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UNCLASSIFIED MARITIME DOMAIN AWARENESS: RESULTS OF AT SEA EXPERIMENTATION DURING SEACAT '18

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THESIS

UNCLASSIFIED MARITIME DOMAIN AWARENESS: RESULTS OF AT SEA EXPERIMENTATION DURING SEACAT '18

by

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June 2019

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The purpose of this thesis is to conduct and observe experimentation, using the unclassified Common Operating Picture tool SeaVision, in conjunction with the Surveillance, Persistent Observation and Target Recognition (SPOTR) program created by Progeny. These systems together will utilize unclassified satellite imagery to detect, classify and identify vessels at sea using computer vision (CV) algorithms. The CV algorithms use imagery of vessels of interest (VOI) to create a three-dimensional model that is used to detect and identify vessels in the satellite imagery. Images and information regarding these vessels were gathered from unclassified sources for analysis and building of the three-dimensional models. The information-gathering process would benefit from infusion or access to intelligence information for building image libraries of VOI. The technology, while still maturing, shows potential for implementation in various facets onboard surveillance platforms and unmanned surface and air vehicles.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	automated information system
AOR	area of responsibility
ASEAN	Association of Southeast Asian Nations
C7F	Commander 7^{th} Fleet
CNFK	Commander U.S. Naval Forces Korea
CONOPS	concept of operations
COP	common operational picture
CTF 73	Commander Task Force 73
CV	computer vision
DoD	Department of Defense
DoT	Department of Transportation
DPRK	Democratic People's Republic of Korea
EEZ	exclusive economic zone
ICC	International Chamber of Commerce
IMB	International Maritime Bureau
IMO	International Maritime Organization
IPC	Initial Planning Conference
IUU	illegal, unreported and unregulated
JIATF	Joint Interagency Task Force
MDA	maritime domain awareness
MPA	maritime patrol aircraft
MSC	Military Sealift Command
POL	pattern of life
SCS	South China Sea
SEA	Southeast Asia
SEACAT	Southeast Asia Cooperation and Training
SFM	structure from motion
SPOTR	Surveillance, Persistent Observation and Target Recognition
UAV	unmanned aerial vehicle
UN	United Nations

UNCLAS	unclassified
UNCLOS	United Nations Convention on the Law of the Sea
UNSC	United Nations Security Council
UNSCR	United Nations Security Council Resolution
USD	United States Dollar
VOI	vessel of interest
WMD	weapons of mass destruction

I. INTRODUCTION

The United States Navy has increased emphasis on Maritime Domain Awareness (MDA) as their operational focus shifts from primarily blue water operations to the littorals (United States, Department of the Navy, 2007). The elements of security, safety, economy, and the environment are included in MDA (United States, Department of Homeland Security, 2005). These elements are negatively impacted throughout the global maritime domain by acts such as piracy, illegal fishing, smuggling, and trafficking (United States, Department of Homeland Security, 2005). These acts are common in the Southeast Asia (SEA) region, near the South China Sea (SCS), which is the focus for our research.

The SCS suffers from expansive incidence of illegal, unreported and unregulated (IUU) fishing, piracy, human trafficking, and seabed resource claims conflicts. Compounding the problem, at least half of all global seaborne commerce crosses through the SCS region. These issues threaten maritime security and the global economy within the region because host nations are unable to contain the problem. The countries in and around the SCS do not collaborate and create partnerships for maritime operations to keep the region fair, secure and reliable. Improved interoperability and information sharing can assist in improving MDA. Improved MDA provides greater actionable information, enabling countries within the region to respond better to incidences of undesired behavior.

A. OBJECTIVE

1. Research Question

If an increase in information availability on MDA can be achieved, are nations better able to prosecute maligned actors, resulting in decreased incidence of unwanted and illegal activity? The study will determine whether the use of SPOTR, a product of Progeny Systems, and satellite or other image sources improve the capability for SeaVision, an unclassified common operational picture (COP), to detect and identify uncooperative vessels.

