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THESIS

**CONCEPT OF OPERATIONS FOR USING COMPUTER
VISION CAPABILITIES ON TACTICAL AIRCRAFT**

by

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June 2018

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**CONCEPT OF OPERATIONS FOR USING COMPUTER VISION
CAPABILITIES ON TACTICAL AIRCRAFT**

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ABSTRACT

The integration of computer vision with existing naval aircraft sensors presents an opportunity to leverage data that is normally overlooked or discarded. Every day, sensors that are designed to aid aircrews in navigation or targeting collect thousands of hours of imagery that could be used for intelligence gathering. With no intended effect on aircraft mission and aircrew procedures, computer vision could be installed as an add-on capability.

This thesis develops a basic concept of operations (CONOPS) for integrating computer vision onto tactical naval aircraft. It explores the capabilities of sample aircraft to check the feasibility of aviation-based computer vision. The procedures and demonstrated capabilities of the Surveillance, Persistent Observation, and Target Recognition (SPOTR) system were used as a starting point for the CONOPS. Subject matter experts were solicited for their initial thoughts and feedback of draft CONOPS. The basic engineering process was used as a framework in which to develop the CONOPS.

The comparatively short timeline and low cost that an add-on computer vision feature could be added to aircraft make systems like SPOTR a viable option to bring a new capability to the warfighter.

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LIST OF ACRONYMS AND ABBREVIATIONS

APB	acquisition program baseline
AS	acquisition strategy
ATARS	Advanced Tactical Air Reconnaissance System
AWCFT	Algorithmic Warfare Cross-Functional Team
BUNO	bureau number
CCMD	combatant command
CMC	Commandant of the Marine Corps
CONOPS	concept of operations
CPRG	Command Patrol and Reconnaissance Group
CPU	central processing unit
CVRS	cockpit video recording system
DAS	Distributed Aperture System
DIA	Defense Intelligence Agency
DNI	Director of National Intelligence
DoD	Department of Defense
DoN	Department of the Navy
DOTMLPF-P	doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy
EMCON	emissions control
EOTS	Electro-Optical Targeting System
FMB	Office of Budget
FMV	full motion video
FOC	full operational capability
FY	fiscal year
GAO	Government Accountability Office
GCC	geographic combatant commander
GCCS	Global Command and Control System
GEOINT	geo-spatial intelligence
GPS	global positioning system
GPU	graphics processing unit

GUI	graphical user interface
HAWK	Hercules Airborne Weapons Kit
HUD	heads-up display
IC	Intelligence Community
IFF	identification friend or foe
IOC	initial operational capability
IR	infrared
IRST	infrared search and track
ISIS	Islamic State in Iraq and Syria
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capability Integration and Development System
JCS	Joint Chiefs of Staff
JIPCL	joint integrated prioritized collection list
LIDAR	light detection and ranging
MAGTF	Marine air-ground task force
MINOTAUR	multi-int operations technologies and unification research
MCIA	Marine Corps Intelligence Activity
MWIR	mid-wave infrared
NATO	North Atlantic Treaty Organization
NGA	National Geospatial-Intelligence Agency
NIPF	National Intelligence Priorities Framework
NRO	National Reconnaissance Office
NSA	National Security Agency
ONI	Office of Naval Intelligence
PED	processing, exploitation, and dissemination
RADAR	radio detection and ranging
RF	radio frequency
RFI	request for information
ROE	rules of engagement
SATCOM	satellite communications
SBIR	Small Business Innovative Research
SDK	software development kit

SHF	super-high frequency
SIPR	Secret Internet Protocol Router
SPINS	special instructions
SPOTR	Surveillance, Persistent Observation, and Target Recognition
SSR	solid state recorder
TDL	tactical data link
TSS	Target Sight Sensor
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
USMC	United States Marine Corps
USN	United States Navy
USV	unmanned surface vehicle
UV	ultraviolet
VTR	video tape recorders
VTRS	video tape recording system
WGS	wideband global SATCOM

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I. INTRODUCTION

Current aviation platforms in the Navy and Marine Corps are equipped with a variety of sensors including visible spectrum video and images, infrared (IR), radio detection and ranging (RADAR), and light detection and ranging (LIDAR) sensors. The combination of this vast amount of data and the lack of manpower to sort and tag the data results in large quantities of this data being underutilized or discarded. Commercial computer vision provides a solution by tagging, sorting, and prioritizing in real-time images that contain objects of interest. While efforts are in progress to use computer vision on newer aircraft, especially unmanned aerial vehicles (UAV), there is little work being done to retrofit older aircraft with computer vision technology.

A. OBJECTIVE

This thesis develops a basic concept of operations (CONOPS) for the integration of computer vision onto existing manned and unmanned Navy and Marine Corps aviation platforms. This study uses Surveillance, Persistent Observation, and Target Recognition (SPOTR) software as an example product. By installing minimal hardware onto aircraft, computer vision software can tag, sort, and prioritize actively- or passively-collected imagery. Using existing data links, such as Link-16, detection systems could send high-priority imagery back to analysts before the aircraft returns to base. The objective is to extract important information from large amounts of raw data and transmit this information to the appropriate agency as quickly as possible. The development of this CONOPS addresses the following questions:

1. Does the fleet currently have computer vision capabilities?
2. Does SPOTR offer enhancements to that capability?
3. How would SPOTR be employed on to airborne platforms with minimum intrusion into existing systems?
4. How is SPOTR trained for objects of interest for specific missions? Who does that training?

5. How are detections, classifications, and identifications passed to other potential customers? Is SPOTR designed to provide a confidence level in its detection algorithms?
6. What other changes to operational practices would be required to best leverage computer vision? Can this vision be extended to other sensor regimes, such as acoustics, LIDAR, and RADAR?
7. What changes across the doctrine, organization, training, materiel, leadership, personnel, facilities, and policy (DOTMLPF-P) spectrum might be required to best employ computer vision?

B. BACKGROUND

In the summer of 1966, as an attempt to use summer workers effectively, MIT professors Marvin Minsky and Seymour Papert assigned the task of developing computer vision to a group of about ten undergraduates. This project was called “The Summer Vision Project” and had three goals: The first goal was to divide images into sectors of likely objects, likely background objects, and chaos. The second goal was to describe each region. The third goal was object identification which matched each object with a vocabulary of known objects. Minsky and Papert expected this to be a summer project, but it ended up being the beginning of decades of research. As these researchers figured out, teaching computers to “see” is a much harder task than one would expect (Papert, 1966). Tasks that are seemingly easy for a human can be extremely difficult for a computer and vice versa. Figure 1 emphasizes this fact by showing how determining exact location is easy for a computer, but determining whether or not something is a bird is difficult.

Today, computer vision is used in many forms. Some examples include barcode scanning, fingerprint scanning, virtual reality, facial recognition, Snapchat filters, Xbox Kinect, industrial robots, and even the yellow first down marker seen in most football broadcasts. These examples vary in difficulty for a computer, but enhance our daily lives.



“In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to use a camera to identify objects in a scene. He figured they’d have the problem solved by the end of the summer. Half a century later, we’re still working on it” (Munroe, 2014).

Figure 1. Task difficulty. Source: Munroe (2014).

1. Computer Vision

In the most basic sense, computer vision aims to pull relevant data and make useful decisions using imagery collected from sensors (Shapiro & Stockman, 2001). To make these decisions, computers will most likely have to describe or categorize the objects that are detected (Shapiro & Stockman, 2001). Because of this, Shapiro & Stockman (2001, p. 1) pointed out that many experts would say “the goal of computer vision is the construction of scene descriptions from images.” Another publication describes computer vision in a similar way:

Computer Vision has a dual goal. From the biological science point of view, computer vision aims to come up with computational models of the human visual system. From the engineering point of view, computer vision aims to build autonomous systems which could perform some of the tasks which the human visual system can perform (and even surpass it in many cases) (Huang, 2018).

Fisher et al. describes terms commonly used in the field of computer vision including:

- Computer vision— “A broad term for the processing of image data” (Fisher et al., 2014, p. 55). It is commonly compared with machine vision, image processing, and pattern recognition. It generally emphasizes understanding instead of automation.
- Machine vision— “A general term for processing image data by a computer” (Fisher et al., 2014, p. 162). The general trend is to use machine vision as a more practical application, such as an industrial setting, while computer vision is used in a more exploratory sense.
- Machine learning—“A set of methods for the automated analysis of structure in data” (Fisher et al., 2014, p. 162). This is broken down into two subtypes. Unsupervised learning looks for interesting patterns or structure in the data. Supervised learning is also known as predictive modeling. Its goal is to predict the value of an unknown variable based on the input of other variables.

While computer vision and machine vision could be synonymous based on the industry, this thesis will use the term computer vision because of its less structured environment and broad variety of target applications.

Object detection, classification, and recognition are different tasks of computer vision, increasing in difficulty in that order. Object detection tries to figure out at the most basic level what is in a picture. For example, it tries to determine how many ships or trees are in a picture and annotate them appropriately. Object classification takes detection one step further and tries to determine what type of class an object is. For example, it may try to determine if a ship is a destroyer, or a tree is an oak. Object recognition seeks to determine if objects in different pictures are actually the same object. The picture may be taken at different times, angles, lighting, etc. Object recognition is especially useful for objects that have the ability to move. Figure 2 shows how a computer can detect and highlight objects of interest in various settings. Not only does the computer determine if an object is in an image, it makes an attempt to describe what it “sees” with a level of certainty.

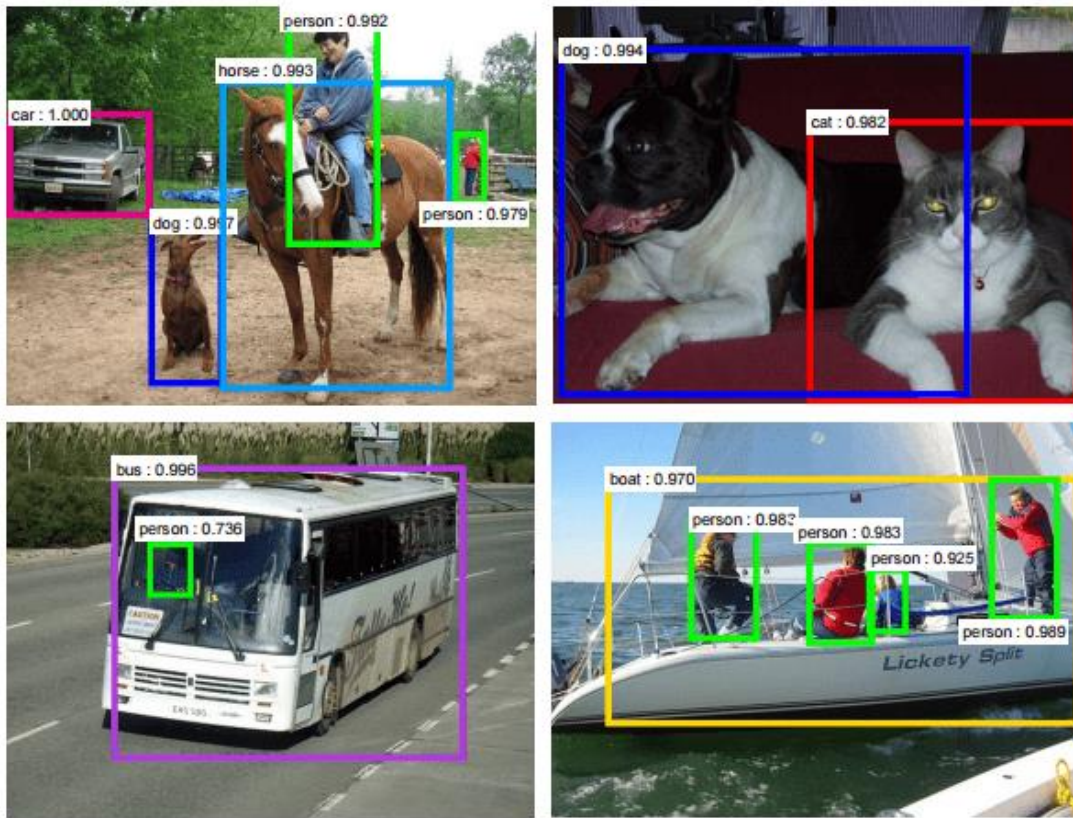


Figure 2. An example of object detection. Source: “Object Detection Deep Learning” (2018).

2. Naval Aviation Imagery Collection

Naval aviation imagery collection has advanced from the days of simply using a pilot’s eyes and memory to collect intelligence to a networked environment of multiple sensors capable of collecting data from across the electromagnetic spectrum. The goal of the U.S. Marine Corps is to move towards a strategy where “every platform contributes and functions as a sensor, shooter, and sharer” (United States Marine Corps [USMC], 2017). Similarly, some of the U.S. Navy’s first principles of intelligence, surveillance, and reconnaissance (ISR) include (Department of the Navy [DoN], 2010):

- Every platform is a sensor
- Every sensor is networked

- Plug-n-play sensor payloads
- Collectors dynamically tasked
- Data discoverable and accessible
- Commonality in interfaces, data links, and control stations

These principles are fully supported by the integration of computer vision on existing platforms.

C. METHODOLOGY

The methodology used in this thesis included a review of current capabilities by examining relevant publications for aircraft, communication systems, computer vision, naval doctrine, and naval policy. Further, it included discussions with subject matter experts in the fields of naval intelligence, naval aviation, and computer vision. The resulting CONOPS draft was proposed by the author based on these sources. Subject matter experts gave their feedback and the author incorporated the revisions into the CONOPS that is presented.

