The Internet of Things Applied to Command and Control Networks

by

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Abstract

The number of people and things connected to the Internet continue growing at an exponential rate. This record setting growth along with the reduction in small sensor costs and machine learning enabled a concept called the Internet of Things (IoT) to thrive. With numerous applications in both commercial and government spaces, the IoT has the ability to transform any organizations network capabilities.

The Air Force has a unique set of requirements centered on cyberspace superiority and the ability to command and control people and things. This paper leverages the traditional systems engineering “V” model as a framework to develop and analyze a concept for an Air Force command and control network. Methods and tools such as stakeholder analysis, hierarchical control structures and object-process diagrams are used to develop the concept of operations, system architecture, and the preliminary design. The programs technology readiness is also assessed before outlining key milestones and deliverables required for transitioning the program forward in the acquisition life-cycle.

Thesis Supervisor: Professor John Williams
Title: Professor of Civil and Environmental Engineering
Acknowledgements

Professor Williams, thank you for introducing me to the Internet of Things and the many other topics in your course. I am grateful for your time and focus on my interests and career.

SDM faculty and staff, thank you for developing and sustaining a world-class program that continues to provide real value to the military Fellows. The last 18 months have been both a challenge and joy. There is no doubt that your efforts will leave a lasting impact on SDM Fellows for years to come. Thank you.

Of course my deepest thanks are always due to my wife and children who continually provide me with their patience and motivation.
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Chapter 1: Overview

Introduction and Problem Statement

Technology continues to advance in accordance with Moore’s law.\(^1\) Semi-conductor costs continue to drop, network speeds are increasing with more advanced software and the number of people and devices connected to the Internet continue to grow. As a result, a concept referred to as the Internet of Things (IoT), first introduced in the 1990’s, describes a state where small devices with sensors are connected through a network to enhance system knowledge by continuous learning and feedback. Research continues in its applications and businesses are capitalizing and the benefits of the new trend by applying IoT to every day life. Proponents boast improvements in areas from farming and big data to environmental savings through the use of smart home devices to regulate energy consumption.

Not only are there commercial and social benefits, but the IoT has the potential to be an extremely disruptive technology that transforms military defense as well. The Department of Defense (DoD) continues to be a leader in advancing the state of the art in network communications and computing technologies. They led the pack through the early years of the Internet development, satellite communications and supercomputing. To remain a leader in technological advancements, they need to stay
relevant in current IoT trends and continue to look for applications and security threats from technology maturation.

This paper will cover future trends in IoT and many of the current applications in both the commercial and military world. It will start by synthesizing around several proposed definitions of IoT to arrive at a working definition. Using a systems engineering approach, the major processes of the engineering “V” from requirements development to architecture design will be used a guide to analyze an IoT system. A discussion of stakeholder needs and the development of a hierarchical control structure will lay the foundation for the remaining sections. Next, documenting requirements and system objectives will lead into design development. Using a variety of systems analysis tools, the concept of operations and a notional architecture for an Air Force command and control system will conclude the system analysis. The concluding chapters will also assess the technology readiness and key deliverables to transition the system from the science and research phase into concept development.

Setting the Stage

Continued advances in technology and the number of devices connected to the Internet have enabled the IoT to take off the way it has. Worldwide sales from the IoT is expected to
increase from $57.7 billion in 2013 to $103.6 billion in 2018.\textsuperscript{2} Trends Magazine outlined several the factors listed below that set the stage for the IoT concept.\textsuperscript{3} It was not just an advance in a single factor that led the charge but the combination of all of them that enabled the connected network of embedded devices to enable the variety of applications.

* Cheap Sensors
* Cheap Bandwidth
* Cheap Processing
* Smart Phones
* Wireless Coverage
* Big Data
* IPV6

In addition to the technological advances listed above, consumer behavior and spending also contributed to the emergence of the IoT. This trend is most evident in Millennials (ages 18-25) and Generation X (ages 26-35). A recent survey by Accenture\textsuperscript{5} shows that:

* Over half of Millennials plan to buy an IoT device for their home in the next five years.
* Nearly 60\% of Generation X plans to purchase wearable fitness technology in the next five years
A last factor that kick started the IoT movement is the exponential growth of the number of devices connected to the Internet. Today the number of connected devices out numbers the world’s population by 50%. Furthermore, the number of people on the Internet continues to increase. As seen below, Internet Live Stats predicts total number is now exceeding 3 billion.

To summarize, the combination of connected devices and people, consumer behavior and technology have enabled the IoT concept. The figure below shows the 4 IoT enablers.
Figure 2: IoT Enablers

Thesis Approach

The DoD follows a traditional engineering process for the design and development of major acquisition systems. Figure 3 below shows the various processes in the standard “V” model in addition to several technical management processes that support the engineering effort.⁵
This paper will focus on the first three technical processes of Stakeholder Requirements Definition, Requirements Analysis and Architecture Design. It will also cover Technical Planning and Technical Assessment. This framework will be used to analyze the IoT concept and also construct a notional architecture to assist in understanding the technology readiness and the work needed to advance the technology forward. Each section of the "V" will include a literature review of some of the relevant systems analysis tools. Then these tools will be applied to the subject command and control network to refine the architecture.
Thesis Objectives

Using this approach the objectives of this thesis are to:

1. Demonstrate how the IoT concept applies to an Air Force command and control network
2. Conduct a stakeholder analysis and outline systems requirements and objectives
3. Use systems thinking methods and tools to evaluate and develop the systems architecture

Definition

Kevin Ashton first used the term “Internet of Things” in 1999 but researches at MIT also are credited with using the phrase “The Internet of Things” when they spoke of combining RFID and electronic product code in their Auto-ID center (EPC). Network giants like Cisco define the term as “when the Internet and networks expand to places such as manufacturing floors, energy grids, healthcare facilities, and transportation”. Industry leading research company Gartner describes IoT as “the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment”. In their piece in Smart Sensors, Measurements and Instrumentation Mukhopadhyay and Suryadevara state “IoT is used to describe embedded devices (things) with
Internet connectivity, allowing them to interact with each other, services and people on a global scale."¹
Definition "When the Internet and networks expand to places such as manufacturing floors, energy grids, healthcare facilities, and transportation".

"The network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment".

"IoT is used to describe embedded devices (things) with Internet connectivity, allowing them to interact with each other, services and people on a global scale."

<table>
<thead>
<tr>
<th>Source</th>
<th>Cisco</th>
<th>Gartner</th>
<th>Smart Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>&quot;When the Internet and networks expand to places such as manufacturing floors, energy grids, healthcare facilities, and transportation&quot;.²</td>
<td>&quot;The network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment&quot;.³</td>
<td>&quot;IoT is used to describe embedded devices (things) with Internet connectivity, allowing them to interact with each other, services and people on a global scale.&quot;¹</td>
</tr>
</tbody>
</table>

Table 1: Comparison of IoT Definitions

The table above compares the definitions in the three sources cited. In order to synthesize these three opinions and arrive at working definition it is helpful to compare the similarities and differences. This technique will not only aid in the understanding of the definition but also set the stage to develop the concept.