2. Research Intent

The purpose of this research is to conduct an MDA experiment within the confines of the Southeast Asia Cooperation and Training (SEACAT) '18 exercise. Nine countries participated in SEACAT 2018, which included Bangladesh, Brunei, Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam, along with the United States (CTF-73 Public Affairs, 2018). The experiment will determine if the actionable MDA qualities of shareability, accuracy, revisit time, and track quality are achievable in an unclassified cooperative environment by using unclassified MDA tools for developing tracks and maintaining persistency. A concept of operations (CONOPS) has been developed for implementation during the SEACAT exercise. The CONOPS proposes the use of unclassified MDA tools to develop tracks on vessels of interest (VOI). MDA tools will ingest the unclassified, space-based imagery, to assist in detecting VOI that may not be broadcasting Automated Identification System (AIS) data, using computer vision (CV). The results will highlight exercise information sharing challenges, determining how they might be resolved and how the challenges might apply to other regions. The MDA CONOPS will then be refined to consider the need for developing maritime behavioral models. These models would increase the ability to deduce specific maritime activity such as IUU fishing, smuggling, military action, and other activities of interest. The concepts of unclassified information sharing and behavior models for pattern of life (POL) will be explored to determine how they can be implemented on a broader level through further research.

The goal is to identify possible enhancements to existing MDA policies and procedures. These will introduce new practices and operational concepts to enhance current MDA warfighting, expose issues, and identify possible solutions. The possibility exists that the experiment could conflict with SEACAT exercise execution. Steps are in progress to mitigate the risk and will be discussed with exercise coordinators and nation participants at the SEACAT Initial Planning Conference (IPC). Expected recommendations are expanded use of SeaVision for information sharing and the Common Operating Picture (COP) tool. Currently, SeaVision utilizes AIS, radar, vessel monitoring systems, and long-range identification and tracking systems (SeaVision Data

Sources). These system inputs, while useful, have difficulty detecting, identifying, and tracking uncooperative targets. This study seeks to explore and adapt the use of Surveillance, Persistent Observation and Target Recognition (SPOTR) computer vision combined with all sources of unclassified imagery to enhance SeaVision's capabilities, including exploring the use of SPOTR on MPA aircraft to improve and accelerate the meaningful delivery of information to users. We anticipate that SPOTR will be able to collect data over time on VOI, creating a historical timeline of locations and behavior.

The study will implement a quantitative research approach to determine the effectiveness of implementing SeaVision and SPOTR in tandem. With the successful implementation of CV to track VOI, the end state will accomplish two Department of Defense (DoD) objectives for building shared MDA with SEA partners. These objectives are to provide public goods and support U.S. exercises, operations, and contingency response missions (Helvey & Harvey, 2018). Ultimately, the sharing of information would increase capabilities and, therefore, empower the Association of Southeast Asian Nations (ASEAN) partners to complete individual operational requirements.

B. PARTNERSHIP

Numerous parties showed interest in the use of CV to enhance MDA at the outset, which included Commander 7th Fleet (C7F), Commander Task Force 73 (CTF 73), Commander U.S. Naval Forces Korea (CNFK), Joint Interagency Task Force (JIATF), and members of the ASEAN. C7F was the operational research sponsor for this project since the SCS is in their area of responsibility. C7F showed minor interest in this particular research and experimental area and directed us to CTF-73 (Boger & Miller, 2018). CTF-73 became the main focus for coordination, since they were the officer in charge of the SEACAT exercise.

Progeny Systems Corporation creates hardware and software solutions for the Department of Defense and other government agencies, including surveillance and computer vision solutions such as SPOTR (Progeny, 2019). Two members from Progeny, Tim Faltemier and Karsten Steinhaeuser, were identified to assist in this research project. Tim and Karsten, using unclassified images of United Nations (UN) sanction vessels provided to Progeny, would create a three-dimensional model of a VOI. This three-dimensional model will be used for vessel identification with input from vessel image libraries. Progeny System employees will determine a method for converting SPOTR output into SeaVision for track creation. SeaVision representatives will provide consultation to Progeny for creating compatible track inputs and for utilizing the information sharing and analysis tools in SeaVision for the benefit of participants.

The resource sponsors, SMEs assigned to the applicable Areas of Responsibility (AORs), and those working in Research and Development for new and future capabilities, will aid in observation and data collection. The CTF-73 MDA Advisor will provide expertise for the SEA region, regarding issues, challenges, as well as regional relations and conflicts. These contributions seek to improve SeaVision and build MDA capabilities through the SEACAT exercise.

C. SHIFT IN FOCUS

Prior to the IPC, we met with Charles Brown, from Booz Allen Hamilton in Singapore, to discuss the operational scenario designed by our predecessors to be implemented during SEACAT 2018 (Charles works as a contractor advising CTF-73 on MDA related matters). During our meeting with Charles Brown and his associates, it was discovered that the scenario we presented was not feasible during SEACAT 2018 due to operational limitations of participating nations.