D. ASSUMPTIONS

In theory, computer vision could be fully integrated into the operational flight program of each tactical aircraft. Depending on the type, complexity, and number of sensors, such integration could cost hundreds of millions of dollars to design, test, integrate, and deploy. This thesis assumes that computer vision is a separate add-on capability that is not completely integrated into all aircraft systems. Rather, computer vision is connected to the aircraft sensor feed and to a data transfer interface, if the aircraft is equipped with one. This thesis assumes that the pilot and aircrew have no knowledge of anything that the computer vision may detect, classify, or identify, and that the computer vision is not a requirement for their mission. Computer vision should not interfere with the primary mission of an aviation platform. The author believes that this is a practical assumption that appreciates the potential large integration costs involved in fully integrating computer vision. Incorporating computer vision into the full system layout is a topic for follow-on research.

E. LIMITATIONS

This thesis is limited to developing the process flows of using computer vision on existing aviation platforms. The sampling of aircraft in this thesis is not all-inclusive, however even the installation of computer vision in the sampled aircraft would, in the opinion of the author, make this project worthwhile. This thesis does not address the technical details of how to physically install new hardware, as this will vary greatly depending on platform, nor does it address the process of certifying new equipment for airworthiness. It does not examine any potential legal issues with using computer vision over United States territory and citizens.

F. THESIS LAYOUT

Chapter II reviews the literature that identifies the key knowledge concepts required to understand computer vision, appreciates the art of developing a concept of operations, and provides background on a sampling of manned and unmanned naval tactical aircraft. Chapter III explains of the methodology used to develop and refine the basic ideas of the CONOPS. Chapter IV is the presentation of key ideas of the CONOPS. Chapter V presents conclusions and recommendations for future research.

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II. LITERATURE REVIEW

In theory, computer vision offers a chance for increasing battlespace awareness, reducing missed opportunities, and improving the analysts' effectiveness and efficiency. This chapter presents reasons why computer vision would be useful on manned and unmanned aircraft; how computer vision works; particulars about the various tactical aircraft and data links related to the use of computer vision; the information flows within the intelligence community; and a background on the components of a concept of operations.

A. COMPUTER VISION

Computer vision can rapidly detect if an object of interest enters the image's field of view. For a human, however, this is an exhausting task. A study by Langley (2012) found that Air Force intelligence personnel were "nearly six times more likely to report high levels of exhaustion than non-intel airmen, and 2.5 times more likely to report high levels of cynicism." Exhaustion leads to poor performance. Military services cannot train and retain enough personnel to keep up with the every-increasing amount of data captured by today's sensors (Chappellet-Lanier, 2017). Even in a unit that has enough intelligence personnel to watch video feed live, the intelligence analysts may miss important details. To be sure nothing was missed, analysts may have to re-watch footage, adding to their workload. The 2013 Unmanned Systems Integrated Roadmap further describes this problem:

As more and more sensors arrive on the battlefield and those sensors' capabilities increase, more data are delivered to warfighters, but the warfighters' ability to process and exploit such a large volume of data in a timely fashion is increasingly challenged. The problem is also exacerbated on both ends of the transmission link. Either huge volumes of data must be downsized before their transmission, or the data highway on which they travel must be increased in size and speed

Further, after reception, the data must be used by analysts to draw conclusions for the decision makers. If the data are already formatted and arrive prioritized, fewer analysts are required to take advantage of the intelligence. Similarly, if the various databases are archived in a standard

way, the various warfighter intelligence cells will use far fewer analysts to exploit databases and draw conclusions (Department of Defense [DoD], 2013).

As demand for bandwidth in the electro-magnetic spectrum increases, the need for efficient data flow increases. The use of computer vision could reduce the amount of data sent over communication links by tagging and prioritizing imagery before transmission. Even on systems that already downlink all sensor data to a ground station (such as a live video feed for piloting), computer vision could prove useful by presorting data or sending high priority data over a separate network other than the one used by the UAV's control station.

1. Current Efforts

Two current efforts involving computer vision and information sharing are Project Maven and Project Minotaur. The former focuses on using computer vision without the emphasis of spreading computer vision capabilities to aviation platforms. The latter seeks to provide a network of information-sharing systems that can be placed on multiple aviation platforms, but does not emphasize computer vision capabilities.

a. Project Maven

In April 2017, Deputy Secretary of Defense Robert Work signed a memorandum that established the Algorithmic Warfare Cross-Functional Team (AWCFT) also known as Project Maven (Work, 2017). The goal of the AWCFT is to turn vast amounts of data into intelligence upon which decisions can be made. According to Secretary Work's guidance, the initial task is to field technology that augments or automates the processing, exploitation, and dissemination (PED) of full motion video (FMV) from tactical and mid-altitude UAVs in use against the Islamic State in Iraq and Syria (ISIS). This technology may come in the form of computer vision algorithms capable of object detection, classification, and alerts (Work, 2017). Additional tasks of the AWCFT are to:

1. Organize a data-labeling effort, and develop, acquire, and/or modify algorithms to accomplish key tasks.

2. Identify required computational resources and identify a path to fielding that infrastructure.
3. Integrate algorithmic-based technology with Programs of Record in 90-day sprints (Work, 2017, p. 1).

In his memorandum, Secretary Work (2017) stresses the urgency of fielding this new technology. To speed up the process of fielding this technology, the AWCFT will consolidate other algorithm-based technology initiatives such as artificial intelligence, automation, machine learning, and deep learning. According to USMC Colonel Drew Cukor, head of the AWCFT in the Intelligence, Surveillance, and Reconnaissance Operations Directorate-Warfighter Support, if the implementation of computer vision goes as planned, in the future one intelligence analyst should be able to do two to three times as much work as they are currently doing (Pellerin, 2017). The immediate focus is on 38 classes of objects that need to be detected in the fight against ISIS (Pellerin, 2017). Data labeling is the first step in developing these classes. From the labeled data, the algorithms can be trained. As quoted by Pellerin (2017), Colonel Cukor described the data labeling process:

That work is inherently governmental and so we have a large group of people—sophisticated analysts and engineers—who are going through our data and cleaning it up. We also have a relationship with a significant data-labeling company that will provide services across our three networks—the unclassified and the classified networks—to allow our workforce to label our data and prepare it for machine learning.

Project Maven’s emphasis is on using computer vision to extract useful information from imagery that is already collected by dedicated ISR assets. It currently is not focused on expanding computer vision capabilities to non-ISR assets, nor is it focused on using imagery collected by non-visual sensors such as RADAR (Allen, 2017). However, it is intended to be a “pathfinder” for other projects across the DoD (Allen, 2017). Those working on the project credit its success up to this point to “a small, operationally focused, cross-functional team that was empowered to develop external partnerships, leverage existing infrastructure and platforms, and engage with user communities iteratively during development” (Allen, 2017). Progeny Systems, the creator of SPOTR, is working with Maven to handle the naval part of their efforts.

b. Project Minotaur

Developed by the Johns Hopkins Applied Physics Laboratory, the Minotaur Mission Processor is used for airborne surveillance of maritime surface traffic and is currently being fielded by the Navy, Air Force, and Customs and Border Patrol aircraft (Anderson, 2016). It is an “automated intelligence correlation processor” that can be installed on aircraft or ground terminals (Anderson, 2016). Minotaur analyzes data from sources such as sea search RADARs, electromagnetic spectrum sensors, and video cameras (Anderson, 2016). It integrates the data from these sensors into a complete picture that it can share with other aircraft (Giangreco, 2016). Its capabilities allow it to detect, track, and classify targets. Captain Jeffrey Czerewko, director of the Battlespace Awareness Division in the office of the Deputy Chief of Naval Operations for Information Warfare, said that Minotaur will “enable one operator to do the work that would normally take three” (Anderson, 2016). Minotaur goals differ slightly from the goals outlined in this thesis. The project attempts to build an information-sharing picture focused on tracking, not a computer vision system focused on detection. At the time of this writing, the amount of money required to accomplish these goals has not yet been allotted to the program.

2. Overview of Computer Vision

Much like the development of the mind of a child, the development of a computer vision capability involves feeding a computer with enough sample data for it to eventually make an intelligent decision on its own. The way in which a computer learns is extremely complex. The method described in this section applies to computer vision systems in general, but uses the specific methods and capabilities of the SPOTR system as an example case.

a. Annotating and Training

According to Karsten Steinhaeuser (email to author, March 28, 2018), enabling computer vision to identify new targets requires the two-step process of annotating example images and training the system. An annotator must pull images from various sources, such as Internet searches or other intelligence sources, then outlines and labels the object of interest within that image. As the number of example images increases, a

computer vision system will be able to better identify potential matching targets. Increasing the number of example images, however, taxes the time of the annotators. For a typical target, annotators can generally annotate an adequate number of images during an overnight shift (K. Steinhäuser, email to author, March 28, 2018). This timeline assumes between a half dozen and one dozen annotators and an image database from 100 to 10,000 images. If the timeline is not urgent, then fewer annotators can be used. The amount of example imagery, while currently the usual limiting factor, should increase in the future. If no example images exist, trainers can update the computer vision system using customized 3D rendered objects, such as those found on commercially available video game like Call of Duty, or an artist's rendition of a 2D image. Annotators also tag "negative samples" which are images that do not contain the object of interest. Around fifty different types of annotation tasks exist including:

- Single Point
- Line
- Bounding Boxes
- Four Point (front, back, left, right). This method tends to be more accurate than bounding boxes for certain annotation tasks.
- Polygons
- Text Annotation
- Video Annotation with Tracker

After the images are annotated, the system must be trained. The length of time that this process takes, again, varies depending on the number of images required, with one day usually being a safe estimate if there is already a baseline model trained (K. Steinhäuser, email to author, May 16, 2018). If there is no baseline model, then training can take several days in a worst-case scenario. Initially, manually annotated images are required, but as the database of annotated images increases, a computer vision system can look for similarities and ask a trainer if the image actually is what the system thinks it is. In other words, the process goes from the trainer telling the computer what it sees to the computer asking the trainer if what it thinks it sees is indeed correct. Training also includes the use of negative

samples. They may contain objects that closely match intended targets of interest that, without the trainer's help, would initially be indistinguishable by the computer.

Machine learning is the process by which the computer updates its database to be able to recognize new objects. With such a complex algorithm, the designers of the system may not actually know how the computer is learning. At any point, the computer may use any combination of size, shape, color, shading, orientation, context, or a number of other features to update its knowledge of an object.

b. Detection, Classification, and Recognition

Computer vision's goal is to detect, classify, and recognize targets whenever the training and raw data make it feasible. Through the use of central processing units (CPU) and graphics processing unit (GPU), computer vision is able to achieve near-real time processing, although detection of objects in a recorded file is also possible. A key capability for aviation is that computer vision is able to learn both nadir and non-nadir (or oblique) targets, an important feature for aircraft that routinely operate at different altitudes and attitudes. Figure 3 illustrates the difference between nadir and oblique angles.

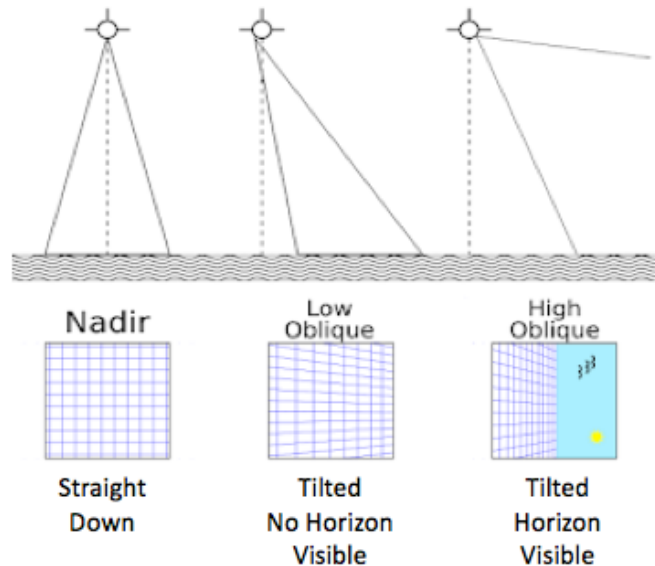


Figure 3. Nadir and oblique viewing angles

The ability of computer vision to detect an object depends on the number of pixels on target. The resolution of the entire image, however, is of lesser importance. The closer the sensor is to the item of interest, the better the computer vision is capable of detecting, classifying, and identifying the object. Generally, 40 pixels lengthwise is required to detect people and vehicles, and 60 to 80 pixels is the minimum requirement to detect ships. Increased distance requires higher zoom, which may introduce jitters onto the image.

If a computer vision system can recognize the same object over a long period of time, it can develop a pattern of life profile of the object. The system can then make predictive models of what to expect in the future. The system can then flag any deviations from this norm.

Computer vision tools can filter images based on its confidence level. The confidence level is a measure of how accurate the computer thinks its guess is. Insufficient training data or significant overlap of characteristics of another object may cause a decreased confidence level.

c. SPOTR Specifics

Surveillance, Persistent Observation, and Target Recognition (SPOTR) is a project in development by Progeny Systems Corporation located in Manassas, Virginia (Faltelier, Steinhäuser, Duong, & Paradis, email to author, October 2, 2017). According to their website, Progeny Systems' mission is "to be a trusted provider of innovative, cost-effective technical solutions and quality products while maintaining positive relationships with our customers, vendors, and employees." (About us, 2018). SPOTR was derived from Small Business Innovative Research (SBIR), with an expiration of data rights of 8 June 2025 (Faltelier et al., email to author, October 2, 2017).