**Similarities**

- A description of a network or connectedness
- Communication amongst embedded sensors
- Application to several industries or services
Differences

- Cisco mentions a condition or state and avoids using "things"
- Smart Sensors refers to an interaction on a global scale

IoT Redefined

It is reasonable to start with the similarities to piece together a new working definition. It might not necessarily be better but will have a hint of flavor from several sources. Table 2 below outlines the three major themes discussed above. The differences in the definitions can be dismissed with some discussion. It is reasonable to include a reference to a condition or state but it is not critical. It is also not crucial to use a reference to a global scale as the applications for the IoT can be realized locally. Even Barb Edson, a general manager at Microsoft Corporation challenges clients to not thinking about the trillions of embedded sensors and devices but focus locally on how the IoT concepts and technology can impact your things and business.⁹

<table>
<thead>
<tr>
<th>Theme 1</th>
<th>Theme 2</th>
<th>Theme 3</th>
<th>Theme 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connected network</td>
<td>Embedded devices or things</td>
<td>Enables communication</td>
<td>Widespread applications</td>
</tr>
</tbody>
</table>

Table 2: IoT Definition Themes
Based on the above discussion IoT can be defined as:

- A connected network of embedded devices which enables communication with widespread applications
Chapter 2: Stakeholder Requirements Definition

Introduction and Literature Review

The importance of meeting stakeholder requirements cannot be overstated. The International Council of Systems Engineers (INCOSE) goes so far to state that there is "unanimous agreement that successful projects depends on meeting the needs and requirements of the stakeholder". Requirements are difficult to develop and analyze unless the connected stakeholders and their needs are identified. Usually it is obvious whom your direct users and/or customers may be but it more difficult to determine if other entities should participate in the requirements generation process. Although not formally required, this extra step can save resources in the future through a mutual understand and documenting the coordination of requirements. For example, it may not be a primary concern to elicit requirements from stakeholders who are responsible for system disposal many years later. However, early coordination will aid in documenting the necessary requirements and avoid costly design changes down the road.
This section will begin with a list of the relevant stakeholders and their needs. It will also describe the relationships and information flows through a hierarchical control structure diagram. From there, Object Process Diagraming will be used to explain the primary concept and functions of IoT and its relationship between stakeholders in order to demonstrate and map information flow between stakeholders.
As previously mentioned, this paper is analyzing the applications of IoT principles to the use of an Air Force command and control system. The aim is to draw out some similarities to aid in the understanding of IoT and how it can enhance military capabilities focused on the systems acquisitions process. The Air Force follows the DoD’s standard gated approach for their product and design and development process. A notional flow diagram with milestones and decisions points is shown below in Figure 5.\[12\] This process starts with the identification of a requirement or need and guides the program through the entire life-cycle to implementation and even disposal.

![Diagram](image)

*Figure 5: Generic DoD Acquisition Process [10]*
Within this process, the assigned Program Management Office (PMO) is responsible to accomplish the reviews and take the required documentation to the Milestone Decision Authority for approval to the next phase. Specifically, a Program Manager (PM), following the guidance a Program Executive Officer (PEO), designs the program and executes the approved plan.\textsuperscript{13} The customer is generally within the same service like the Air Force or Army. However many times the acquisitions can cut across several services or agencies. For example the Air Force's Global Positioning System program serves customers in all military services and several other federal agencies like the Department of Transportation.\textsuperscript{14}

**Hierarchical Control Structure Overview**

Hierarchical controls and feedback is based on systems thinking and control theory. Systems theory author Peter Checkland writes about a concept where "the architecture of complexity is hierarchical and that different languages of description are required at different levels".\textsuperscript{15} In addition his theory deals with differences between various levels and the goal is to define and develop the interactions between the levels. Most important is the emergent properties that form out of the developed control structure. These properties are the
result of constraints, feedback and controls placed on the different controlled processes by the controllers.

Leveson explains this concept of control structures in her work in *Engineering a Safer World: Systems Thinking Applied to Safety*. She discusses how control structures have both a downward communication channel that provides information or constraints and an upward channel that provides feedback on the process. She used the below diagram to explain these communication channels.¹⁶

![Diagram of Communication Channels from Leveson](image)

*Figure 6: Communication Channels from Leveson [14]*

**Stakeholder Needs**

In the next section the interactions between stakeholders will be mapped-out but first it is necessary to identify the main stakeholder, their primary functions and needs moving on in
the design process. The primary need for this exercise is in the context relating to the IoT program office.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Primary Responsibility</th>
<th>Primary Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoD</td>
<td>Provide military forces to prevent war and protect nations security.</td>
<td>Develop effective acquisition systems.</td>
</tr>
<tr>
<td>Legislative Committees</td>
<td>Oversees military operations and expenditures.</td>
<td>Represent constituents, gain political capital.</td>
</tr>
<tr>
<td>Other Federal Agencies</td>
<td>Monitor and enforce regulations.</td>
<td>Job satisfaction, security.</td>
</tr>
<tr>
<td>Combatant Commands</td>
<td>Execute operational missions.</td>
<td>Protect military forces and win battles decisively.</td>
</tr>
<tr>
<td>Air Force</td>
<td>Train and equip air, space and cyberspace forces.</td>
<td>Design and develop effective systems.</td>
</tr>
<tr>
<td>Air Force Acquisitions</td>
<td>Oversight of acquisition programs and personnel.</td>
<td>Delivery effective systems on time and on cost.</td>
</tr>
<tr>
<td>AF PEO</td>
<td>Manages a portfolio of programs.</td>
<td>Experienced program managers, clear guidance from Air Force and DoD.</td>
</tr>
<tr>
<td>Acquisition Program Office</td>
<td>Deliver capable systems to operational units.</td>
<td>Clear requirements, sufficient budget and time, trained and experienced staff.</td>
</tr>
<tr>
<td>Operational Units</td>
<td>Operate deployed systems.</td>
<td>Training, manuals dialogue on requirements.</td>
</tr>
<tr>
<td>Development Contractor</td>
<td>Design and develop systems within cost, schedule and scope.</td>
<td>Clear requirements, direction and sufficient resources.</td>
</tr>
</tbody>
</table>

Table 3: Stakeholder Needs

As a government entity, acquisition programs are subject to congressional oversight in addition to a variety of DoD regulations and internal Air Force directives and instructions. The hierarchy of control includes several presidential appointed members of the DoD who are responsible for the acquisition as whole. It also includes career service members and government civilians who are responsible for various aspects of the program. These positions range from the program office jobs...
like a budgeting or contracting officer to different staff positions at the Pentagon who advise and assist the service’s leadership on the program’s executions status.

At first glance the relationships between stakeholder’s becomes confusing and responsibilities even more so. An organized and effective way to map out these relationships and responsibilities is through the use of a hierarchical control structure.

**IoT Program Hierarchical Control Structure**

Government organizations operate within a hierarchical structure where different entities provide feedback to or oversight on subordinate organizations. Other offices provide deliverables to higher headquarters like finance reports, design specifications, or other required documentation. Based on the control theory communication channels reviewed above, a notional structure can be developed to describe the relationships between stakeholders contained in an IoT program office.
Figure 7: Notional Acquisition Program Hierarchical Control Structure
The control structure in Figure 7 represents these communication channels and the various roles, responsibilities of the stakeholders surrounding a notional Air Force acquisition office. It does not cover all secondary stakeholders but it does provide enough detail to identify and analyze the primary stakeholders for a typical program office.

The figure depicts the two applicable areas of government in the Executive and Legislative branches. The President and his Executive Office’s provide strategy and guidance to the DoD and in return the department is obligated with meeting the objectives and fulfills various other reporting requirements. The DoD provides direction to the Combatant Commands or the elements of the military that operate and deploy defense systems. In addition, they provide direction to the services like the Air Force who are responsible for training and equipping the various commands.