Based on these facts, the decision was made to shift focus to the UN-sanctions list for target VOI. This was predicated on an increased interest by C7F in the location and undertakings of Democratic People's Republic of Korea (DPRK) vessels listed on the sanctions list. The challenges encountered with SEACAT participants' information sharing capabilities, as well as the scarce amount of information received on VOIs used in the upcoming SEACAT exercise, contributed to the shift in focus.

A discussion was held with a representative from SeaVision, during the IPC, regarding what our thesis wanted to accomplish and how SeaVision could interact with SPOTR to assist in achieving the desired results. The scenario developed for implementation during SEACAT allowed for experimentation within a semi-controlled environment. Testing would be conducted during a real-world scenario within an uncontrolled environment. The uncontrolled nature of the problem also necessitated that we find information for the VOIs instead of receiving information, as would be the case with the contracted vessels for SEACAT.

D. LIMITATIONS

Discussions regarding our area of research were held with some members of participating countries to explain to them what we are trying to accomplish in enhancing the MDA in the SCS. ASEAN countries demonstrated the willingness to participate but cited issues with implementing the use of SeaVision as an information sharing MDA tool. Countries lacked the organic technology onboard operational maritime units capable of accessing and utilizing the SeaVision program. This includes limited or no internet access, which negates the use of SeaVision as an internet-based tool. Limited resources allocated to defense spending also results in limited deployment of naval units. Units that do not deploy suffer from mounting maintenance issues and untrained crews. The result is insufficient operational proficiency to utilize information that would be gleaned from using SeaVision for developing POL analysis for designated VOIs.

Countries within the SCS were willing to share information with the United States, but not necessarily with each other. Regional conflicts and rivalries influence political relationships among countries. In order for SeaVision to operate to its fullest potential, these countries must be willing to work and share with each other to maximize MDA in the region. Differing priorities in what illicit activity takes precedence contributes to the divide. Illegal fishing may be more important to one country while another prioritizes smuggling or trafficking. Further, the entity conducting the illicit activity may belong to a country seen as an antagonist by the country labeling that vessel as a VOI. These limitations stunt the ability of fully deploying SeaVision as the information-sharing tool it is meant to be.

E. APPROACH

Since the original thesis approach was not supported by CTF-73, we chose an alternative path. This thesis will explain how the experiment might have been conducted, but with emphasis on the UN-sanctioned list of ships. The idea is to still research and assess the viability of using SeaVision and CV to enhance observation of non-cooperative vessels of interest, especially the UN-sanctioned ships, and then make recommendations to resource sponsors and operational commanders on how such tools can be added to the MDA toolkit.

Chapter II reviews the literature on MDA in general, UN-sanctioned ships, computer vision, and situation awareness. It also explores key concepts like information sharing between nations. Chapter III explains the methodology used to gather the information. Chapter IV presents the results of our analysis of these emerging capabilities, and how they can be used to support existing MDA processes. It also suggests how some of those processes ought to be amended. Chapter V summarizes our findings, reemphasizes key recommendations, and suggests areas of future research.

II. LITERATURE REVIEW

The maritime domain of SEA is vital for global trade, making safe and secure sea lanes much more important, especially with eight of the ten busiest container ports in the world located in the Asia-Pacific region (Department of Defense, 2015). This region has roughly two-thirds of the world's oil shipments transit through it, along with about 30 percent of the world's maritime trade that passes through the SCS alone (DoD, 2015). The amount of global trade transiting SEA should concern all nations, including the United States, where the maritime trade heading to the United States is approximately $1.2 trillion (DoD, 2015).

The large amount of global commerce in the region, along with a lack of law enforcement, contributes to illegal activities such as piracy, fishing that is illegal, unreported and unregulated (IUU), smuggling, and trafficking. Our thesis focuses on the use of computer vision to enhance MDA in SEA by combining products and tools, such as unclassified commercial imagery and SeaVision, a program used to share AIS information. The importance of cooperation and information sharing between partner nations cannot be overstated. Tools like SeaVision allow for quick access to shared information between authorized users.

In our thesis, we intend to use computer vision to create three-dimensional models of VOIs. These three-dimensional models will be used to conduct image analysis with new commercial images to detect, classify, and identify VOI. Metrics will be used to determine whether the process and tools are useful in improving MDA. The use of computer vision utilizing image analysis and information sharing can be tested at the SEACAT exercise or any other maritime exercise designed to locate or detect a VOI.

A. MDA

The United States defines MDA as anything related to the maritime domain that can impact the security, safety, economy, or environment of the United States, such as any activities, infrastructure, vessels, or even cargo (Department of Homeland Security, 2013). The maritime domain, which includes everything above, on, under, and adjacent to any navigable waterway, continues to be vital to the success, prosperity, and security of the United States and its global partners (Ombo, 2015). The protection of the maritime domain impacts the entire population of the Earth as the waterways are used for transportation, shipping, providing food and water sources, international trade, and border protection for countries and protection from other countries.