According to an internal brief, Computer Vision & Imagery Analytics, SPOTR is a "suite of image processing, computer vision, and pattern recognition tools" (Faltelier et al., email to author, October 2, 2017). It is a software package that uses machine learning to adapt its techniques instead of only utilizing static templates, features or patterns (Faltelier et al., email to author, October 2, 2017). It also comes pre-programmed for generic applications such as people or vehicles; however, specific DoD targets of interest

would need to be programmed into the system (Faltemier et al., email to author, October 2, 2017). SPOTR is modular in design which allows it to work with a wide variety of GPUs or CPUs (Figure 4 is an example) and storage equipment, which in turn, allows for rapid prototyping and customization (Faltemier et al., email to author, October 2, 2017). Different aircraft platforms could use different processors based on the video output interface of their video equipment. The SPOTR system works on Windows and Linux as a software development kit (SDK) or as a stand-alone application (Faltemier et al., email to author, October 2, 2017).

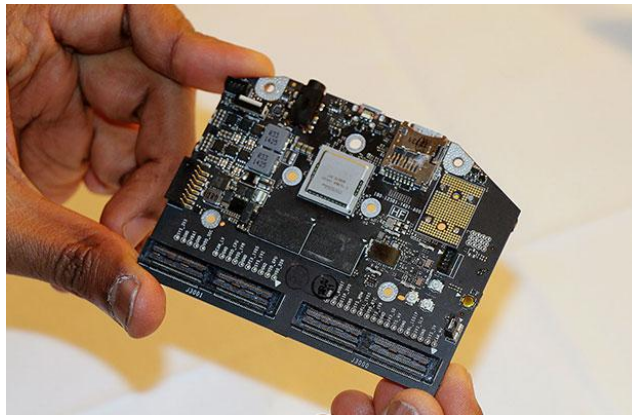


Figure 4. Example of SPOTR hardware. Source: Faltemier, Steinhäuser, Miller, and Paradis, email to author, October 2, 2017.

According to Karsten Steinhäuser (personal communication, March 24, 2018), three user tools exist or are in development. The first is a graphical user interface (GUI) that is web-based for uses on multiple types of devices. This GUI is used for the searching and extraction of intelligence from collected data. Figure 5 is a screenshot of the SPOTR for geo-spatial intelligence (SPOTR for GEOINT or “SPOTR-Geo”). SPOTR-Geo is specifically used for aerial/overhead imagery. There are other GUIs for other applications such as surface, tower, and other viewpoints (K. Steinhäuser, email to author, May 16, 2018). In this image, SPOTR has been configured to look for ships in a port. The web interface of SPOTR can be run on the Secret Internet Protocol Router Network (SIPR) or networks of other classifications. The second tool is used to task SPOTR devices installed on aircraft. This tool is currently under development and will be used to send short tasking

commands via a communications link. The third tool is used to annotate imagery for training SPOTR and is also under development.



Figure 5. Screenshot of the SPOTR web interface. Source: Faltemier, Steinhäuser, and Miller, email to author, March 28, 2018.

SPOTR has been successfully employed on several UAVs and unmanned surface vehicles (USV). In one exercise, SPOTR was able to increase the number of vessels of interest from 10 to more than 100 in a 10-day span. In another exercise at Camp Pendleton, it was able to detect ground-based objects of interest.

3. Potential Capabilities

The Navy and Marine Corps employ a very diverse inventory of manned aircraft which outnumber the current number of UAVs in the Naval service. Each of those aircraft is equipped with sensors that could leverage computer vision. Tables 1 and 2 show the variety of aircraft type and mission projected for fiscal year (FY) 2017 through 2019. While this table does not consider the hours flown by each platform, the variety of mission types and aircraft sensors could bring added value to the intelligence gathering.

Table 1. DoN Aircraft inventory by year (Office of Budget [FMB], 2018)

Class Category	FY 2017	FY 2018	FY 2019
Attack	271	278	273
Fighter	57	58	58
In Flight Refuel	77	79	78
Patrol	185	206	209
Rotary Wing	1,057	1,085	1,084
Strike Fighter	1,132	1,145	1,042
Tilt Rotor	279	295	311
Training Jet	278	279	277
Training Prop	310	324	311
Training Rotary	115	113	115
Transport	103	107	108
UAV	54	83	99
Utility	30	29	29
Warning	99	104	100
Total	4,047	4,185	4,094

Table 2. DoN Aircraft Inventory by service (FMB, 2018)

	FY 2017	FY 2018	FY 2019
Primary Authorized Aircraft (PAA)—Active	3,289	3,586	3,556
Navy	2,219	2,362	2,314
Marine Corps	1,070	1,224	1,242

The number of UAVs in military service is only expected to increase in the future. While larger UAVs may be able to incorporate additional hardware, smaller UAVs may have issues with the additional weight. Fortunately, UAVs usually have some sort of data link, which almost always includes real-time video for use by their controllers. In these cases, the computer vision system could be installed in the ground terminal rather than the aircraft itself. The categorized imagery could be sent over the ground terminal’s network connection to the appropriate intelligence agency.

The bottom line is that it is time for Naval aviation to embrace computer vision and leverage it daily. As mentioned, fully integrating computer vision into advanced aircraft will be quite expensive, but adding computer vision capabilities, such as SPOTR, as an

add-on to existing sensors, may not be so difficult. In the case of helicopters, strapping on small form factor capabilities which weigh less than a pound but add considerable capability, seems like an obvious idea.

B. AIRCRAFT CAPABILITIES

Imagery collection systems already exist on several aircraft currently employed by the U.S. Navy and Marine Corps. An exhaustive survey is beyond the scope of this thesis; however, the following sampling, which spans multiple mission types, provides examples of systems that computer vision could complement. Aircraft like the unmanned MQ-4C Triton are capable of long dwell times at high altitudes, providing a persistent view at a long distance. In contrast, the AH-1W provides less dwell time, but at a much lower altitude and different look angle. These two aircraft generally operate over different domains, maritime and land, respectively.

1. F/A-18C/D/E/F Hornet/Super Hornet

The McDonnell Douglas F/A-18C/D Hornet is currently in use by the U.S. Marine Corps for fighter and attack missions and is the primary bridging platform for the transition to the F-35B and has a planned sunset of 2030 (USMC, 2018). The mission statement of the F/A-18C/D is to “support the MAGTF commander by providing supporting arms coordination, conducting multi-sensor imagery reconnaissance, and destroying surface targets and enemy aircraft” (USMC, 2018). It is equipped with an APG-65/73 RADAR, AN/AAQ-28 LITENING Pod Gen 4 (Figure 6), and the Advanced Tactical Air Reconnaissance System (ATARS on F/A-18D only). These systems allow F/A-18C/D to collect RADAR, visible light, and infrared (IR) imagery. The aircraft is able to record video of what the pilot sees through the heads-up display (HUD), including HUD symbology. Its network systems include Link-16, LITENING ROVER downlink, and Intrepid Tiger II (USMC, 2018).



Figure 6. F/A-18 AN/AAQ-28 LITENING Pod

The earlier version of the F/A-18A-D (bureau numbers [BUNOs] 161353 to 164912) are designed to record the RADAR, visible light, and IR imagery using its video tape recording system (VTRS) (DoN, 2017a). Through a composite video link, this system is able to store a minimum of thirty minutes of footage onto one removable 3/4-inch U-matic tape cartridge (DoN, 2017a).

The later version of the F/A-18A-D (BUNOs 164945 and up, and 163985 to 164912) are designed to record the same types of imagery using the cockpit video recording system (CVRS) (DoN, 2017a). The CVRS utilizes two 8-mm video tape cartridges that provide a minimum of 120 minutes of recording time (DoN, 2017a). The pilot can set both the VTRS and CVRS to record continuously or during specified events (DoN, 2017a).

The F/A-18E/F Super Hornet, manufactured by Boeing after its merger with McDonnell Douglas, is currently in use by the U.S. Navy. The left and right digital display indicators (DDI) are capable of displaying a customizable layout of engine and system status and RADAR and weapon videos. Like the Hornet, the Super Hornet can record video feed of the pilot's HUD with symbology superimposed. The CVRS uses either video tape recorders (VTR) or solid state recorder (SSR) (DoN, 2017b). The VTR provides a

minimum of 120 minutes of record time on removable 8-mm video tape cartridges (DoN, 2017b). The SSR provides a minimum of 180 minutes of record time on a removable memory module (RMM) (DoN, 2017b).

2. KC-130J Super Hercules

The Lockheed Martin KC-130J Super Hercules is in use by the U.S. Marine Corps as a multi-mission combat assault support airframe. Its mission statement is to “support the MAGTF (Marine Air-Ground Task Force) commander by providing air-to-air refueling, assault support, close air support (CAS), and multi-sensor imagery reconnaissance (MIR)...” (USMC, 2018). Typically, the KC-130J flies aerial refueling and transport missions at altitudes in the 20,000 to 25,000 feet range, but is capable of flying low-level missions down to 300 feet above the ground. In spite of its mission statement, the KC-130J does not have an inherent imagery collection system (other than a weather and ground-mapping RADAR) in its non-Harvest HAWK (Hercules airborne weapons kit) variant. There are plans to install upgraded Harvest HAWK equipment onto all KC-130Js, although the timeline for completion is uncertain (Eckstein, 2016). The new equipment would move the target sight sensor (TSS) (Figure 7) from the left wing of the aircraft into the nose cone. Harvest HAWK missions can last up to 10–12 hours.

The current version of the Harvest HAWK is capable of recording visual and IR imagery. A commercial Sony DXC-390 color TV camera senses visual imagery and outputs video in a composite 525-line analog format. The SATCOM capabilities of KC-130J are limited to voice and very low-bandwidth data transmissions. While the KC-130J does not currently have any TDL capabilities, the Harvest HAWK variant is capable of establishing a tactical downlink via an L-3 Communications Mini-TCDL modem. This modem has a 5-mile range and only sends FLIR sensor video with no overlaid symbology. Plans exist to add Link-16 capabilities to all Super Hercules aircraft in the near future.



Figure 7. KC-130J Harvest HAWK Target Sight Sensor (TSS).

3. P-8A Poseidon

The Boeing P-8A Poseidon is currently in use by the U.S. Navy. As a replacement for the P-3 Orion, the P-8A is designed for long-range anti-submarine warfare, anti-surface warfare, and ISR missions (United States Navy [USN], 2016). Its sensor suite is designed with an open architecture that allows for “rapid insertion of state-of-the-art sensors [and] net-ready technologies” (USN, 2016). One of these sensors is the L-3 Wescam MX-20HD electro-optical sensor system (Figure 8) (“Navy Selects L-3 Wescam,” 2015). It is capable of supporting up to seven sensors simultaneously including sensors for high definition visible light and IR cameras. The latest contract for the P-8A includes the integration of the Minotaur software (Giangreco, 2016). The U.S. Navy already has plans to integrate a Wideband Global SATCOM system on the P-8A (Keller, 2017a).



Figure 8. L-3 MX-20HD for the P-8A Poseidon.
Source: “Navy Selects L-3 Wescam” (2015).

4. AH-1Z Viper

The Bell AH-1Z Viper is a light attack helicopter employed by the U.S. Marine Corps. Its mission is to “provide offensive air support, utility support, armed escort, and supporting arms coordination...” (USMC, 2018). Until the AH-1Z fully replaces the AH-1W SuperCobra, the U.S. Marine Corps will employ both platforms in its light attack squadrons. Its operational range is typically 50 nautical miles with one hour time on station (USMC, 2018). As with other helicopters, the AH-1Z’s low-altitude missions provide a look angle much different from the look angle of transport aircraft flying overhead. The AH-1Z is equipped with the AN/AAQ-30A TSS capable of capturing mid-wave infrared (MWIR) and visible light (TSS, 2018). The TSS is capable of high magnification, continuous zoom, and matching of visible and MWIR field-of-views (TSS, 2018). Similar in looks to the MX-20HD on the Poseidon, the AH-1Z TSS is shown in Figure 9 mounted on the nose of the aircraft.



Figure 9. Lockheed Martin AN/AAQ-30A TSS for the AH-1Z Viper.
Source: TSS (2018).

5. F-35B/C Lightning II

The Lockheed Martin F-35B/C Lightning II is a fifth-generation multi-service, multi-mission fighter aircraft. The Lightning II's AN/AAQ-37 Distributed Aperture System (DAS) allows the aircraft to detect and transmit to the pilot a spherical 360-degree view of the environment. Since it uses the IR band, the DAS is useful in multiple weather conditions, day and night ("Mission Systems," 2018). Additionally, the DAS integrates with other sensors on the aircraft such as RADAR, as well as information from other platforms such as the MQ-4C Triton, P-8A Poseidon, E-2D Advanced Hawkeye, EA-18G Growler, and the F/A-18E/F Super Hornet (USN, 2016). The Electro-Optical Targeting System (EOTS) (Figure 10) combines forward-looking infrared (FLIR) with infrared search and track functionality (IRST), enabling precision air-to-air and air-to-surface targeting capabilities ("Mission Systems," 2018). The Lightning II has the most advanced communications system of any fighter aircraft to date, enabling it to transmit data beyond line of sight over satellite links ("Mission Systems," 2018).