The operational units provide requirements to the acquisition offices through staff organizations at a higher headquarters. Acquisition offices do not approve requirements but they do coordinate on the feasibility of meeting them. The program team provides requirements to a contracting team through the government's Request for Proposal (RFP) process and through the development process outlined in Figure 5 above. Through this
process, the system is developed and provided back to the operational units. For IoT technology, there is a possibility that the user will actually be the acquisition office. For example, applications in supply chain or subcontractor management could be useful for a PM to execute his program.

The right side of the figure shows the Legislative Branch and the two types of committees that provide oversight and funding of Air Force programs. The program offices often interact with staff members of the various committees but most communication happens at the service level.

Summary

This section provided a short overview of the DoD’s gated acquisition process focusing on the importance of the stakeholders involved. Specifically for an IoT system, the major players are the program office themselves and the primary customer is the end user in the operational unit or possibly in the program office. A hierarchical control structure described the interactions between stakeholders and began to show the complexity of the system and the significant oversight involved. Moving forward, these stakeholders and their interactions will be considered in developing the preliminary system design and architecture.
Chapter 3: Requirements Analysis

Introduction

Like stakeholder definition, requirement definition and analysis can make or break a program. Requirements add scope to a project and each individual requirement comes at a cost that should be evaluated for inclusion. Requirements have the ability to translate customer needs into technical specifications and drawings that begin to build the documentation needed for the system architecture and design. Early requirements solicitation, definition and allocation to subsystems are extremely important. The cost associated with changes later in the engineering process can be much greater than the cost of upfront rigorous systems engineering. It is not just the direct cost of implementing an engineering change but also the propagation of changes of that ripple through to other components and subsystems.

This section will begin with a discussion about some of the Air Force's high-level needs or capabilities that relate to IoT technologies. From that foundation, a notional list of system objectives will be documented to allow for the development of a system design and architecture in the next few chapters.
Core Capabilities and IoT Requirements

The Air Force develops and publishes its core capabilities in Air Force Doctrine Document (AFDD) 1. These functions are derived from legal roles and statutory responsibilities. The twelve core functions listed below are a decomposition of these roles and responsibilities.20

- Nuclear Deterrence Operations
- Air Superiority
- Space Superiority
- Cyberspace Superiority
- Command and Control
- Global Integrated ISR
- Global Precision Attack
- Special Operations
- Rapid Global Mobility
- Personnel Recovery
- Agile Combat Support
- Building Partnerships

Of these twelve functions, there are a few that seem to align nicely with the capabilities of the IoT. Most obvious is cyberspace superiority. The functions sub-elements include cyberspace force application, defense and support. Specifically
in cyberspace support the doctrine places emphasis on the ability to ensure availability of networks but also to "establish, extend, secure, protect, and defend" the missions that networks support.¹⁹

Command and control also aligns well with the IoT concepts. Sometimes called C2, this function is related to the degree of authority around all forces and missions. It relies on the ability to make decisions in a timely and effective manner. The Defense Information Systems Agency categorizes a C2 system as one that provides a commander the necessary information to make decisions.²¹

A third function that matches up with the IoT is Space Superiority. Again, there are multiple sub functions, one of which is Space Force Enhancement. Under this function are the missions of intelligence, surveillance, reconnaissance in addition to C2, and environmental monitoring.

All three functions surveyed above rely on a network of connected devices to perform a C2 mission. They all depend heavily on real time information from multiple platforms and the ability to synthesize large amounts of data to make critical decisions. These functions could benefit from the capabilities the IoT can provide. The working definition of IoT seems to fit perfectly in this discussion of Air Force core functions.
Now that the high level functional requirements are aligned to the general IoT concept, additional needs will be extracted out of AFDD-1 and compared to IoT capabilities. Below is a list of ten functional requirements that could be satisfied through the IoT.

**AF Functional Requirement**

<table>
<thead>
<tr>
<th>AF Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command and Control</td>
</tr>
<tr>
<td>Timely Decisions</td>
</tr>
<tr>
<td>Secure and Protect Networks</td>
</tr>
<tr>
<td>Establish and Extend Networks</td>
</tr>
<tr>
<td>Availability of Networks</td>
</tr>
<tr>
<td>Low Cost Acquisition</td>
</tr>
<tr>
<td>Timely Acquisition</td>
</tr>
<tr>
<td>Modular</td>
</tr>
<tr>
<td>Scalable</td>
</tr>
<tr>
<td>Maintainable</td>
</tr>
</tbody>
</table>
Notional Statement of Objectives

Now that the high level needs are identified, a notional set of system objectives can be developed that would provide some direction to the rest of the design process. These objectives will allow the formation of a concept of operation or ConOps and progress towards a detailed architecture. Numerical values for the various system objectives are also notional.

The analysis of needs above shows emphasis placed on the ability to provide C2 capabilities to decision makers. Not only does the information need to be accurate but provided in a timely manner but better yet, real-time. A reasonable first system objective is listed below.

System Objective #1: The system shall provide commanders enhanced C2 capabilities to include accurate real-time information about their area of responsibility.
The next area of importance is the idea of establishing networks. To be useful these networks should be highly available and protected from the numerous cyber threats.

*System Objective #2: The systems connected network shall approach 100% availability and minimizes external threats.*

A third category of needs covers the ability to quickly and efficiently acquire systems and deliver them to the operational users. This process needs to be quick in order to provide current technology and efficient to make the program cost effective. Low cost is also a customer need however for the purposes of this study it is difficult to quantify what cost is acceptable. Therefore a reasonable cost goal would be to keep management overhead costs under a certain target.

*System Objective #3: The system program office shall deliver new system to the operational users within one year of finalizing and reaching agreement on requirements and shall keep management costs under 7% of the system cost.*

The fourth objective targets the modular and scalable needs. As discussed in Table 3, the Internet continues to
expand at a rapid rate. The number of users continues to increase, as does the number of connected devices. Any IoT system, especially a military system, should be scalable to accommodate this expected growth rate. In addition, as technology continues to change with advances in semi-conductor speeds, the system should be modular to account for these technological advances.

System Objective #4: The system shall be designed to scale up to 20 times its current size. It should also be constructed in way to design and develop modular components with common interfaces and subsystems that are easily removed and replaced with improvements in technology.

A final object aims and reducing the cost and increasing the ease of maintenance. Network systems are complex and require qualified technicians and service contracts to perform the daily upkeep. Future systems should focus on ways to increase maintainability.

System Objective #5: The system shall maximize the ability to perform remote troubleshooting and maintenance from a centralized service facility. The system shall also have
the ability to self-diagnose issues and self-correct though redundant capabilities and systems.

Summary

The Air Force outlines its basic functional needs in AFDD-1. After a close examination of these needs, it is apparent that the IoT concept and associated technology would be a good platform to fulfill these needs in an efficient and effective way. Based on the current functional needs, system objectives were generated to guide the remainder of the design process staring with ConOps and architecture development.
Chapter 4: Concept of Operations

Introduction

This section will start with a discussion of the systems high-level ConOps. The ConOps will include an analysis of the users, technology, system description and operational scenarios.