Our thesis focuses on the Asia-Pacific region, but, more specifically, it focuses on Southeast Asia and the South China Sea. MDA is critical in this area, as a significant portion of the global maritime trade transits through the region, and a large number of piracy incidents occur in the region (Bueger, 2015). Also, disputes among nations due to geographical concerns and historical tensions hinder cooperation in the region (Bueger, 2015). Decision-makers require accurate, relevant, and timely information to be able to anticipate potential threats and to take decisive and appropriate actions against existing threats (DHS, 2013). Information needs to be collected and disseminated between nations to improve MDA so the nations receiving the information can analyze the data to make informed decisions to increase maritime security in the region (DHS, 2013).

1. Overview

Issues that continue to concern nations regarding the maritime domain in the SCS include IUU fishing, piracy, human trafficking, and smuggling. Piracy has seen a significant rise in incidents since the 1980s and has remained a persistent problem in the region ever since (Bueger, 2015). Each nation in the region feels the effects of these issues differently, and, therefore, each of their respective priorities differ from one another. Differences in priorities amongst nations may impede the progress of increasing MDA in the area, but ultimately all of the nations are affected by these issues and would greatly benefit by cooperating and sharing with each other.

a. IUU Fishing

According to a National Intelligence Council memorandum in 2016, an estimated 15 to 30 percent of global annual catches are being conducted by IUU fishing. IUU fishing not only heightens tensions between neighboring countries, but it can also encourage piracy due to the lack of skill required to conduct piracy operations (NIC, 2016). It is hard to enforce fishing laws due to the difficulty in distinguishing between legal and illegally caught fish, and the profits obtained exceed the potential risk involved (NIC, 2016). See Figure 1 for a graphic of common forms of IUU Fishing. A large number of nations border the SCS, including members of the ASEAN. These coastal communities rely heavily on fishing and other resources from the ocean to produce a food source and a means of earning a living for their families (United Nations, 2017). A country's right to the Exclusive Economic Zone (EEZ) in the SCS is being taken advantage of by these illegal practices of fishing. The United Nations Convention on the Law of the Sea (UNCLOS) establishes a country's EEZ. Unfortunately, not all countries abide by UNCLOS, or follow its rulings, causing more concern in a high traffic area such as the SCS.