Figure 10. F-35 Lightning II EOTS encased in sapphire window.
Source: “Mission systems” (2018).

6. MQ-4C Triton

The Northrop Grumman MQ-4C Triton is a UAV currently in development for use by the U.S. Navy. Based on the Air Force’s RQ-4B Global Hawk design, it has a planned initial operational capability (IOC) of 2018 and full operation capability (FOC) early next decade (USN, 2016). As a land-based platform, it will complement the P-8A Poseidon on maritime ISR patrols (USN, 2016). It is capable of providing 24 hours of continuous surveillance with an operational range of 8,200 nautical miles a maximum altitude of about 56,000 feet (“MQ-4C Triton,” 2018). It will be equipped with the Raytheon AN/DAS-4 Multispectral Targeting System (MTS) (Keller, 2017b). The AN/DAS-4 includes four high-definition cameras that cover five spectral bands, including the visible, IR, and ultraviolet (UV) bands (Keller, 2017b). All of the MTS sensors will be able to provide 360-

degree coverage (“MQ-4C Triton,” 2018). The communications system includes relay equipment and Link-16 capability. Figure 11 is a summary of its capabilities.



Figure 11. Northrop Grumman MQ-4C Triton system capabilities.
Source: “MQ-4C Triton” (2018).

C. DATA LINKS

While USMC ground units establish tactical radio based networks, USMC aircraft are not equipped with the correct radios to join these networks. Tactical ground networks are based on relatively static participants, and aircraft’s dynamic motion compared to the static-based ground network makes integration difficult. Link-16 and satellite communications (SATCOM) networks, however, are specifically designed to overcome these technical obstacles.

1. Link-16

Link-16 is a commonly used tactical data link (TDL) that is being fully integrated into service for use by Joint Services, the North Atlantic Treaty Organization (NATO), and other allies (Northrop Grumman, 2014). Ground stations, ships, and aircraft can use TDLs to transmit information captured from RADAR, SONAR, identification friend or foe (IFF),

electronic warfare, and visual observations (Northrop Grumman, 2014). Link-16 is a jam-resistant and high-capacity connection (Northrop Grumman, 2014). It was estimated that over 5000 aircraft would be equipped with Link-16 by 2015 (Northrop Grumman, 2014). Other common TDLs include Link-11 and Link-22.

The term “Link-16” refers to the message standard that is described in MIL-STD-6016. Link-16 formats information into J-series messages to efficiently transmit commonly used data (Northrop Grumman, 2014). It utilizes 51 frequencies to generate a pseudorandom frequency hopping pattern that changes frequency every 13 microseconds (Northrop Grumman, 2014). Transmissions over the Link-16 network are broken down into time slots of 1/128 of a second (Northrop Grumman, 2014). Each user is assigned a set of timeslots to use for transmission (Northrop Grumman, 2014). A Link-16 network is defined as a set of users with a common understanding of when time slots begin and end (Northrop Grumman, 2014). A Link-16 net is a set of users that are on the same network and share the same frequency hopping scheme (Northrop Grumman, 2014). There can be multiple nets on a single network. Figure 12 illustrates this idea.

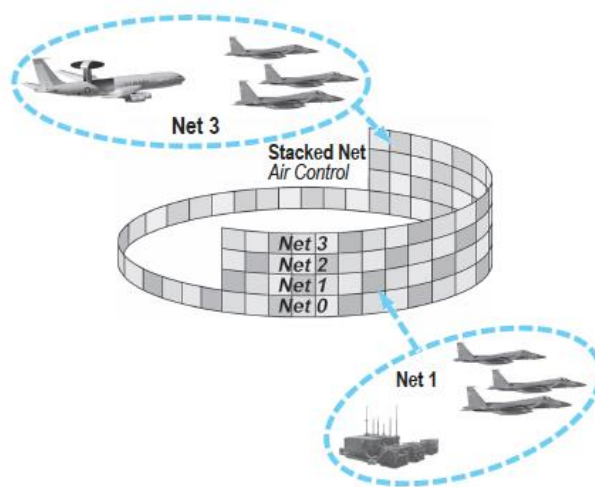


Figure 12. Stacked nets on a Link-16 network.
Source: Northrup Grumman (2014).

Within the physical networks and nets of Link-16 is a logical structure that separates messages based on their function (Northrop Grumman, 2014). Users can listen

to or discard messages based on the relevancy to their mission (Northrop Grumman, 2014). The types of J-series messages that are important to a user will determine which one of the 512 numbered network participation groups (NPG) they will join (Northrop Grumman, 2014). A user can join multiple NPGs. NPG 11 refers to the group that is interest in receiving imagery (Northrop Grumman, 2014). Any unit that wants to receive imagery updates from computer vision systems via Link-16 should set their Link-16 terminal to receive NPG 11 transmissions. This logical separation of NPGs would allow the transmission of imagery to interested parties without interfering with the communications link of disinterested parties. However, the overall throughput of the net must be considered or the imagery could end up flooding the network.

The widespread and flexible use of Link-16 make it a prime candidate for transmitting detected objects of interest, although the specific link is less important than the resultant capability. According to the 2018 Marine Corps Aviation Plan, by fiscal year 2023, all Marine Corps aviation platforms will have multiple standardized data links (USMC, 2018).

2. SATCOM

An alternative to using TDLs is using satellite communications (SATCOM). SATCOM has the capability of global connectivity and is especially relevant to larger aircraft whose missions may take it out of range of other aircraft or tactical ground stations. These aircrafts' large size also make installing SATCOM capabilities less of a size and weight issue.

Wideband global SATCOM (WGS) is the current initiative, providing high-speed data including photos and videos to troops on the battlefield ("Wideband global SATCOM," 2018). Its high bandwidth makes it an attractive alternative to using a TDL. Each WGS satellite is capable of 2.1 to 3.6 gigabits of throughput and operates in the super-high frequency (SHF) band ("Wideband global SATCOM," 2018). A system such as SPOTR would have little effect on the throughput capabilities of WGS. In contrast, the use of ultra-high frequency (UHF) SATCOM radios is very widespread including in ground

units, but does not have as large of a throughput. USF is capable, but not ideal for transmitting large amounts of imagery.

D. INTELLIGENCE COMMUNITY FLOWS

Understanding which agencies are requesting intelligence and which units are supporting that intelligence request can clarify how a computer vision platform could be integrated into the intelligence gathering process.

1. Intelligence Community Structure

The United States Intelligence Community (IC) is comprised of seventeen different agencies, each agency focusing on a different aspect of the IC mission (Member of the IC, 2018). Eight of the agencies comprise the DoD elements: the Defense Intelligence Agency (DIA), the National Geospatial-Intelligence Agency (NGA), the National Reconnaissance Office (NRO), and the intelligence agencies of the four DoD branches, including the Marine Corps Intelligence Activity (MCIA) and the Office of Naval Intelligence (ONI) (Members of the IC, 2018).

The National Intelligence Priorities Framework (NIPF) is “the primary mechanism to establish, disestablish, manage, and communicate national intelligence priorities” (Director of National Intelligence [DNI], 2015). The president of the United States and the National Security Advisor determine the priorities of top-level NIPF (DNI, 2015). From this national guidance, individual agencies can prioritize their intelligence gathering. In the absence of specific intelligence requests, this document provides general guidance as to the classes of imagery to look for.

In joint operations, subordinate tactical units develop their collection requirements based current and future operations and commander’s priorities and objectives (Joint Chiefs of Staff [JCS], 2017). The units send these collection requirements to their joint force J-2 for validation and tasking of tactical collection assets (JCS, 2017). If the tactical unit J-2 does not have the capability to collect the data, they send a request to the combatant command (CCMD) J-2 (JCS, 2017). Even if the tactical unit is able to support their own requirement, they should inform the CCMD J-2 of the intelligence gathering in order to

prevent redundant data gathering (JCS, 2017). The CCMD J-2 is responsible for tracking the research, validation, submission, and satisfaction of all collection that it receives (JCS, 2017). By compiling requests from various tactical units, the CCMD collections managers create a joint integrated prioritized collection list (JIPCL) (JCS, 2017). If theater assets cannot meet the collection requirements, these requirements are then forwarded to the DIA (JCS, 2017). Collections managers are responsible for determining which collection assets have the capabilities to collect data and have access to the locations and targets of interest (JCS, 2017). They are directed to task available collection assets first before requesting support from higher, adjoining, or supporting units (JCS, 2017).

Data analysis help is available through the national reach back architecture from the IC, Navy Information Operations Command and fleet (Anderson, 2016). ONI will generally handle intelligence regarding the maritime domain. As in the joint environment, in the USMC, collection managers plan and execute intelligence collection activities (Commandant of the Marine Corps [CMC], 2004). USMC collection managers are directed to task organic assets first before asking for outside assistance (CMC, 2004). The MCIA will handle intelligence relevant to Marine Corps operations. Figure 13 illustrates the Marine Corps Intelligence cycle. Computer vision would greatly enhance the processing and exploitation and production phases.

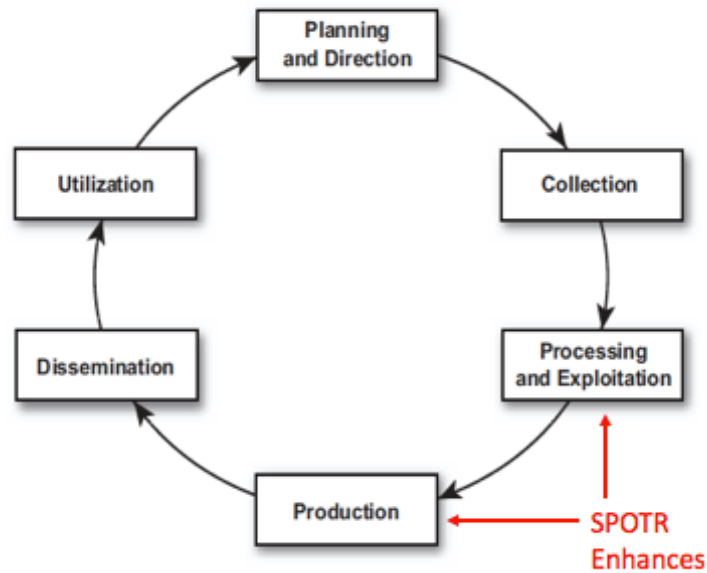


Figure 13. The Marine Corps intelligence cycle. Adapted from CMC (2004).

2. Intelligence Collection Command and Control

According to Joint Publication 3–30, the geographic combatant commander (GCC) may establish, prioritize, and validate theater collection requirements (JCS, 2014). He also may establish sensor tasking and theater-wide collection guidance and policies (JCS, 2014). This authority may be delegated to component commands. Units requesting support should not specify the type of platform they want, rather they should specify the type of information they need (JCS, 2014). Only after he evaluates how re-tasking could impact the current mission should the appropriate commander dynamically re-task ISR assets during a mission (JCS, 2014). Rules of engagement (ROE) and special instructions (SPINS) must include re-tasking priorities and procedures (JCS, 2014). The installation of computer vision should not create a new fleet of assets whose primary mission is ISR. The data collected by these systems would complement existing ISR platforms.

E. CONCEPT OF OPERATION BASICS

According to the Fleet Concept of Operations Writing Guide (2012), a concept of operations (CONOPS) “details the operational application of a concept in the language of

the stakeholders and users, including operators, maintainers, trainers, and suppliers” (DoN, 2012). It provides a high-level overview while making recommendations concerning “doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy (DOTMLPF-P)” (DoN, 2012). A CONOPS is not a directive, but explains the following:

- How to employ a warfighting capability
- How a system/process works
- Where to employ a system/process
- When to employ a system/process
- Stakeholder and user interdependencies
- The desired result (DoN, 2012)

The DoN’s CONOPS writing guide (2012) describes how a new CONOPS can relate to existing doctrine. First, the CONOPS could fall completely within existing doctrine, improving a system or process without the need to change the doctrine. Second, the CONOPS could require the modification or expansion of existing doctrine. Third, a CONOPS could fall completely outside of existing doctrine. Figure 14 illustrates these ideas. This thesis intends to present a CONOPS of the first type, one that requires no changes to existing doctrine.

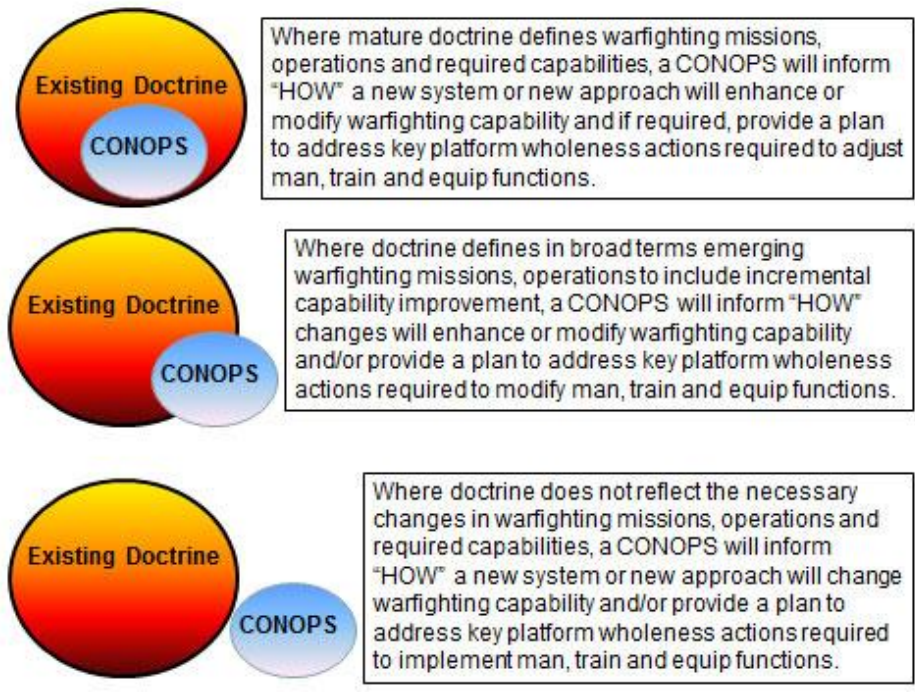


Figure 14. CONOPS relationship to doctrine. Source: DoN (2012).