System Description

The primary function for this notional system is to increase C2 capabilities for decision makers. To accomplish this function the system will establish, extend and protect networks to gain real-time information about the area of responsibility for the system’s users. The system will utilize existing commercial sensor, network and communications technology to minimize acquisition risk deliver a system to the user as quickly as possible. Through the use of small sensors integrated in a larger network, communication technology operators can gather and process data about their mission faster then before. A summary of the system description is provided in the table below.
To develop and refine this concept, the users, technologies, operational scenarios, the operational view will all be explored in further detail.

**Users**

For the purposes of this study, the system users will be a typical Air Force operations squadron for a communications network. This unit will have a Commander, Director of Operations and several branches in charge of various functional areas like network or user equipment. The unit will include active duty military, government civilians and private contractor network operations and maintenance personnel. The squadron maintains all the base switches, routers, servers, computers phones and other information technology equipment.
The squadron will have several other sister squadrons that conduct specialized operations or support functions specific to the base. For example, 50th Space Wing at Schriever Air Force responsible for the operations of Air Force space systems. Different groups and squadrons are charged with the operations and maintenance to fulfill the bases mission to “command satellites to deliver decision global effects”. The communications squadron, within the Network Operations Group, supports the mission by providing the various operational squadrons in the Operations Group information technology support and the transport of the data they collect and process to provide decision makers C2 capabilities. The communication squadron also supports the Mission Operations Group that
provides the many base support functions like medical care, civil engineering and security forces.

Even though there are IoT applications in multiple groups and squadrons in this organization, for simplicity, the ConOps will focus on the communications squadron.
Key Technology Overview

The IoT is enabled by a variety of communications and network technologies. Most systems rely on a technology type from each of the below categories. A brief discussion of communication and machine learning technologies are also outlined below.

- Communication technologies
- Network backbone technologies
- Hardware types
- Type of Protocol
- Software
- Cloud Platform
- Some type of machine learning

Communication technologies focus on getting information from one place to the next. On one end of the spectrum you can utilize printed-paper hand carried between two people to communicate. Recent advances in wireless technology have advanced the state of the art much beyond wired Ethernet to 4G LTE or Long-Term Evolution. Most have just noticed the benefits of higher cell speeds. Behind the scenes LTE technology is easier to deploy, has lower latencies and utilizes different interfaces for uplink and downlink, which optimizes the
connections. In the middle of the spectrum are lower bandwidth and more passive technology like Bluetooth and Radio-Frequency identification (RFID). RFID is an attractive technology for the IoT because it is relatively low cost and can be used to connect a large network of objects. The technology uses radio waves to help automatically identify a person or thing that the tag is attached to. Usually there is a unique number that identifies the thing and an antenna is used to communicate the objects information back to central receiver. It does not take long to visualize how a network of things with automatic RFID tags will instantly and virtually extend a network beyond its previous state.

Machine learning is probably closer to the cutting edge and has the biggest chance to change the landscape of the IoT. As previously discussed, technology is continuing to advance at a record pace and the costs of sensors and other technologies continue to decrease. As a result data is being collected at levels beyond what any human can comprehend. This phenomenon opens the door for the concept of machine learning to enter into the discussion. In his article in IT Professional, Seth Earley effectively outlines how the cloud and machine learning can enable both commercial and government operations. He uses a few examples from fitness bracelets to smart thermostats to show the
value of a large connected network of small sensors utilizes machine learning. What is most important about the date collected is what computers can predict about future use, not necessarily a record of usage. Probably the most valuable insight Earley provides is he prediction of what organizations must to do keep up with the competition. He warns that although big data and analytics have the ability to transform companies, they will be limited in their effectiveness if the organizations business model does not allow for them to fully utilize their capabilities. In sum, the organizations business model is no longer relevant. For example, the government may invest heavily in an IoT type infrastructure but its acquisition business model rigorous system engineering with lengthy design cycles would prohibit the system from reaching its full potential.
Operational View

Operational views help to visualize the system beyond a description in words. The DoD uses several operational views (OV) from OV-1 High Level Operational Concept Graphic to OV-6c Event-Trace Description. The OV-1 uses graphics to depict the system architecture and the missions and people involved in order to provide context for further system development. For the IoT C2 system, the concept starts with the network of sensors on virtually all the equipment the operations squadron operates. Many of the devices, like computers and services have built in sensors but the concept extends sensors to places like server rooms office doors, the outside of buildings and other customer spaces.

The Architecture Working Group of the IoT Forum Steering Committee developed an IoT Reference Model to help standardize the nomenclature and concepts surrounding the IoT. This framework provides seven layers of placeholders to provide users with a way to design and develop their own IoT Systems. More importantly, this model attacks the challenges of IoT expansion by increasing interoperability by increasing productivity and collaboration. At the very least, the model provides a common script all parties can use to discuss the IoT.
Using the above model as a starting point, the C2 system concept can be developed in more detail. The table below maps the reference model to the notional C2 system for a communications squadron. For each level of the reference model, a concept for the notional system is listed.
<table>
<thead>
<tr>
<th>Level #</th>
<th>IoT Reference Model</th>
<th>C2 System for Communications Squadron</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Collaboration Processes</td>
<td>Daily operations, network operations monitoring personnel</td>
</tr>
<tr>
<td>6</td>
<td>Application</td>
<td>Network status, outages, weather forecasts, # employees</td>
</tr>
<tr>
<td>5</td>
<td>Data Abstraction</td>
<td>Develop processing systems to compile and applied gathered data</td>
</tr>
<tr>
<td>4</td>
<td>Data Accumulation</td>
<td>Existing data storage devices</td>
</tr>
<tr>
<td>3</td>
<td>Edge Computing</td>
<td>Existing virtual server infrastructure</td>
</tr>
<tr>
<td>2</td>
<td>Connectivity</td>
<td>Existing network routers, switches</td>
</tr>
<tr>
<td>1</td>
<td>Physical Devices and Controllers</td>
<td>Computers, VoIP phones, webcams, security cameras, weather sensors, door alarms</td>
</tr>
</tbody>
</table>

*Table 4: IoT Reference Model Mapped to C2 System*

In addition to the reference model provided by the IoT architecture working group, the below IoT communications diagram developed by Diogo, Reis and Lopes aids in understanding the IoT operational view. This diagram shows the flow of information from the actor interacting with a smart device through a cloud service providing servers to other embedded devices. The diagram is simple but shows how simple the communication paradigm can be. The developers of this information flow also note that the clouds services need to be open in order to move
information effectively. Only then can machine learning take place and enable the benefits of IoT. This diagram can also be used as the foundation to develop an operational view for the C2 system for this paper. The diagram shows users, hardware, software and several required interfaces.

![IoT Communications Diagram](image)

**Figure 9: IoT Communications Diagram**

Based on the CONOPS discussion thus far, a basic OV-1 can be developed to tie together the system goal, description, and users. This view also helps in mapping the concept to the IoT
reference model along with the communications diagram. This operational view shows pictorially the flow of information from physical devices through the various levels to the people and processes that need the application provided. The bottom portion of the view shows a typical communications network layout with various users, switches, routers and servers. With the expansion into the cloud and utilizing satellite communications, the C2 network is expanded to include additional users, sensors and other devices. In this concept, the network operations center is able to gather, process and disseminate information gathered from video cameras, vehicles, cellular phones and other sensors like listening devices. The applications are vast and this view is simple but it allows for users to understand the basic concept of operations in order to have a detailed discussion about requirements and architectural decisions. Now that basic system concept is understood, the architecture will continue to be developed through drafting object-process diagrams and decomposing the form and function of the system.
Chapter 5: Architecture Design

Introduction

The architecture design process takes the user needs and requirements and begins to build a description of the system in terms of its form and function. The process aids engineers and managers to conceptualize the system in order to find ways to meet requirements in a creative way. The system architecture is the "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of design and evolution". The architecture is not the final design, but architectural decisions can limit the trade space for design future design options. Therefore it is important for the architect to develop clear and concise representations of the system to share with the design team. A systems structure also determines the emergent behavior it will produce. Developing a solid architecture can help to minimize undesired emergent behavior. Although the development of the system architecture is meant to reduce complexity, systems do grow and the complexity becomes so overwhelming that the system becomes inoperable and its behavior cannot be changed.