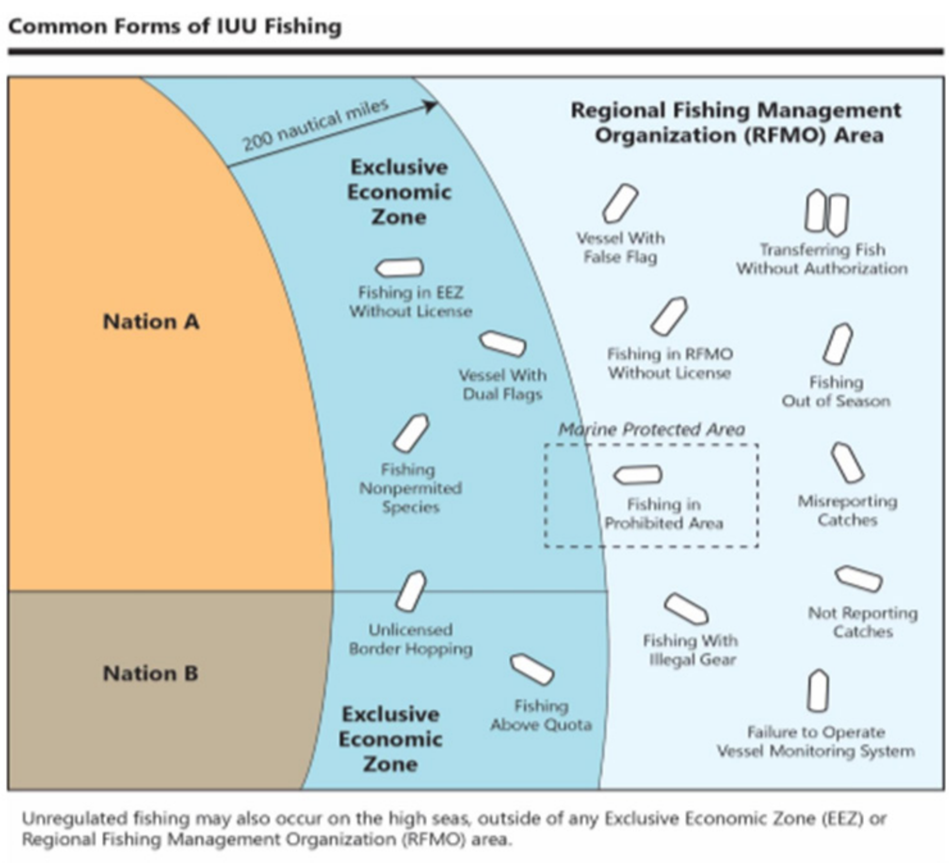

Figure 1. IUU Fishing Forms Found in South China Sea. Source: National Intelligence Council (2016).

b. Piracy / Trafficking / Smuggling

Along with IUU fishing, piracy is another major concern in SEA that creates issues in the maritime domain. Countries such as Indonesia, Malaysia, Singapore, and Thailand are cooperating with each other to reduce piracy in the region (Valencia, 2018). Piracy is an issue that receives more attention from nations than other concerns such as trafficking and smuggling. Piracy attacks affect more countries than smuggling or trafficking, therefore, they receive more attention and resources from nations to combat it. This common problem allows countries to work with each other toward a common goal of eliminating piracy.

The International Maritime Bureau (IMB) is a division of the International Chamber of Commerce (ICC) and tracks piracy and armed robbery attacks against ships throughout the world (IMB, 2019). According to the IMB 2018 report, the total number of attacks in SEA dropped from 76 attacks in 2017 to 60 attacks in 2018 (IMB, 2019). The decline in number of reported attacks in SEA is a good thing, but the total number of attacks in the region is still one of the largest in the world. See Figure 2 for a breakdown of reported incidents separated by region. The numbers listed in the IMB report are just the confirmed, reported attacks and may not represent the total number of attacks in the region, as there are most likely attacks that occurred and went unreported (IMB, 2019).

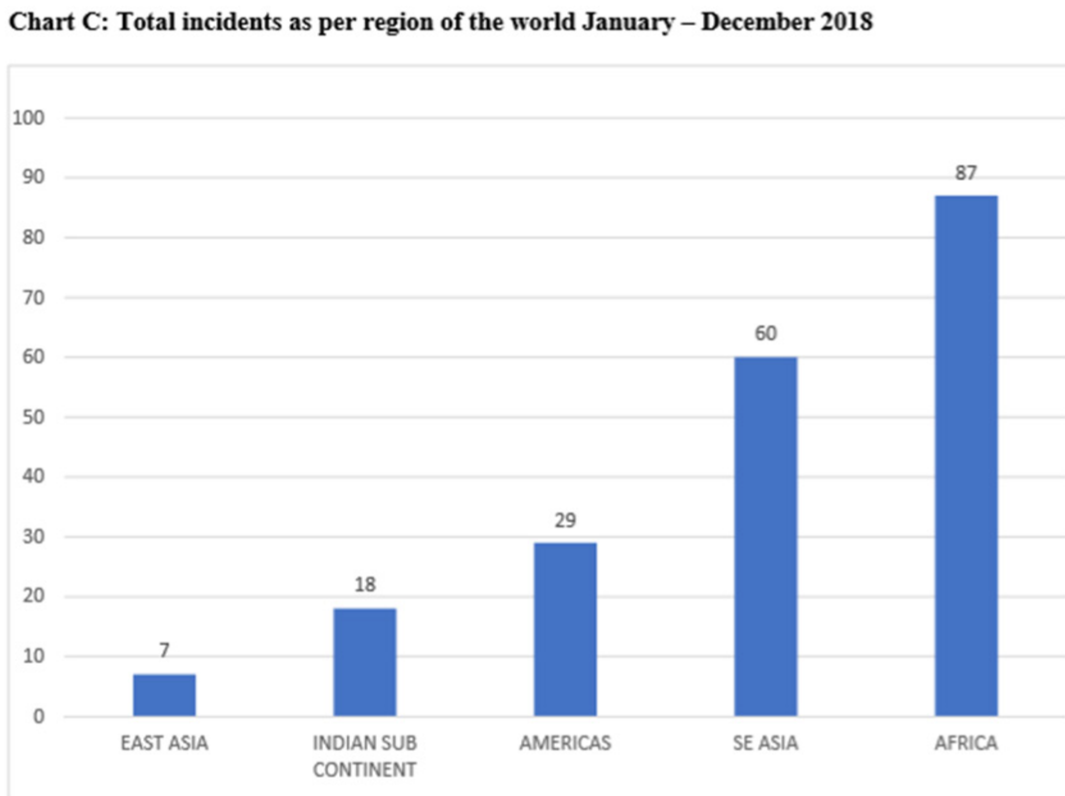

Figure 2. Reported Piracy Incidents Reported in 2018. Source: International Maritime Bureau (2019).

