakeholders' interests into the otherwise technical task of determining potential for commonality and reuse in complex systems. Stakeholders may have reasons to support or go against increasing commonality and they should be understood. These reasons may be related to risk, culture, policy, strategy, political, security, or others. And, the reasons for or against commonality may not be able to be expressed for quantitative solutions. We believe the stakeholders' interests may be more important than the quantitative reasons for commonality in some systems.

Another strength of this process is that all the data for the systems exists. We do not depend on early development models with estimates of the system in our determinations. Much of the existing literature focuses on developing product platforms [21] and product families [22] instead of increasing commonality in fielded systems. While we do not suggest developing commonality plans based on modifying systems as an initial acquisition strategy, we offer this method as a way to increase commonality in systems that have been fielded.

Our process may require substantial effort to develop functional taxonomy and common dictionary. This task becomes more apparent if the domain of interest does not have a common language or understanding of functions across the systems.

Our analysis relies on qualitative analysis when performing pairwise system comparison. We are considering possibilities of expanding the analysis to set-based analysis to expand the number of systems that can be simultaneously considered for commonality.

5.2 Further work

We have suggestions for expanding the method.

First, we have not tested our method beyond the UAS domain. We would be interested in seeing the results of applying the method in a situation where a firm as acquired or merged with another firm and they wish to increase commonality across their merged product lines.

Second, after adding more data from multiple systems we would be interested in learning how the characteristics of systems cluster with potential for commonality. From this clustering, we would explore developing metrics that would quantitatively calculate commonality opportunities and predict the feasibility of increasing commonality in specific applications.

Third, we would next attempt to apply our method in developing systems. We see the potential for shaping systems in development by incorporating elements of existing systems. This method may allow increased opportunities for commonality in systems going through development processes.

Fourth, we understand that one scenario to be considered is the case of finding a competitor's subsystem that would be appropriate for commonality in another company's system. This does raise issues of proprietary data and how future acquisitions should be shaped with respect to open architectures.

5.3 Conclusions

We support increasing commonality across fielded systems as a way to resolve diminishing manufacturing sources, reducing life cycle costs, and eliminating duplicated functionality in the system. In this paper, we presented a method to help identify opportunities for increasing commonality across multiple unmanned aircraft systems, the domain of our study. Our examples showed the process and corresponding results using both modular systems (transponder and sensors) and a more integral airframe system (landing gear). We report the importance of aligning stakeholders, performing functional decompositions, a method to compare system architectures, and developed a validation step that engages stakeholders to help make system decisions.

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