This section will first decompose the system in terms of its form and function. This analysis will provide the starting
point to develop object process diagrams to describe the systems primary and secondary functions as they relate to internal processes and objects of form. These diagrams will also provide a starting point to discuss the systems major architectural decisions.

**Functional Decomposition**

The use of hierarchies within a system is helpful to break the system into parts in order to better understand the individual pieces. These hierarchies are often shown in a system view or in an organizational view. This partitioning of relationships is particularly important to ensure all system life-cycle concerns are addressed. For the purpose of developing the architecture, the system hierarchy concept will be used to develop both a functional and form decomposition. The functional breakout starts with the primary function or purpose of the system at a "level 0" or the top level of the hierarchy. Below that is the various function or elements that the system is required to perform at a "level 1" layer. This breakout can continue as low as necessary to secondary and tertiary levels but it becomes difficult to dissect the functions below the third or fourth level. Figure 11 below shows a notional functional decomposition. It many ways it looks exactly like a basis organizational chart used in most
In terms of a functional decomposition of the command and control system, the hierarchy would start at "level 0" with the primary function discussed earlier. At the top level the primary function is to provide command and control capabilities.
At the next layer, "level 1", the three main functions are, extending networks, increasing communication and machine learning. These functions are derived from the primary function above and also from the working definition of the IoT and the main stakeholder needs.
At "level 2" the sub-functions start to decompose the system into more manageable parts. Starting with Function #1, extending networks, there are at least 3 such sub-functions. To extend the network, the system needs to place devices, connect devices and operate the network. The figure below shows the first function and its related sub-functions.

![Diagram showing functional decomposition]

*Figure 14: Level 1 and 2 Functional Decomposition A*

Function #2, increasing communication, also contains several sub-functions. This function is performed by collecting data, processing data, and sharing data. The figure below displays the second function and its sub-functions.
The remaining function is machine learning. Its functions also include sub-functions of gathering and processing data but combines a third sub-function of continuous improvement. The following figure lays out the three sub-functions of machine learning.
To summarize, the system includes a primary function, 3 major functions and each has multiple corresponding sub-functions. The sum of all these functions can be combined in single structure. The figure below shows this entire hierarchal functional decomposition.
Figure 17: C2 Network Level 2 Decomposition
Form Decomposition

Form is different from function in several ways. The easiest way to differentiate is to think of form as what the system is and function as what the system does. Crawley, Cameron and Selva define form as “the physical or informational embodiment of a system”. The system that is implemented has a form of its own and larger parts of the system can be divided into numerous smaller pieces of form. Like in a functional decomposition, this process starts at a “level 0” system layer and is dissected down as low as the architect wishes to break down the system. For the purpose of this paper and evaluating a notional system, a “level 2” breakout is sufficient.

At the top level, the system can best be described as a C2 network. By its very nature it is made up of small-interconnected devices that communicate as part of a larger system. The C2 network is developed by manufacturing or assembling various subsystems and components into a system that meets requirements. The figure below starts that form decomposition at the top level by assigning the name C2 Network.
At the next level the items of form are divided up into the major subsystems. Referring back to the IoT reference model, the top five layers of an IoT system can be contained within a single building or network operations center. The reference model lists these items as collaboration processes, applications, data abstraction and data accumulation. The items of form that perform these functions can be located in a single subsystem or location. For simplicity, these items can be compartmentalized into the network operations center. The remaining layers of the reference model describe two other subsystems of connectivity and peripheral devices. The peripheral devices subsystem includes layer #1 of the reference model. The connectivity subsystem covers the connectivity layer and edge computing layers of the reference model. The table below summarizes the reference model layers broken down by C2 network subsystem.
<table>
<thead>
<tr>
<th>IoT Reference Model Layer</th>
<th>C2 Network Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collaboration Processes</td>
<td>Network Operations Center</td>
</tr>
<tr>
<td>Application</td>
<td></td>
</tr>
<tr>
<td>Data Abstraction</td>
<td></td>
</tr>
<tr>
<td>Data Accumulation</td>
<td></td>
</tr>
<tr>
<td>Edge Computing</td>
<td>Connectivity</td>
</tr>
<tr>
<td>Connectivity</td>
<td></td>
</tr>
<tr>
<td>Physical Devices and Controllers</td>
<td>Peripheral Devices</td>
</tr>
</tbody>
</table>

*Table 5: Reference Model Mapped to C2 Network Subsystem*

As in the functional hierarchy, the items of form are decomposed into the "level 1" subsystems in the figure below. The reference layers are divided up into the three subsystems as seen in Table 5 above. Compartmenting the system into these three subsystems allows for further decomposition into additional subsystems and components that will continue to simply the system into manageable pieces.
First the items of form within the Network Operations Center need to be identified. Referring to the reference model again, the network operations center includes all physical items needed for data accumulation, data abstraction, application and collaboration processes. Data accumulation and abstraction is performed through various information technology hardware. Network servers, routers, switches and hard drives are able to accomplish these two functions. The connectivity subsystem, which includes the connectivity and edge computing items of the reference model, requires all the items that bring the network together. Looking back at the OV-1 from the CONOPS, this would include items like an antenna, the cloud hardware, relay satellites and additional servers and switches on the edge or outside the main operations center. Lastly, the peripheral
devices subsystem includes a mix of sensors and transmitters that are able gather and send data back through the connectivity subsystem to the network operations center. Table 6 below divides up the three subsystems into additional components.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Additional Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Operations Center</td>
<td>Servers</td>
</tr>
<tr>
<td></td>
<td>Switches</td>
</tr>
<tr>
<td></td>
<td>Routers</td>
</tr>
<tr>
<td></td>
<td>Hard Drives</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Antenna</td>
</tr>
<tr>
<td></td>
<td>Cloud Hardware</td>
</tr>
<tr>
<td></td>
<td>Relay Satellites</td>
</tr>
<tr>
<td></td>
<td>Servers</td>
</tr>
<tr>
<td></td>
<td>Switches</td>
</tr>
<tr>
<td>Peripheral Devices</td>
<td>Sensors</td>
</tr>
<tr>
<td></td>
<td>Transmitters</td>
</tr>
</tbody>
</table>

Table 6: Subsystems Decomposed into Components

At this point the hierarchical structure can be drawn down to the "level 2" layer. The figure below shows the entire structure broken out in the previous tables and figures.
Figure 20: C2 Network – Level 2 Decomposition of Form
Object-Process Diagrams Literature Review

The aim of most systems engineering tools is to analyze or simplify a system so it can be understood and therefore developed effectively. These tools also help identify several types of architectures. These architectures can be physical, functional, technical, and dynamic or operational. Object-Process Diagrams (OPDs) is one of these tools that puts objects or things and the processes that act on them into a simply language. OPD uses symbols and shapes to gather the items of form and function into a common language that users can understand. The hope is that through developing OPDs and simulating the interactions of the system, the architectural design can be improved. One of the creators of OPD, Dorv Dori, explains that systems all have three things in common in that they all have functions, structure and behavior. In OPD language, functions are synonymous with processes, structure with objects and behavior with states. The example from Dori’s book below shows a simple example of system that changes states. The legend includes an oval for the process, a rectangle for the object and the oval inside the rectangle box for the state of the object. In addition, arrows represent inputs and outputs.
Marrying changes Person from single to married.