A CONOPS needs to consider all components of the DOTMLPF-P spectrum. A good starting point for a CONOPS is to explain a mission task flow chart, derived from standard systems engineering practices. The CONOPS owner usually has many of the DOTMLPF-P tasks, but often other commands must accomplish tasks, especially those that involve specialized expertise or changes to hardware, software, curriculum, or policy documents (DoN, 2012).

F. SUMMARY

Computer vision can provide a capability that relieves humans of tiresome tasks of extracting and categorizing data. A survey of naval aircraft showed that they are equipped with a variety of sensors and tasked with a variety of missions that would make implementing computer-vision a worth-while endeavor. Data links and intelligence community structure already exist to support this information sharing. By developing a CONOPS that falls within existing doctrine, naval aviation can leverage computer vision with minimal impact to existing procedures.

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III. RESEARCH METHODOLOGY

The process for developing this CONOPS involved a literature review and discussions with subject matter experts to survey current capabilities and processes. From there, the concepts used in the systems engineering process provided a guideline as to the development of a CONOPS. Subject matter experts reviewed the draft CONOPS to ensure feasibility.

A. SUBJECT MATTER EXPERTS

Subject matter experts provide an inside view of a community that is often not captured by formal documentation. By listening to the facts, opinions, and ideas of subject matter experts, the author was able to speculate how a system or process could work even if it was not formally designed to support aviation-based computer vision.

1. SPOTR

All information regarding SPOTR came from representatives of Progeny Systems Corporation. The author solicited their expertise through a combination of emails, phone calls, and in-person discussions. Progeny Systems also provided copies of internal briefings which detailed the capabilities and processes of the SPOTR system. A representative of Progeny Systems reviewed this thesis for accuracy and thoroughness.

2. Marine Corps and Navy Aviation

The author solicited information about the capabilities of naval aircraft platforms from pilots and aircrew of various types of aircraft. Their knowledge was combined with a brief survey of capabilities described in the respective aircraft's Naval Air Training and Operating Procedures Standardization (NATOPS) and other online sources. One goal was to discover if aviation assets had enough accessible sensors to make the integration of computer vision a worthwhile endeavor. The survey of aircraft systems provided a feasibility check as to whether computer vision integration could be done. It did not address the specifics of how it could or should be done.

3. Intelligence

The information regarding the intelligence community structure and processes came from various publications and online sources distributed by the IC. In addition, the author consulted multiple IC personnel in paygrades ranging from O-3 to O-6 as a sanity check. Their first-hand experience helped validate or discredit ideas that the author had about the use of personnel and data flow.

B. DEVELOP BASIC CONOPS

After discussion with subject matter experts and a review of appropriate literature, the author developed a CONOPS using the basic systems engineering process. The author then created process flows to show an example of how aviation-based computer vision could be implemented.

1. Basic Systems Engineering Process

The method used to create the CONOPS was the basic systems engineering process. Systems engineering is used to establish the “technical framework for delivering capabilities to the warfighter” (DoD, 2017). It seeks to balance cost, schedule, performance, and risk (DoD, 2017). Another of its goals is to enable the development of “resilient systems that are trusted, assured, and easily modified” (DoD, 2017). Through systems engineering, one should be able to identify how to deliver a capability in the most effective and efficient way (DoD, 2017). According the Government Accountability Office (GAO) report 17–77, the systems engineering process answers if and how a capability requirement can be solved by available resources (Sullivan, 2016). Some additional benefits of the systems engineering process are:

- Supports development of realistic and achievable program performance, schedule and cost goals as documented in the Joint Capabilities Integration and Development System (JCIDS) documents, Acquisition Program Baseline (APB) and Acquisition Strategy (AS).
- Provides the end-to-end, integrated perspective of the technical activities and processes across the system life cycle, including how the system fits into a larger system of systems construct.

- Emphasizes the use of integrated, consistent and repeatable processes to reduce risk while maturing and managing the technical baseline. The final product baseline forms the basis for production, sustainment, future changes and upgrades (DoD, 2017).

The CONOPS developed in this thesis seeks to bring a capability to various platforms by utilizing existing technology. While fully integrating computer vision into aircraft systems may provide useful capabilities, the time and money required to fully develop new systems makes that alternative a less beneficial option than the option of fielding computer vision as soon as possible. This CONOPS is intentionally generic in nature in order to provide a solution that is easily modified to suit the needs of the specific user.

2. C2 and Information Analysis

The intent of this CONOPS is not to create a new fleet of assets that are primarily ISR platforms. The command and control structure should remain the same. Command and control considerations were taken from various publications.

3. Draft Process Flows

Process flow diagrams were created by the author after a review of current capabilities and processes. The current processes of SPOTR were used a starting point upon which to build the entire CONOPS. In the opinion of the author, reasonable (but not trivial) assumptions were made as to how current aviation and intelligence community processes could support the integration of computer vision. These process flow diagrams were submitted to subject matter experts in the intelligence and aviation community as well as Progeny Systems. Their feedback and opinions were incorporated to update and refine the process flow.

4. Specific Use Cases with SPOTR

Representatives of Progeny Systems Corporation reported the results of specific use cases of the SPOTR system. Their field tests have successfully demonstrated the capabilities attributed to SPOTR in this thesis. Their work, up until this point, has been with UAVs and USVs.

5. DOTMLPF-P Ramifications

Following the basic systems engineering process covers many of the aspects of the DOTMLPF-P ramifications. A goal of this CONOPS is to minimize the DOTMLPF-P ramifications in order to make the implementation of computer vision a quicker process. This results in a capability that is less intrusive to current operations, but still provides a significant capability improvement.

IV. CONCEPT OF OPERATIONS EXPLANATION

This chapter explains the concept of operations derived from the analysis and development conducted according to Chapter III. This CONOPS applies to all naval aircraft, and the explanation that follows does not account for differences of aircraft in some relevant cases. Again, for specific adaption to a specific platform, some adjustments would be required.

A. CONOPS OVERVIEW

The overall goal of the CONOPS is to leverage the existing sensors on naval aircraft to provide intelligence that would otherwise be overlooked or discarded. Once computer vision is installed on aircraft, objects of interest can be identified from sensors on an aircraft. The entity that determines what objects are important could be the intelligence community or a tactical unit. Humans must train the computer vision system to detect any object it has not been previously trained to detect. The object of interest request is then sent to all networked SPOTR systems. The aircrew flies their mission the same way as if SPOTR was not installed. If SPOTR detects an object of interest and is configured to use an aircraft's TDL, then that image is sent over the TDL to a ground station. If SPOTR does not have access to a TDL, then the collected data is downloaded once the aircraft returns to base. All relevant intelligence will be moved from a tactical computer system into an intelligence computer system for sharing.

B. INSTALLATION ON AIRCRAFT

The choice of physical installation location depends on the type of aircraft. The hardware that hosts the SPOTR software is about the size of a desktop computer's graphics card. The tradeoff between size and functionality provides some flexibility, but all SPOTR systems that are designed for aircraft installation would generally be about the same size. Figure 15 is an overview of how SPOTR would integrate into aircraft systems. The minimum required inputs into the SPOTR system are power and a sensor feed (lines B and C). As discussed in Chapter II, aircraft systems have video cables coming from sensors and going into displays. These cables could be spliced, with one splice returning to the display

and the other to the SPOTR equipment. This leaves all aircraft sensors and displayed unaltered. If the signal that is coming from the sensor is analog, which is the case with composite video, then it must run through an analog to digital converter. The converter would also ensure that the video is in a standard digital format such as H.264. The output of this converter is then fed into the graphics card hosting SPOTR. Cables coming from the converter (or directly from the sensor if the video feed is already a compatible digital format) must be a type compatible with the graphics card chosen to host SPOTR. SPOTR must have access to the aircraft's power bus, but requires little power and can be configured for a variety of voltages.

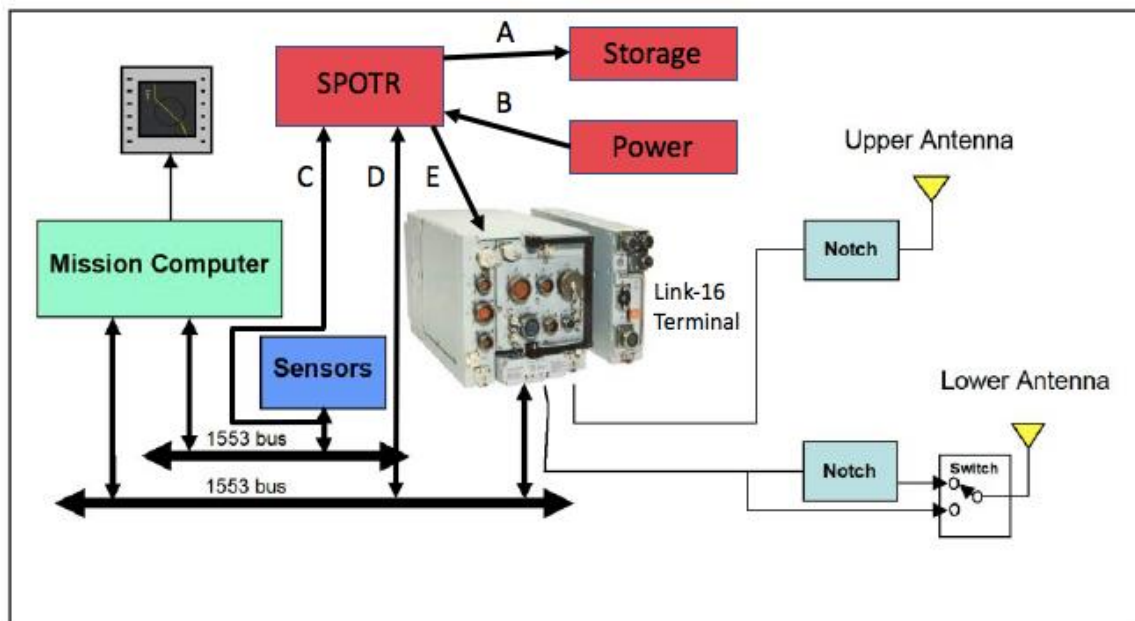


Figure 15. SPOTR installation. Adapted from Sabatini et al. (2008)

In order to improve the value of the information gathered from SPOTR, it should be connected to the aircraft's data bus (line D on Figure 14), such as the MIL-STD-1553 on the KC-130J and F/A-18. From this connection, SPOTR can receive information regarding the aircraft's position, altitude, heading, speed, the look angle and zoom factor of the sensor, and other useful inputs. Having the aircraft's location is only enough information to tell where the detector was when it saw the object, but not enough to

determine the location of an object of interest on the surface or in the air. Figure 16 illustrates the disparity between sensor surface location (green circle) and target location (red star) if SPOTR does not receive additional sensor information. This data bus link could be spliced similar to the sensor video cable scenario. The connection to the data bus would also allow SPOTR to have access to an installed TDL. If SPOTR is not connected to the data bus, it could use a separate link such as Ethernet (line E on Figure 14) to interface directly with the Link-16 terminal.