While trafficking and smuggling may not get the attention or resources to combat these issues as piracy does, they are still a major concern in the region. Military confrontations, disputes over territory, and nuclear proliferation are not the only threats to security (Caballero-Anthony, 2018). According to the Asia-Pacific Maritime Security Strategy published by the United States' Department of Defense, non-traditional threats, such as illegal trafficking and smuggling, pose significant security challenges (DoD, 2015). Transnational crimes, such as human trafficking, are prevalent throughout the world with a large portion coming from SEA. This crime generates a lot of money globally, more than $150 billion each year (Caballero-Anthony, 2018). Figure 3 shows the percentage of human trafficking profits by region. The Asia-Pacific region is the highest with 34 percent of the world's total profit received from human trafficking (Caballero-Anthony, 2018).

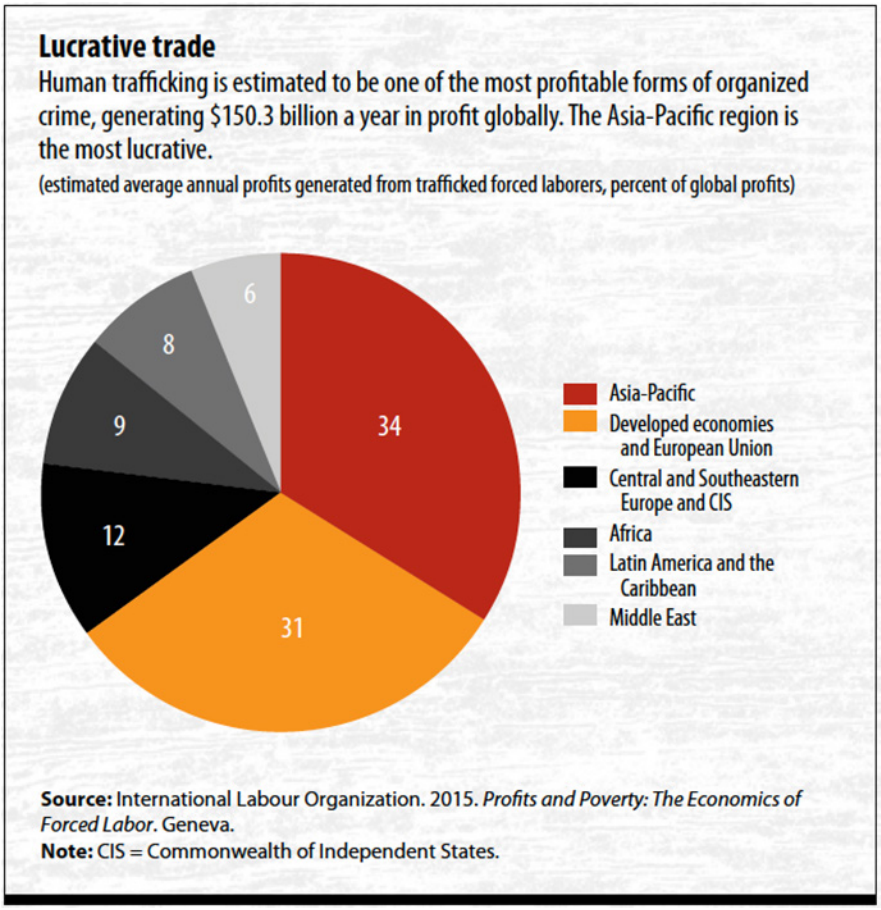

Figure 3. Percentage of Human Trafficking Profits from around the World. Source: Caballero-Anthony (2018).