Figure 21: OPD Legend Taken From Object-Process Methodology – A Holistic System Paradigm

The example in Figure 21 shows how a person changes state from single to married through the processes of marrying. In this case, the person is the object and the arrows show this transition from single to married through marrying.

C2 Network OPDs

Applying OPDs to the C2 network and IoT will aid in continuing to develop the architectural design. In the previous section both the top-level items of form were identified to start to develop the systems structure. In addition, the systems primary function and decomposed functions were also developed. To begin developing an OPD for the C2 Network, the main operand or person receiving value from the system is
identified. In this case the commander is provided command and control from the C2 network. The systems primary function, providing C2, is decomposed into the three “level 1” functions of increasing communication, extending networks and machine learning. Each corresponding process has an object that acts upon or handles each function. The NOC subsystem increases communication, the peripheral device subsystem extends networks, and the connectivity subsystem enables machine learning. Through the process of providing C2, the commander transforms his state from unaware to aware. In sum, this is the value that is provided by the system, to provide knowledge or information to the commander to make him aware of the area he is monitoring. Using the OPD development tool, OPCAT, the below figure was developed to model the systems structure and behavior.
The small boxes in the commander box represent his two states of "unaware" and "aware". The small triangle below the "Provide C2" process represents that the function breaks out into other sub functions. The line with the open dot on the end shows that the respective instrument handles that function.

An OPD diagram adds more depth to the architectural design than just the identification of structure and behavior in the previous sections. Decomposing the system by form and function are useful but those methods stop short of outlining any modeling any interactions or system states. Even the basic OPD
in Figure 22 provides much more insight into the systems structure, behavior and states than any traditional hierarchical decomposition tree. The basic decompositions, however, are not without value. They provide a useful starting point and put the system architect on the right track to simplifying the system into manageable pieces. As seen in this section, the basic decompositions also set the stage for OPD modeling. Based on those breakouts, further OPDs can be developed and modeled to continue refining the system architecture and explore additional system insights.

The systems sub-functions in Figure 17 will be used to start developing the next OPD layer (Figure 23 below). Building on the high level OPD above, the three main subsystems are further decomposed into their components. The black triangle represents this decomposition. The various components are listed alongside their respective subsystem. Furthermore, the systems supporting processes are listed alongside the different components. Each supporting process assists one or more object of form represented by an arrow. In addition, all the supporting processes are part of or contribute to the process of operating the network. The OPD still contains the Commander as the primary beneficiary with the same states of "aware" and "unaware". As seen in Figure 23, even modeling the systems structure and behavior at a "level 2" layer provides additional
insights and detailed interactions between components and functions. This information is not obvious looking at a traditional decomposition of form or function.
Figure 23: Detailed C2 Network Object-Process Diagram
Modeling through OPDs can add other details as well. Figure 24 below adds to the previous OPD by identifying each column as the appropriate process or subsystem. It also draws a system boundary around the functions and objects to clarify where to focus the architectural design. This allows the architect to identify system interfaces and begin develop specifications and interface control documents. This will reduce risk and issues with the system complexity especially around interface control. For the C2 network, the OPD below identifies several interfaces that the system interacts with. For this exercise the interfaces are taken from the hierarchal control structure in Figure 7 of Chapter 2. The items listed are primarily external departments or agencies that they system deals with throughout its life-cycle. Although this example uses primarily regulatory or organizational interfaces, it could also be beneficial to identify and model other physical or informational interactions.
Figure 24: C2 Network OPD with External Interfaces
Major Architectural Decisions

Up to this point the C2 Network’s initial system design has been developed. Based on the stakeholder needs and requirements, the initial CONOPS was constructed to allow for the development of functional and form hierarchal decompositions and Object-Process Diagrams. All these products are part of an initial iteration of the design. Before maturing the system design too far, it is important to identify the major architectural decisions that will enable or prevent future design decisions. For example, a decision now to use existing network equipment or software could cause future compatibility issues. In terms of this exercise, and the initial design of the C2 Network, a brief identification and discussion of the major architectural decisions will aid in future work. Outlining these choices also helps prevent system failure by predicting emergent behavior. This idea of emergence is common among system architects and refers to a state when the systems functions and objects interact to produce more or different functions.\textsuperscript{39} The initial development of the design choices below aim to both prevent unwanted emergent behavior and avoid the restriction of future design choices.
<table>
<thead>
<tr>
<th>Design Decision</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Size</td>
<td>Regional</td>
</tr>
<tr>
<td>Code Type</td>
<td>Open</td>
</tr>
<tr>
<td>Backwards</td>
<td>Highly compatible</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Highly Modular</td>
</tr>
<tr>
<td>Modularity</td>
<td>Intuitive</td>
</tr>
<tr>
<td>Usability</td>
<td>Complex</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>Active</td>
</tr>
</tbody>
</table>

*Table 7: Major Architectural Decisions*
Chapter 6: Technology Assessment and Planning

Introduction and Literature Review

Based on the initial work, the C2 Network is still a concept that needs to be further developed. Both industry and the DoD have similar process frameworks to mature a program from science or exploratory phase through design and development.

<table>
<thead>
<tr>
<th>LIFE-CYCLE STAGES</th>
<th>PURPOSE</th>
<th>DECISION GATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPLORATORY</td>
<td>Identify stakeholders’ needs</td>
<td>Decision Options</td>
</tr>
<tr>
<td>RESEARCH</td>
<td>Explore ideas and technologies</td>
<td>- Proceed with next stage</td>
</tr>
<tr>
<td></td>
<td>Refine stakeholders’ needs</td>
<td>- Proceed and respond to action items</td>
</tr>
<tr>
<td>CONCEPT</td>
<td>Explore feasible concepts</td>
<td>- Continue this stage</td>
</tr>
<tr>
<td></td>
<td>Propose viable solutions</td>
<td>- Return to preceding stage</td>
</tr>
<tr>
<td>DEVELOPMENT</td>
<td>Refine system requirements</td>
<td>- Put a hold on project activity</td>
</tr>
<tr>
<td></td>
<td>Create solution description</td>
<td>- Terminate project.</td>
</tr>
<tr>
<td></td>
<td>Build system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Verify and validate system</td>
<td></td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>Produce systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inspect and verify</td>
<td></td>
</tr>
<tr>
<td>UTILIZATION</td>
<td>Operate system to satisfy users’ needs</td>
<td></td>
</tr>
<tr>
<td>SUPPORT</td>
<td>Provide sustained system capability</td>
<td></td>
</tr>
<tr>
<td>RETIREMENT</td>
<td>Store, archive, or dispose of the system</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: INCOSE generic life-cycle stages

The INCOSE handbook outlines the generic life-cycle program stages in the table above.\textsuperscript{40} Based on the work thus
far on the C2 Network, it is appropriate to place the system in the exploratory research stage. This section will focus on this stage and the milestones and deliverables needed to advance the program onto the concept stage. The DoD utilizes a similar path to progress its systems throughout the life-cycle. The figure below shows these stages and associated gated reviews. Based on this framework, the C2 Network would still be in the pre-acquisition phase because no program documentation has been developed or taken to a Materiel Development Decision.