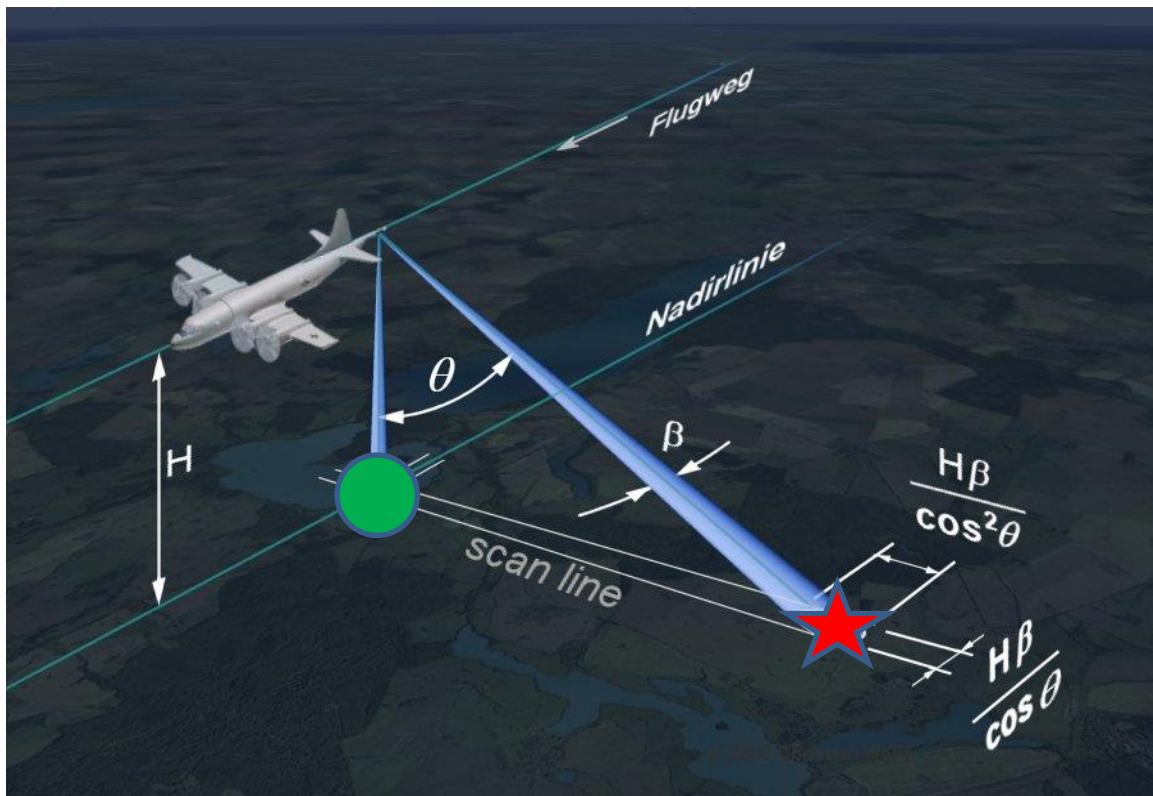


Figure 16. Difference between sensor position and target position.
Adapted from Wolff (2018).

If an aircraft does not have a method to transmit imagery over a data link, then it must store its imagery onboard the aircraft (line A on Figure 14). Any kind of storage device must be kept in an area easily accessible to intelligence personnel for removal and re-installation. This is not an ideal situation because communities would have to incorporate procedures for accessing the storage devices into their NATOPS or

maintenance publications. Any data that is stored on a removable storage device should be encrypted. The metadata stored on such storage devices could contain enough information for an adversary to reconstruct a profile regarding the aircraft's flight path, sensor capabilities, or mission. Encryption comes at a computational expense, so it must be considered when choosing the processing power of the SPOTR hardware.

For aircraft without inherent sensors, another alternative is a stand-alone SPOTR system. This system could include a sensor, graphics card, battery, storage, global positioning system (GPS) receiver, and communications link. These removable systems could be mounted in the windows of larger aircraft. This scenario may limit the ability of SPOTR to accurately determine location and other meta data because it would not have access to the aircraft's data bus.

C. INTELLIGENT PREPARATION OF BATTLESPACE

Intelligent preparation of battlespace involves making the necessary decisions to maximize the use of ISR assets. This includes deciding what objects to look for and where, ensuring the equipment is capable in aiding in that search.

1. Identify Objects of Interest

Using the same process that currently exists, any unit can make a request for information. Tactical units could identify objects of interest from the "bottom up" as their mission evolves. If identified during the mission, this request for information is passed to the intelligence community for the appropriate tracking and tasking just like any request for information (RFI) is currently processed. In the absence of a tactical request or if a commander deems a higher-echelon request more important, SPOTR users could push national-level intelligence requests from the "top down" to SPOTR-equipped systems. A central database of RFIs, marked with a priority level by the appropriate authority, could be kept in the same location as the collected imagery.

2. Ensure Objects of Interest Are Trained into SPOTR

The unit that makes a request for target imagery must determine if SPOTR has been trained to detect that target. If the system has been trained in the past for the same object,

no new training would be required, unless it needs refinement. If it has not been trained, then the unit must find personnel to annotate images to be used in the update of SPOTR.

Depending on the priority and detail required of a target image, a wide range of manpower could be required to annotate images for SPOTR. Ideally, the unit that requests imagery would source the personnel required. This provides the most efficient and accurate annotation because the unit could give instantaneous feedback to the trainers regarding specifics about the target. Intelligence community personnel are ideal to annotate images for SPOTR because they are most familiar with sources of potential training imagery. However, any member of a unit can be taught how to annotate images with very little training. If the unit generating a request does have the personnel required to annotate images, it can request support from higher, or push requests to any subordinate units. Higher commands would then source personnel as their workload allows. If no unit in the chain of command is able to source personnel to annotate images, then the request could be prioritized and placed in a database of requested model files. Ideally, if there are pending requests and available personnel, those personnel should annotate images. Figure 17 demonstrates how request for annotations could flow through the chain of command in a similar way that other general requests for support flow. This requirement to tag images is a big up-front cost. As more model files are created, the demand for annotating could go down. However, units could continue to require additional or more detailed data files, so the demand curve is difficult to judge.

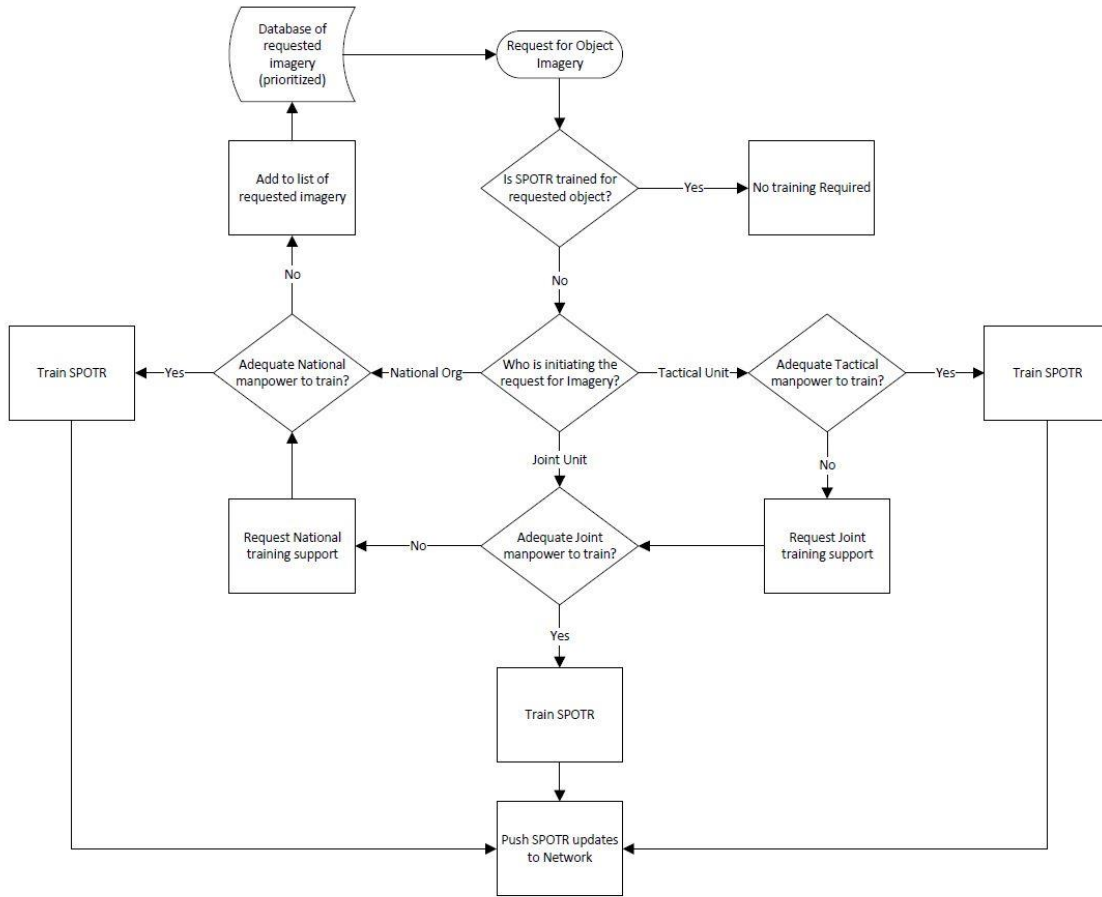


Figure 17. SPOTR training flowchart.

According to multiple individuals who work in or closely with the USMC IC, there is adequate manpower, especially in non-deployed units, to support the training of computer vision platforms. Combined with the fact that projects like Maven will likely reduce the manpower needed for imagery analysis, the Marine Corps should not need to increase its IC manpower to incorporate computer vision. Reserve units are a prime candidate to source the manpower needed to train computer vision systems. Services could give reservists credit for time spend annotating images as production incident to training. They could complete tasks from any reservist drilling station. As of now, personnel at Progeny Systems train SPOTR based on requests they receive. Their familiarity with the annotation system allows for a quicker and more accurate training profile than if

inexperienced personnel annotate images. In contrast, the infrequent duty days and high turnover rate of reservists could limit their proficiency.

The entire database of training images does not need to be stored on each SPOTR device. This dramatically reduces the storage requirement on board each aircraft. The only requirement is to update the model files for a specific target. This file is generally small and can be pushed over a communications link or TDL. This allows for the simultaneous update of search parameters of any SPOTR system connected to a TDL mid-mission.

D. MISSION PREPARATION

Mission preparation builds upon intelligent preparation of the battlefield by telling the now-capable devices what their mission is. This phase is flexible because it could actually occur in the middle of the aircraft's mission.

1. Entering Objects of Interest into the Airframe

In the same way that users can transmit model files to SPOTR devices, users can transmit simple commands to re-task SPOTR at any phase in the mission over a communications link. The user can even specify which detectors to use within certain areas. The list of objects of interest come from the central RFI database. As previously discussed, the computer software tool that would be used for tasking is still under development, but will be made available to the appropriate authority. An example task could be a commander asking for all images of vehicles within a 50-km radius of a remote location. One of three scenarios occur when new tasking is desired:

1. A detector for a target of interest has been trained and loaded onto the platform. This is the best-case scenario. The user just re-tasks the sensor.
2. A detector for a target of interest has been trained but not loaded onto the platform. The user must send the model file and the new tasking.
3. No detector for the target of interest exists. This is the worst-case scenario. The model must be trained as previously discussed, then the user sends the model file and new tasking.

SPOTR devices installed on aircraft without a communication link would have to get their tasking on deck pre-mission.

2. Taskable Assets

A key point to this CONOPS is that the SPOTR device itself is the new taskable asset to the intelligence community, not the aircraft that hosts the SPOTR device. In the case that no aviation asset are already planned to be in place to support an RFI, Figure 18 shows how units should then try to support their RFIs. Any requests for non-organic or non-ISR platforms to conduct ISR missions would have to be routed through the air tasking order (ATO) process.

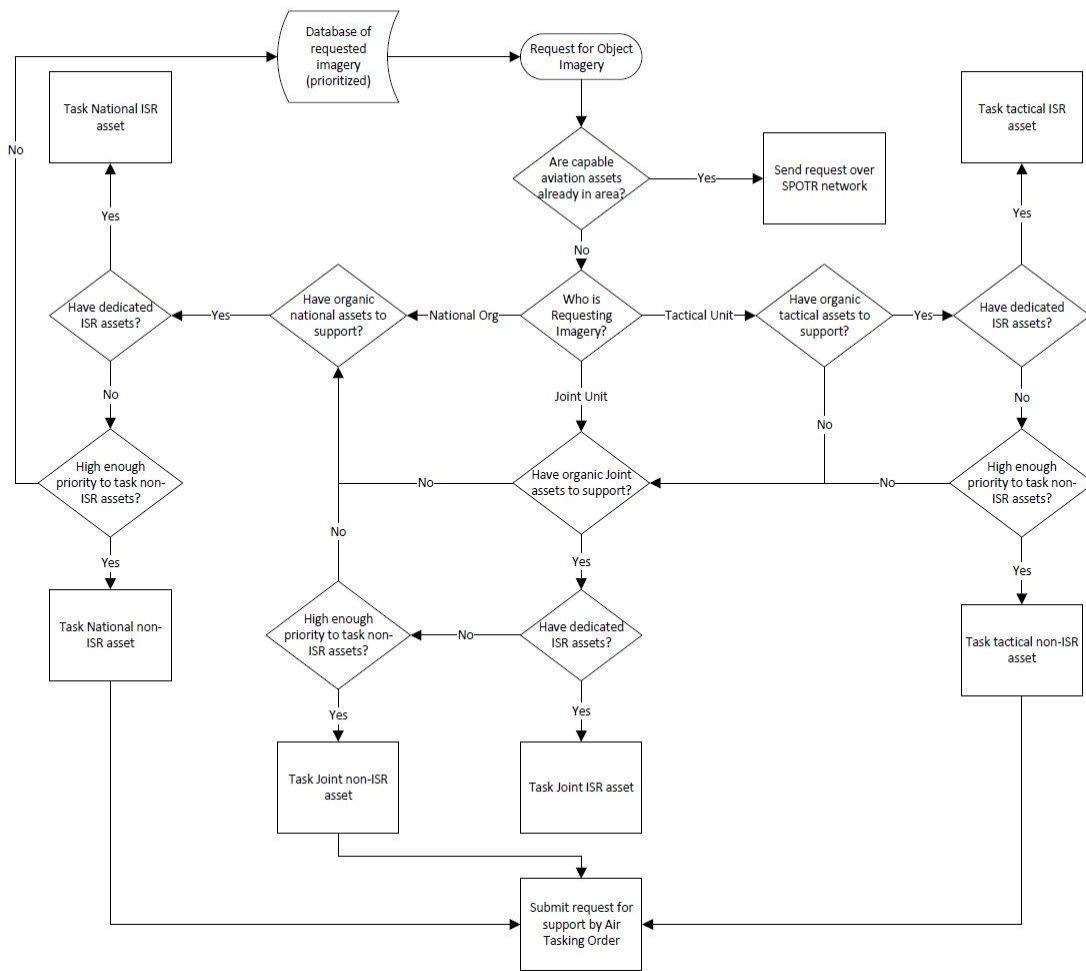


Figure 18. Aircraft tasking flow

E. MISSION EXECUTION

Unless specifically tasked for an intelligence, surveillance, and reconnaissance (ISR) mission that intended to use computer vision, the pilot would fly the aircraft as if SPOTR was not installed. There would be no modifications to the aircraft's instrument displays or procedures. The information collected by SPOTR would be transparent to the pilots and aircrew. The intent is to turn every capable aircraft into an ISR platform, but not task every platform as such.