The severity of the security challenges depends on what material or items are being smuggled and whether the material or items will affect only the southeast region of Asia but the entire world. The region of SEA is a major transit and shipping area for maritime cargo, as many of the world's busiest ports are located within the countries of China, Singapore, and South Korea (Kassenova, 2012). A major security concern deals with the threat of smuggling weapons of mass destruction (WMD) or materials that can aid in the creation of WMD, such as nuclear and radiological material (Kassenova, 2012). This threat is elevated with the uncertainty of North Korea's nuclear program and can be a significant concern to all of the nations in the region.

c. MDA that is UNCLAS

Our thesis focuses on the sharing of unclassified (UNCLAS) information that will improve the MDA of the United States and its partners in the South China Sea. Sharing UNCLAS information is easier than sharing classified information among partnering nations, requires fewer resources, and information sharing can develop trust and confidence in the partnerships (Bueger, 2015). Policies and procedures that are followed for sharing classified information are too time consuming for some of the information to be useful. Unclassified information is more accessible to all nations involved and poses a lower risk to security than sharing classified information.

d. Easy to Share

The sharing of information amongst partners in the SEA will increase the ability to detect, identify, and classify VOI and improve the overall MDA in the area. One way to increase the information sharing is to establish a web-centric enterprise service, such as SeaVision, to share the information gathered by individual nations (DHS, 2013). This web-centric enterprise will allow authorized users access to a large volume of data from multiple sources that can be used to accomplish each country's priorities and missions (DHS, 2013). The web-centric approach allows for quick and easy access to information in near real time and allows for responsive actions.

e. Resources

The resources available to each country and ability to gather, process, and disseminate information vary. A lack of resources by one country can be alleviated by the sharing of information from another. With information sharing, the limited resources one has may be better allocated to a particular geographic area or particular action such as piracy or IUU fishing. Allocating resources to a particular focus will provide a better product and more specific data to be easily shared into a database for others to access. Information on the maritime domain is being collected by many agencies, both military and civilian, and from many countries (Gusti, Dharma, Anak, & Perwita, 2018). This amount of information gathering is not only redundant, but also a waste of resources. Much of the same information is being gathered from multiple sources and by multiple nations. The sharing of information will free up resources that may be better served participating in other tasks or missions.

A navy is one of the most important assets for collecting information and establishing MDA (Gusti et al., 2018). The size of a navy plays an important role in developing MDA and would benefit greatly from information sharing as the strength of each navy in SEA varies drastically. According to the Global Firepower website (2019), the total naval strength of Cambodia, Laos (though landlocked, the Mekong River has its own share of irregular water-based activities), and Singapore in 2018 were 27, 36, and 40 ships, respectively. This does not appear to be enough assets to collect data and process the information, use the information to meet the tasks required, and to defend one's territory. Sharing information will assist in utilizing the resources of each nation to maximize the potential and limit redundancy by separate agencies.

f. Develop Trust

A sense of trust needs to be present when working with partners to accomplish a common goal. Unfortunately, many nations in SEA harbor deep-seated mistrust toward each other based on historical events (Valencia, 2018). According to Bueger, information sharing in SEA is influenced heavily by the relations between each nation and their respective national interests (Bueger, 2015). In addition to national interests, the disagreements, tensions, historical friendships, alliances, and struggles over influence also shape not just the quantity but the quality of information to be shared as well (Bueger, 2015). This becomes very problematic when trying to increase MDA and counter the rising threat of piracy and IUU fishing in the region.

A willingness to share data among nations must be evident for trust and cooperation to develop. A way trust can be built is by sharing information about issues with partners that are interested in that particular area. Some countries are more concerned with piracy while others are more focused on illegal fishing or smuggling (Bueger, 2015). Countries will be reluctant to share information unless they are receiving information in return. This information being shared must be reliable, important, and helpful to meet the individual needs and interests of each country participating. Our thesis focuses on the use of computer vision to increase the ease and ability to share information. Information sharing has the potential to strengthen the trust and confidence among partner nations in SEA (Bueger, 2015).

2. COP

A COP is a situational awareness tool that will benefit the Southeast Asia region and increase MDA. The DoD defines a COP in the Joint Publication 3-0 as a single identical display of relevant information that is shared by more than one entity and facilitates collaborative planning; it also assists in achieving situational awareness (Joint Chiefs of Staff, 2017). Satellites, radars, unmanned aerial vehicles (UAV), and other forms of human collection or reconnaissance used to gather information can be fused into a COP to provide near-real time data for decision-makers in the maritime domain (Ombo, 2015). A COP should be easy to use and should allow each partner to analyze the information provided and use it to meet its individual objectives.

There are numerous collection and information sharing centers in Southeast Asia, including the International Maritime Bureau, Piracy Reporting Centre (IMB PRC), the Regional Cooperation Agreement on Combating Piracy and Armed Robbery against Ships in Asia, Information Sharing Centre (ReCAAP ISC), and the Information Fusion Centre (IFC) (Bueger, 2015). Each of these centers has its own function and approach to information sharing. One of the centers reports, one shares, and the other fuses information as indicated in the organization's respective names (Bueger, 2015). These organizations provide many pieces to the puzzle but ultimately for the information to be useful to increase MDA in the region, each country would need to have access to each organization. Unfortunately, not all nations participate in each of these information sharing centers (Bueger, 2015). A COP will allow all users to insert information into one place, be able to access this information, and see a universal display with all relevant inputs from other nations. Although there may be several advantages to having multiple information sharing centers, a COP presents a clearer picture.