**Figure 25: DoD System Engineering Milestones**

The following analysis will start with an assessment of program risk and lay out some of the program challenges. This section will also outline the initial milestones and deliverables needed to refine the C2 Network concept into a mature system design and real program. In addition, a
notional list of milestones will be arranged to provide a sense of the programmatic complexity.

**Technical Readiness**

The gated review processes discussed above both hinge on the idea of readiness. For each gate or milestone there is a Milestone Decision Authority (MDA) who approves transition into the next program phase. One of the criteria evaluated is the Technology Readiness Level (TRL) of the proposed technology. An independent office using an object scale usually does this evaluation. One of the most common TRL systems used was developed by NASA (See Figure 26)\(^2\). A TRL is assessed for each item or component at level below the subsystem. The TRLs are rolled-up to the subsystem level and a number is assigned for each subsystem. For example, if a subsystem has four components and they all have a TRL of 6, it is likely that the subsystem will also be assessed at a TRL of 6. If a TRL is not at the desired level, a technology maturation plan can be developed to apply resources to bring the technology to the appropriate TRL before the next gated review.
Because not all systems are built for space applications, the DoD developed their own measurement for its systems. The table below lists more generic measurements with associated definitions. The table uses relevant or mission operations terms to substitute for the flight-tested terminology from NASA.
<table>
<thead>
<tr>
<th>Level</th>
<th>Definition</th>
<th>DoD DAG Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported</td>
<td>Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated.</td>
<td>Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept.</td>
<td>Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.</td>
</tr>
<tr>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment.</td>
<td>Basic technological components are integrated to establish that they will work together. This is relatively &quot;low fidelity&quot; compared to the eventual system. Examples include integration of &quot;ad hoc&quot; hardware in the laboratory.</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in relevant environment.</td>
<td>Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in a relevant environment.</td>
<td>Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in an operational environment.</td>
<td>Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and qualified through test and demonstration.</td>
<td>Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.</td>
</tr>
<tr>
<td>9</td>
<td>Actual system proven through successful mission operations.</td>
<td>Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.</td>
</tr>
</tbody>
</table>

Figure 27: DoD Technology Readiness Levels\(^{43}\)
The readiness assessment of the C2 Network technology is fairly straightforward. The process starts with evaluating the system architecture developed in Chapter 5 and bucketing the components into key or critical technologies. Based on this assessment, the technologies are compared to the DoD measurement above and assigned the appropriate TRL. The most challenging part of this exercise is the determination of a relevant environment. NASA developed this idea to ensure systems were tested in a "space like" environment and properly assessed before launch. For an IoT system like the C2 Network, the environments are many and can always be changing. For example, the system could be exposed in various climates or locations. It could also be exposed to hostile cyber or physical attacks. Exposure to these environments is contingent on stakeholder requirements and finalizing the major architectural decisions. For that reason, this TRL assessment will assume the system is operating under normal environment and threat conditions. Table 9 summarizes this assessment. Values are assigned based on engineering judgments and available information. As seen below, many of the technologies are proven systems based on commercial or readily available hardware. These systems are assessed at or close to a TRL 9. Alternatively, the processing and
applications software and technology exists but is not integrated into a system and tested in a relevant environment. These systems tend to hover closer to TRL 3 to TRL 5. In the end, the peripheral device subsystem is assessed at a TRL of 6, the NOC at a TRL of 4 and the connectivity subsystem at a TRL of 3. This assessment confirms that the C2 Network system belongs in an exploratory research or pre-acquisition phase. Generally TRLs need to be in the 4 to 6 range to be considered for entrance into concept development.

Based on this assessment, the system carries a moderate level of risk because of the additional research and testing needed to mature the key technologies. Following basic systems engineering and program management methods increases the chances of progressing the program along to the next life-cycle phase. The next section will address some of the relevant planning and scheduling considerations.
<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>TRL</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Operations Center</td>
<td></td>
<td>4</td>
<td>NOC is assessed at TRL 5. Majority of hardware is mature but several processes remain at TRL 5.</td>
</tr>
<tr>
<td></td>
<td>Switches</td>
<td>9</td>
<td>System proven. Commercial hardware readily available.</td>
</tr>
<tr>
<td></td>
<td>Routers</td>
<td>9</td>
<td>System proven. Commercial hardware readily available.</td>
</tr>
<tr>
<td></td>
<td>Servers</td>
<td>7</td>
<td>System Demonstrated in a relevant environment but interaction with collaboration and applications processes not tested.</td>
</tr>
<tr>
<td></td>
<td>Hard Drives</td>
<td>9</td>
<td>System proven. Commercial hardware readily available.</td>
</tr>
<tr>
<td></td>
<td>Process Data</td>
<td>5</td>
<td>Data processing for IoT C2 Network is not tested in relevant environment.</td>
</tr>
<tr>
<td></td>
<td>Data Application Process</td>
<td>5</td>
<td>Application processes not tested in relevant environment.</td>
</tr>
<tr>
<td></td>
<td>Data Accumulation Process</td>
<td>7</td>
<td>Prototypes near operational.</td>
</tr>
<tr>
<td></td>
<td>Collaboration Process</td>
<td>4</td>
<td>Basic technology components are integrated.</td>
</tr>
<tr>
<td>Connectivity</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Antenna</td>
<td>9</td>
<td>System proven through mission operations</td>
</tr>
<tr>
<td></td>
<td>Relay Satellites</td>
<td>9</td>
<td>System proven through mission operations</td>
</tr>
<tr>
<td></td>
<td>Switches</td>
<td>9</td>
<td>System proven. Commercial hardware readily available.</td>
</tr>
<tr>
<td>Category</td>
<td>Rating</td>
<td>Status</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------</td>
<td>------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Servers</td>
<td>7</td>
<td>Prototypes near operational for IoT applications</td>
<td></td>
</tr>
<tr>
<td>Cloud Hardware</td>
<td>4</td>
<td>Basic technology components are integrated.</td>
<td></td>
</tr>
<tr>
<td>Edge Computing</td>
<td>4</td>
<td>Basic technology components are integrated.</td>
<td></td>
</tr>
<tr>
<td>Machine Learning</td>
<td>3</td>
<td>Active research is underway.</td>
<td></td>
</tr>
<tr>
<td>Continuous Improvement</td>
<td>4</td>
<td>Basic technology components are integrated.</td>
<td></td>
</tr>
<tr>
<td>Peripheral Device</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>6</td>
<td>Technology is integrated and tested in relevant environment.</td>
<td></td>
</tr>
<tr>
<td>Transmitters</td>
<td>6</td>
<td>Technology is integrated and tested in relevant environment.</td>
<td></td>
</tr>
<tr>
<td>Place Devices</td>
<td>7</td>
<td>Prototypes near operational for IoT applications</td>
<td></td>
</tr>
</tbody>
</table>

*Table 9: C2 Network Technology Readiness Assessment*
Technical Planning

Some technical planning and development of an acquisition schedule is the first step to move the system along to the next life-cycle stage. This section will outline the required milestones and deliverables to ready the system for a Materiel Development Decision (MDD) or the first opportunity to transform the science and technology into a major system acquisition. This first milestone requires several forms of documentation but most important are the Initial Capabilities Document (ICD) and a Analysis of Alternatives (AoA). The ICD is the first real set of approved requirements from the stakeholders. AoAs can vary but they focus on comparing possible solutions in terms of programmatic cost and schedule and a sense of risk or technical complexity. In addition to those two documents, the program should also develop an initial Cyber Security Plan. This plan is required for all programs that include Information Technology. Although it is not usually required until later in the programs life-cycle, it would be beneficial to have a draft ready at the MDD to answer any significant program protection concerns. Other relevant deliverables would be a draft acquisitions plan, ConOps and Systems Engineering Management Plan. Again,
these documents are usually required until subsequent phases but a notion of the technical and programmatic plans would help in advocating for the program. The table below outlines these deliverables and several others leading up to the MDD gate.