Figure 19 is a generic overview of what happens starting from the time a target of interest comes into view of an aircraft sensor. If SPOTR is not installed, then any imagery can be stored as usual on the aircraft's built-in storage device, such as the 8-mm tapes on the F/A-18. If SPOTR is installed, then it immediately analyzes the images for possible objects of interest. It does this by cross-referencing the database of requested imagery, in other words, its task list. This task list is determined by the appropriate authority as previously discussed. If the object is of little-to-no immediate importance, but SPOTR has enough storage to save it anyway, it will save it in case the image becomes useful in the future. If there is limited storage, SPOTR will discard the image. If an image is of an object that SPOTR has been tasked to look for, and it is high priority, SPOTR will attempt to send it over a TDL or SATCOM. The person operating the terminal that receives the imagery will then ensure it is uploaded into the appropriate IC database, such as the Global Command and Control System (GCCS). Any imagery that is not transmitted over a TDL or SATCOM can be downloaded post-mission. Unanalyzed images (such as those stored on the F/A-18's 8-mm tapes) would need to be uploaded to a computer that has SPOTR installed where SPOTR could then analyze the entire mission's imagery at once. Based on the intelligence that SPOTR provides, agencies could then modify or reprioritize their requests for information.

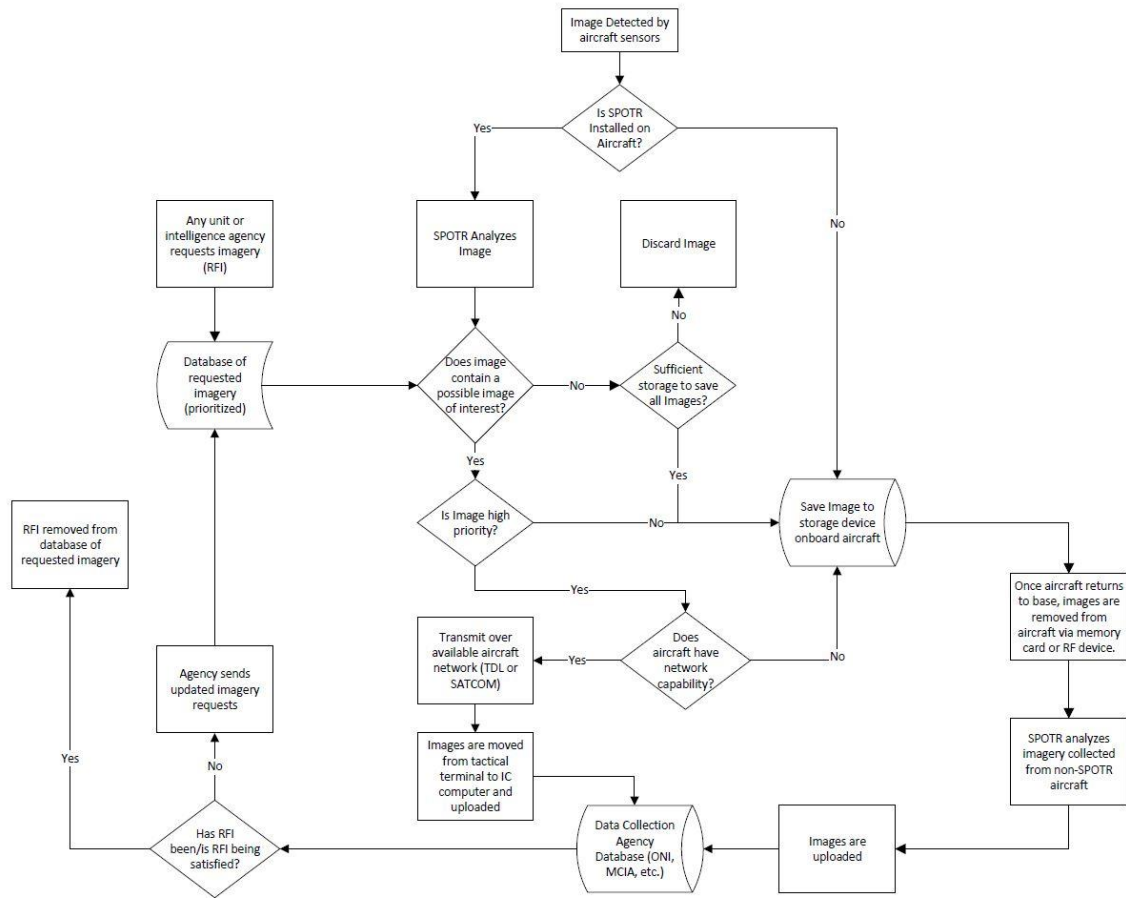


Figure 19. Object detection flowchart

1. Emissions Control

Emissions control (EMCON) procedures should not change for any aircraft employing SPOTR. Since SPOTR is passively using data collected from aircraft sensors, it should not initiate any emissions from the aircraft such as target designation or range finding. However, if SPOTR is using a tactical data link (TDL), it could send communications without the pilot’s knowledge. The TDL itself would need to be secured or set to receive-only mode. In an EMCON scenario, SPOTR should have data storage available to save any imagery that it cannot transmit immediately over a TDL.

2. Receiving Imagery

The reception of imagery from aviation platforms can occur in two different ways, during a mission and after a mission. Image transmission during a mission will generally be used for high priority imagery and the need for real-time intelligence. Larger quantities of data and low-priority target imagery could be transmitted post-mission.

a. During a Mission

Any system capable of receiving Link-16 messages could be programmed to listen to NPG 11. SPOTR could then use a J16.0 message to send its imagery data. Since TDLs are not designed to be constantly flooded with imagery, the decision to send imagery over a TDL must be determined by a target's priority and the confidence level of the SPOTR system. For example, users could program SPOTR to send high-priority images with a confidence level of 90 percent or greater. As available bandwidth increases, SPOTR could send lower priority images or images with a lower confidence level. SPOTR can also use SATCOM links to send data. SPOTR can be set up to "process then push," which means SPOTR analyzes a high-definition image but sends a lower resolution compressed image across the network. The higher-definition image is downloaded post-mission.

Any unit that desires to receive imagery directly from a SPOTR-enabled aircraft must have Link-16 or another TDL-capable receiver or SATCOM capability. Ships and ground bases usually have TDL-capable receivers. Mobile units are less likely to have Link-16 receivers that can display and store images. Once the images are downloaded to the Link-16 or SATCOM ground terminal, intelligence personnel would transfer the images from the terminal to a computer attached to an information-sharing network such as GCCS.

b. Post-Mission

If no method of transmitting imagery exists on the aircraft platform configured to use SPOTR, then the imagery collected during a mission could be stored on a memory card. As discussed before, intelligence personnel would have to access the card and transfer that data to an intelligence network. An alternative to having to physically remove the

storage device would be to equip the SPOTR hardware with a short-range communications system (similar concept as Bluetooth technology on cell phones). Intelligence personnel could get within range of the antenna to download data from and clear the storage card. The hardware for intelligence personnel could be a SIPR laptop with a RF (radio frequency) card.

Another post-mission way to use SPOTR to analyze aircraft imagery is to use storage media that is already on an aircraft. These devices, such as the 8-mm tapes on the F/A-18, could be removed and analyzed by SPOTR that is installed on a desktop or laptop computer.

F. MISSION COMPLETION AND LESSONS LEARNED

Like mission preparation, mission completion for SPOTR devices does not have to coincide with the mission completion of the host aircraft. This phase involves data transfer and storage, and evaluating lessons learned.

1. Data Storage

The data collected from SPOTR systems and the images used for training SPOTR must be stored in a central database for retrieval. Figure 20 illustrates the relationship between database and other SPOTR processes. The current location of the database is Naval Research Laboratory (NRL) Stennis Space Center in Mississippi. Depending on the demand for data, a new location may need to be identified. This is not because of the storage capability of NRL Stennis, but because of the bandwidth coming to and from their servers. Possible alternate locations include the NGA or classified Amazon Web Services. While it is difficult to predict the amount of storage required for a SPOTR database, the low cost of modern storage makes finding a system to host SPOTR imagery an almost non-issue.

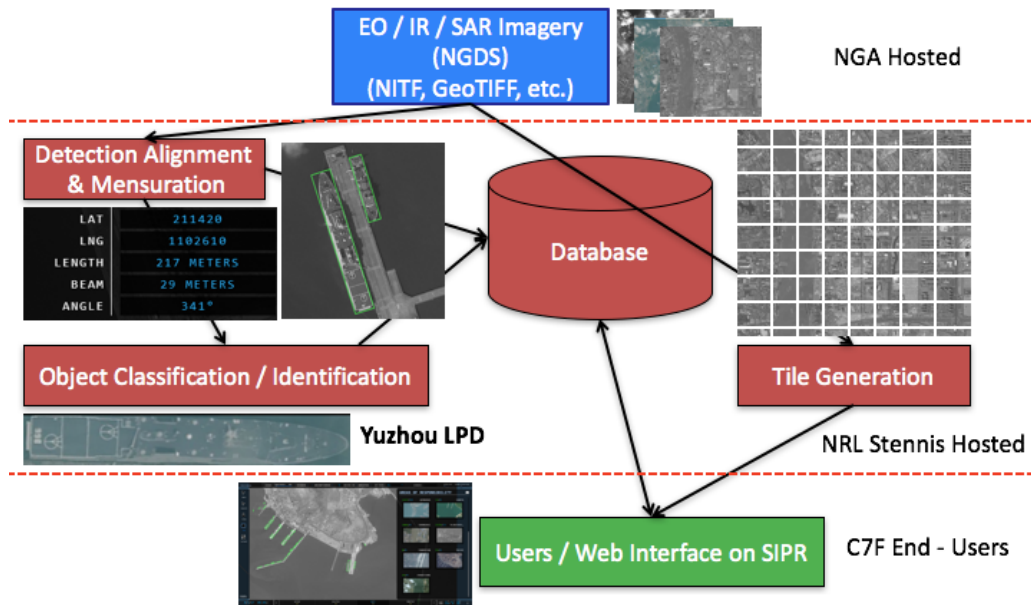


Figure 20. SPOTR system overview. Source: Faltemier et al., email to author, March 28, 2018.

2. Incorporating Lessons Learned

Any CONOPS needs to be updated over time. As technology and policy change, processes need to change. The flexible nature of computer vision software and hardware allow it to remain useful in a variety of platforms and conditions. Users should pass lessons learned to the appropriate organization for incorporation into future publications. In addition, some questions to ask specifically about the performance of SPOTR are:

- Did the SPOTR provide useful information to the requester?
- If SPOTR did not provide useful information, why not?
 - Was it due to a lack of training images or poor annotation?
 - Was it due to installation or mechanical issues?
 - Was it due to lack of connectivity?
- Did the information collected make it to the appropriate agency?
- Is the current database capable of providing fast access to the imagery collected?
- Are agencies aware of SPOTR's capabilities?

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V. CONCLUSIONS

The need and capability for computer vision exists in naval aviation. By adapting current systems, policy, procedures, and technology, naval forces could have computer vision capabilities installed on almost all naval aircraft. Instead of wasting much of the collected imagery data, the naval services will be detecting nuggets that might make the difference in mission success. Moving the processing and tagging of imagery as close to the source as possible will save much-needed bandwidth. A summary of DOTMLPF-P ramifications provides a big-picture view of what is need to quickly implement computer vision. In addition, there are several areas of future research that could help further validate this CONOPS.

A. SUMMARY OF DOTMLPF-P RAMIFICATIONS

- Doctrine—No changes in doctrine are required for the implementation of SPOTR computer vision tools.
- Organization—the organizational structure does not change, nor is there a need for additional structure.
- Training—Personnel will need to be trained on how to use the SPOTR web interface in order to search the intelligence collected. Personnel must also be trained to label imagery in order to update SPOTR’s algorithm. A few hours of on-the-job training is adequate for both.
- Materiel—Services must initially acquire SPOTR software and the necessary hardware for installation on aircraft. The hardware necessary is available commercially off the shelf. The software is available through Progeny Systems. Existing computer systems and networks can be used to interface with SPOTR.
- Leadership and education—No new leadership positions or school-house education is required for the implementation of SPOTR.
- Personnel—The personnel running the SPOTR system will most likely come from the IC. Reservists are an excellent source of manpower to train SPOTR. IC personnel could incorporate SPOTR tasking and data searching into their daily rhythm. Any personnel, however, may be used in the implementation of SPOTR. Progeny Systems personnel are also available for annotation and training tasks.
- Facilities—SPOTR will need a facility to centrally store training images and imagery. Currently, NRL Stennis is hosting SPOTR images, but a new

facility may be needed if NRL Stennis reaches a point where it cannot keep up with demand for data.

- Policy—Policy regarding who has priority of access to SPOTR assets is already covered in existing intelligence gathering policy.

B. RECOMMENDATIONS

After researching computer vision and the maturity of systems such as SPOTR, the author recommends that NAVAIR immediately try prototyping this capability aboard their test aircraft fleet. Evaluating its efficacy will expose more questions, but their solutions will make adaptation easier. The rapid deployment of computer vision technology on a variety of aircraft will help the naval services make immediate use of data they are already collecting as well as identify issues that may arise in the development of a more permanent, integrated solution.

C. FUTURE RESEARCH

Future research opportunities include technical issues and non-technical issues such as training and policy. Technical issues may range from simply assembling a proof of concept to more difficult engineering hurdles. Likewise, non-technical issues could range from simply verifying that an established process can support SPOTR to creating a training plan. Groups or individuals with expertise in a given field could explore methods of implementing the necessary components of the process flows.

1. Installation on Aircraft

A suggestion for future research is to pick a manned aircraft and complete the installation of SPOTR onto that aircraft. Researchers could ensure the compatibility with power, sensors, data, and communications systems. A successful demonstration in one aircraft could prove to be a near solution for multiple other aircraft. The integration with a communications system would not be necessary to support this proof of concept.

2. Compatibility with Link-16 and SATCOM

Successfully demonstrating the integration of SPOTR with Link-16 would further the connectivity capabilities of SPOTR. This could be done without the need for an aircraft.

Stand-alone Link-16 terminals could be used to send and receive SPOTR imagery. The same procedure could be used with SATCOM. A study on the throughput of various types of satellite systems while using SPOTR could help determine which systems are realistically capable of supporting SPOTR.

3. Integration with Aircraft Instrumentation

The emphasis of this thesis has been the quick implementation of computer vision. Once an initial implementation is complete, a longer timeline and increased budget could allow for exploring the concept of integrating computer vision into the instrumentation and mission computer of aircraft. In this case, the pilot would be aware of what the computer vision system is seeing and sending over the Link-16 connection. The pilot would also be able to re-task SPOTR during a mission. In the same way, SPOTR could begin to use active sensors to determine range from sensor to the target, for example, as additional metadata. These types of integration would also require and update to the NATOPS normal procedures to ensure aircrew are properly informed and trained on the operation of computer vision software.

4. Use of Computer Vision with Other Sensor Types

As mentioned, it is likely that computer vision would work on other sensor types, such as synthetic aperture RADAR, LIDAR, and multispectral sensors. The algorithmic approach might be the same, but the details deserve scrutiny in follow-on research.

5. Training

While the training required to make use of SPOTR technology is minimal, it must be standardized. Researchers could develop a training program that is succinct yet thorough enough to provide consistent, reliable results. Topics for training could include:

1. How to annotate images
2. How to train SPOTR
3. How to task SPOTR
4. How to upload and share tagged imagery
5. How to extract useful information from collected data

6. Computer Vision Data Architecture

Mentioned in the discussion on facilities is the need for an extension to the current NRL support of SPOTR. A needed research effort would focus on how the naval services aggregate all the computer vision detections for broad trend analysis, and how they disseminate specific detections to the edge users. That daunting architecture challenge has impacts on many other emerging Big Data capabilities for the naval services

7. Completion of the SPOTR Annotation and Tasking Tools

As previously mentioned, Progeny Systems is currently developing computer tools to annotate and task SPOTR systems. While this is a technical issue that is being addressed by Progeny Systems, researchers could determine what features, layouts, and commands would be most useful to the warfighter and provide this feedback to Progeny Systems.

D. SUMMARY

The fleet is currently in the process of developing computer vision, but not focusing on retrofitting current aircraft. SPOTR enhances that capability by providing a flexible software-based solution that can be installed on various aircraft. SPOTR can be employed with minimal intrusion into aircraft systems by employing an architecture that primarily pulls information from the aircraft and does not require reconfiguration of existing electronics. Reservists, IC personnel, Progeny Systems employees, or any other available person could train SPOTR by using the training software interface. Detections, classifications, and identifications are passed to potential customers by TDL, SATCOM, or physical removal from the aircraft and can include confidence levels. SPOTR is capable of analyzing imagery in other sensor regimes such as acoustics, LIDAR, and RADAR. Minimal changes across the DOTMLPF-P spectrum would be required. Aviation-based computer vision capabilities should be implemented in the very near future.

LIST OF REFERENCES

- About us. (2018, May 26). Retrieved from <http://www.progeny.net/about>
- Allen, G. C. (2017, December 21). Project Maven brings AI to the fight against ISIS. Retrieved from <https://thebulletin.org/project-maven-brings-ai-fight-against-isis11374>
- Anderson, S. (2016). Delivering decisive understanding to the commander. Retrieved from <http://www.doncio.navy.mil/mobile/ContentView.aspx?ID=7899&TypeID=21>
- Chappellet-Lanier, T. (2017, November 2). Project Maven right on schedule, Air Force's Shanahan says. Retrieved from <https://www.fedscoop.com/project-maven-dod-machine-learning/>
- Commandant of the Marine Corps. (2004). *MAGTF intelligence collection* (MCWP 2-2). Retrieved from <http://www.marines.mil/Portals/59/Publications/MCWP%202-2%20MAGTF%20Intelligence%20Collection.pdf>
- Department of Defense. (2013). *Unmanned systems integrated roadmap FY 2013-2038*. (14-S-0553). Washington, DC: Author. Retrieved from <http://archive.defense.gov/pubs/DoD-USRM-2013.pdf>
- Department of Defense. (2017). *Defense acquisition guidebook*. Washington, DC: Author. Retrieved from <https://www.dau.mil/tools/dag>
- Department of the Navy. (2010, May). *The U.S. Navy's vision for information dominance*. Washington, DC: Author. Retrieved from <http://edocs.nps.edu/dodpubs/topic/vision/vision2010.pdf>
- Department of the Navy. (2012, August). *Fleet concept of operations writing guide*. Norfolk, VA: Author.
- Department of the Navy. (2017a, February 15). *NATOPS flight manual Navy model F/A-18A/B/C/D aircraft* (A1-F18AC-NFM-000). Patuxent River, MD: Author. Retrieved from <https://mynatec.navair.navy.mil/loggedon/manuals/fa18abcd/a1-f18ac-nfm-000.pdf>
- Department of the Navy. (2017b, February 15). *NATOPS flight manual Navy model F/A-18E/F aircraft* (A1-F18AE-NFM-000). Patuxent River, MD: Author. Retrieved from <https://mynatec.navair.navy.mil/loggedon/manuals/fa18ef/a1-f18ae-nfm-000.pdf>

- Director of National Intelligence. (2015, January 2). *National intelligence priorities framework* (IC Directive 204). Washington, DC: Author. Retrieved from <https://www.dni.gov/files/documents/ICD/ICD%20204%20National%20Intelligence%20Priorities%20Framework.pdf>
- Eckstein, M. (2016, May 11). Marines to add 'Harvest Hawk' weapons kit to entire C-130J, V-22 fleets. Retrieved from <https://news.usni.org/2016/05/11/marines-to-add-harvest-hawk-weapons-package-to-entire-c-130j-v-22-fleets>
- Fisher, R., Breckon, T., Dawson-Howe, K., Fitzgibbon, A., Robertson, C., Trucco, E., & Williams, C. (2014). *Dictionary of computer vision and image processing*. West Sussex, UK: John Wiley & Sons Ltd
- Giangreco, L. (2016, August 11). Newest P-8A Poseidon upgrade includes 'Minotaur' software. Retrieved from <https://www.flightglobal.com/news/articles/newest-p-8a-poseidon-upgrade-includes-minotaur-sof-428396/>
- Huang, T. (2018). Computer Vision: Evolution and Promise. Retrieved from <https://cds.cern.ch/record/400313/files/p21.pdf>
- Joint Chiefs of Staff. (2014). *Command and control of joint air operations* (JP 3–30). Retrieved from http://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_30.pdf
- Joint Chiefs of Staff. (2017). *Joint and national intelligence support to military operations* (JP 2–01). Retrieved from http://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp2_01_20170705v2.pdf
- Keller, J. (2017a, September 25). Navy eyes high-speed SATCOM capability for P-8A Poseidon surveillance and maritime patrol aircraft. Retrieved from <http://www.militaryaerospace.com/articles/2017/09/p-8a-high-speed-satcom.html>
- Keller, J. (2017b, November 3). Raytheon to provide multispectral sensor system for Navy MQ-4C Triton maritime surveillance UAV. Retrieved from <http://www.militaryaerospace.com/articles/2017/11/surveillance-multispectral-uav.html>
- Langley, J. K. (2012). *Occupational burnout and retention of Air Force Distributed Common Ground System (DCGS) intelligence personnel* (Dissertation). Retrieved from https://www.rand.org/content/dam/rand/pubs/rgs_dissertations/2012/RAND_RGSD306.pdf
- Members of the IC. (2018, March 9). Office of the Director of National Intelligence. Retrieved from <https://www.dni.gov/index.php/what-we-do/members-of-the-ic>
- Mission systems and sensor fusion. (2018, May 26). Lockheed Martin. Retrieved from <https://www.f35.com/about/capabilities/missionsystems>

- Munroe, R. (2014, September 24). Tasks. Retrieved from <https://www.xkcd.com/1425/>
- MQ-4C Triton. (2018, May 26). Retrieved from <http://www.northropgrumman.com/Capabilities/Triton/Pages/default.aspx>
- Navy selects L-3 Wescam electro-optical sensors for P-8A jet. (2015, August 19). Retrieved from <http://www.militaryaerospace.com/articles/print/volume-26/issue-8/electro-optics-watch/navy-selects-l-3-wescam-electro-optical-sensors-for-p-8a-jet.html>
- Northrop Grumman. (2014). *Understanding voice and data link networking* (Report No. 135-02-005). Retrieved from http://www.northropgrumman.com/Capabilities/DataLinkProcessingAndManagement/Documents/Understanding_Voice+Data_Link_Networking.pdf
- Object detection deep learning. (2018, May 26). Retrieved from <https://sigmoidal.io/dl-computer-vision-beyond-classification/>
- Office of Budget (2018). Highlights of the Department of the Navy FY 2019 budget. Washington, DC: Department of the Navy. Retrieved from http://www.secnav.navy.mil/fmc/fmb/Documents/19pres/Highlights_book.pdf
- Papert, S. (1966, July 7). *The summer vision project* [Memorandum]. Cambridge, MA: Author. Retrieved from <http://hdl.handle.net/1721.1/6125>
- Pellerin, C. (2017, July 21). Project Maven to deploy computer algorithms to war zone by year's end. Retrieved from <https://www.defense.gov/News/Article/Article/1254719/project-maven-to-deploy-computer-algorithms-to-war-zone-by-years-end/>
- Sabatini, R., Aulanier, L., Marinoni, G., Martinez, M., Pour, B., & Rutz, H. (2008). Multifunctional information distribution system (MIDS) low volume terminal (LVT) development and integration programs towards LINK-16 network centric allied/coalition operations. *NATO RTO-MP-IST-083 Military Communications, RTO-MP-IST-083*. 11-1-11-34. Retrieved from https://www.researchgate.net/publication/264742534_Multifunctional_Information_Distribution_System_MIDS_Low_Volume_Terminal_LVT_Development_and_Integration_Programs_Towards_LINK-16_Network_Centric_AlliedCoalition_Operations
- Shapiro, L. G. & Stockman, G. C. (2001). *Computer vision*. Upper Saddle River, NJ: Prentice-Hall, Inc.
- Sullivan, M. J. (2016). *Weapon systems requirements: Detailed systems engineering prior to product development position programs for success* (GAO-17-77). Washington, DC: Government Accountability Office.

- TSS. (2018, March 24). Retrieved from <https://www.lockheedmartin.com/us/products/TSS.html>
- United States Marine Corps. (2017). *2017 Marine aviation plan*. Washington, DC: Government Printing Office. Retrieved from <http://www.aviation.marines.mil/Portals/11/2017%20MARINE%20AVIATIOIN%20PLAN.pdf>
- United States Marine Corps. (2018). *2018 Marine aviation plan*. Washington, DC: Government Printing Office. Retrieved from <http://www.aviation.marines.mil/Portals/11/2018%20AvPlan%20FINAL.pdf>
- United States Navy. (2016). *Naval aviation vision 2016–2025*. Washington, DC: Government Printing Office. Retrieved from http://www.navy.mil/strategic/Naval_Aviation_Vision.pdf
- Wideband Global SATCOM (WGS) satellite. (2018, May 26) Retrieved from <https://www.aerospace-technology.com/projects/wgs-satellite/>
- Wolff, C. (2018, May 26). Side looking airborne radar (SLAR). Retrieved from <http://www.radartutorial.eu/20.airborne/ab06.en.html>
- Work, R. (2017, April 26). *Establishment of an algorithmic warfare cross-functional team (project Maven)* [Memorandum]. Washington, DC: Department of Defense. Retrieved from https://www.govexec.com/media/gbc/docs/pdfs_edit/establishment_of_the_awcft_project_maven.pdf

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