<table>
<thead>
<tr>
<th>MDD Deliverables (12-18 Months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Stakeholder Analysis Complete</td>
</tr>
<tr>
<td>✓ Initial Capabilities Document Complete</td>
</tr>
<tr>
<td>✓ Analysis of Alternatives Complete</td>
</tr>
<tr>
<td>✓ Initial CONOPS Developed</td>
</tr>
<tr>
<td>✓ Draft Systems Engineering Management Plan Complete</td>
</tr>
<tr>
<td>✓ Draft Acquisition Plan Complete</td>
</tr>
<tr>
<td>✓ Cyber Security Plan Complete</td>
</tr>
<tr>
<td>✓ Initial Cost Estimate Complete</td>
</tr>
<tr>
<td>✓ Market Research Complete</td>
</tr>
<tr>
<td>✓ Technology Maturation Plan Complete</td>
</tr>
<tr>
<td>✓ Continue Research and Technology Development</td>
</tr>
</tbody>
</table>

Table 10: MDD Milestone Deliverables
Preparation for this first milestone requires a full time staff of a government and contractor workforce. Although the program will not have the support of an established program office, it should enlist the help of a mix of technical and management personnel. Also, the system engineering staff should have a background and current experience with information technologies and cyber defense. This small-dedicated team with some matrixed help from other functional areas could complete the required deliverables and coordination in approximately 12-18 months. Although the required deliverables are necessary for entrance into the next phase, continuing research and development of key technologies are more important for long-term program success. In addition, immature technologies are a valid reason to deny transition to the next life-cycle stage. Early investment in technology maturation will assist with integration and interface control issues later on. A reasonable goal is to develop these technologies to a TRL of 4-5 before the MDD. If the C2 Network capabilities are not desirable by the users, there are other applications worth considering. Some of these concepts will be discussed in the next chapter.
Chapter 7: Other Relevant Applications

Introduction

The C2 Network system is one application where IoT technologies and concepts can be used to increase Air Force cyber capabilities. Of course there are other applications that are worth discussing. Two such applications are in the areas of supply chain or subcontractor management and small satellites. It is also valuable to provide a brief overview of current commercial uses to demonstrate the breadth of IoT.

Commercial Applications

A brief search for journals and articles on IoT applications yields numerous results. Many of the published papers are proposing applications in health care, environmental monitoring, and even many home uses.

One promising concept is the environmental monitoring and control of server rooms. By placing several temperature and humidity sensors in communication rooms, data can be gathered to improve the operational conditions. Some concepts even use lasers to obtain a 3D model of server farms and devices to obtain more accurate and current device operating status.
In terms of healthcare applications, concepts span all corners of the imagination. Research is active in drug compliance\textsuperscript{47}, imagining\textsuperscript{48}, and heavy in wearable devices. One promising concept in wearable devices is based on the combination of multiple sensors. Originating from Toshiba, this idea uses both a wristband and a chest sensor to increase monitoring capabilities.\textsuperscript{49} These sensors can detect several heart metrics in addition to temperature and movement. This technology could be used in several hospital settings in addition to other personal uses. There could also be the potential for benefits for employees that perform physical labor, athletes and industries that produce a large amount of stress.

Probably one of the most well known applications is in home use climate control. This simple application cuts down on costs, energy consumption and increases personal comfort. Taking this idea one step farther, environmental monitoring and control is also valuable on a larger scale. Taking an office building for example. The entire energy consumption for each room or person, services like lighting and air-conditioning can all be tracked in real time and controlled with better effectiveness.\textsuperscript{50}
Military Applications

The C2 Network system is one of many concepts that could provide value to the Air Force and DoD. The commercial uses discussed above also have the potential to translate over to the military arena. Other applications do exist in supply chain and subcontractor management and small satellites.

Acquisition programs battle several challenges. As systems grow more complex, so do the issues surrounding supply chain and subcontractor management. IoT has the ability to transform the way systems are developed and managed. Starting from the piece part assembly and higher-level integration, applying the new technologies can track and detect system components from the start of production to the final assembly. Some research and architectural design work takes advantage of RFID sensors to optimize processes and management functions. In their paper in *Applied Mechanics and Materials*, Liang and Pan proposed a warehousing management function with six distinct modules. The system management function uses IoT technology and concepts to provide additional contract management functions and additional oversight using role-based assignments. Acquisition programs could use these concepts to locate, track and control the location and authenticity
of its materials and systems. Program managers can also provide more efficient contractor oversight by architecting a system that provides real-time monitoring of contractor location, material usage, work progress, and financial billing. Of course there are privacy issues with gaining too much information but having additional "eyes and ears" monitoring program success is worth exploring.

Satellite applications have great potential mainly because users already collect and processes large amounts of data. One idea is to utilize current space platforms and layer on machine learning to existing data collection and processing systems. By doing so you can take advantage of sensors' collecting weather, signals, imagery, radiation and location of monitored assets. This concept could be straightforward to implement as it utilizes existing sensors and thus requires an investment into the processing and machine learning software technologies. In the future, more sensors can be added to various platforms to fill any gaps users see. Similar to small satellite concepts, the aggregation of multiple sensors can exponentially increase performance.
Chapter 8: Summary and Future Research

The number of connected devices and people along with advances in technology has set the stage for the IoT to thrive. The IoT concept is transforming systems in commercial companies and has the ability to do the same for the military. Establishing a network of embedded connected devices to increase communication enables machine learning and the potential for continuous improvement.

Moving forward, additional research and development is needed to support the initial requirements and design work in this paper. Formal market research and requirements development would provide the basis for a detailed analysis of the system architecture. Additionally, a thorough cyber security plan based on the decomposition of potential threats and security concerns is needed to make the concepts proposed possible.

The research and analysis of this paper demonstrated how the IoT concept applies to a C2 network using systems thinking and traditional engineering methods. This paper completed a first design iteration of an Air Force C2 system by applying IoT concepts. A systems thinking approach followed the traditional systems engineering "V" model. Various methods and tools began refining the system concept and architecture. Stakeholder needs and
interactions were developed and used to develop a program hierarchical control structure. The stakeholder analysis led to a requirements analysis and the development of system objectives. Next, the system ConOps detailed the systems description and operational view based on a reference model from the IoT Architecture Working Group. Additionally, a decomposition of the C2 Network system allowed the architecture to be modeled using object-process diagrams showing the systems structure and behavior. Finally the key technologies were assessed using a TRL scale and led to the development of technical deliverables to move the program into concept development.
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