B. COMPUTER VISION

Computer vision attempts to create track data by detecting, classifying and identifying vessels captured in satellite imagery (North Carolina State University, 2016). Creating usable data in this manner is a complex process because computer vision is an inverse problem (Szeliski, 2010). Through computer vision, we are seeking to find an unknown solution without having sufficient data, requiring the creation of models for determining probability among potential solutions (Szeliski, 2010). Computer vision allows machines to accomplish this task through recreating the three-dimensional structure of an object within imagery (Szeliski, 2010). Image capturing devices project the features of three-dimensional objects into two-dimensional images using points, lines and planes (Szeliski, 2010). Vision systems must recreate these features and project them back into a three-dimensional model. That is where the inverse problem originates, since a two-dimensional image will not have all the information required to develop a three-dimensional model. Structure from motion (SFM) techniques assist in defeating the inverse problem (Verhoeven, 2011). SFM reconstructs the three-dimensional geometry of an object from a sequence of two-dimensional images captured by a camera moving around the scene (Verhoeven, 2011). This enables the capturing of an object from multiple angles and increases the likelihood of retrieving the complete three-dimensional details of the scene (Verhoeven, 2011). Computer vision within this study develops models of ships at sea. The VOI are not available for an imaging device to capture from multiple angles at a single instance. The solution that supplements this detriment is capturing and compiling numerous images of VOI from multiple angles into a library for generation of three-dimensional models.

The vision system matches vessels detected in satellite imagery to three-dimensional models created from images in the library. The matching is accomplished through feature extraction and matching, which are essential components of the computer vision application (Szeliski, 2010). The process is described by Szeliski (2010), where computer vision analyzes the images in the image library and extracts identifying features for the objects of interest. These features, once extracted, enable matching to objects in future images (Szeliski, 2010). This is the premise for model-based reconstruction, extracting features from multiple images of multiple angles of an object, creating a three-dimensional model and matching future images of objects to that model with some level of probability (Szeliski, 2010). Szeliski (2010) introduces the machine learning aspect of computer vision, where the system accurately identifies and classifies objects. The machine accomplishes identification and classification through detection and extraction of identifying features (Szeliski, 2010). After feature extraction from chosen images, Szeliski (2010) describes how the machine can identify objects in future images through feature matching.

1. Machine Learning

Machine learning is a versatile technology capable of detecting objects within an image and classifying or identifying these objects into specific categories (LeCun, Bengio & Henton, 2015). The machine learning system trains towards the scenario to ensure an accurate and desired outcome (Soni, 2018). There are two main categories of machine learning introduced by Soni (2018), supervised learning and unsupervised learning. Unsupervised learning, according to Soni (2018), is more exploratory in nature and geared towards identifying structure in raw data. Soni (2018) presents that supervised learning performs in the context of regression or classification, where the goal is to find specific relationships or structures between the input and the output. In this instance, we want to train the machine to detect the presence of an object in an image as the input and determine whether the object is an ocean-going vessel, what the vessel type is and, optimally, the specific identification of that vessel as the output (Soni, 2018). We collect a large dataset of images, some with ships, some without, and feed these images into the machine (LeCun et al., 2015). During training, according to LeCun et al. (2015), the machine is shown each image and outputs a vector of scores for each category, i.e., ship or not a ship. The desired outcome, per LeCun et al. (2015) research, is for images with ships to have higher scores on this vector. An objective function is created to measure the error between the actual output of scores and the desired output of scores (LeCun et al., 2015). Research conducted by LeCun et al., (2015) finds that the machine modifies its internal parameters according to the existing error in order to reduce the error and output scores closer to the desired output. The process of feeding the machine the input vector or set of images, computing the output and associated errors, computing a gradient vector for the weighting of the machine's parameters and adjusting of the weighting to match the gradient vector repeats until the average of the objective functions ceases to decrease (LeCun et al., 2015). Once training is complete, LeCun et al. (2015) determined that the machine would be fed test data to determine the ability to generate sensible results from data is has never seen before.

The training regimen perpetrates over several cycles. The first cycle trains the machine to identify the presence of a ship or lack thereof. Subsequent cycles train the machine to differentiate between classes or types of ships. These classifications can include broad categorizations such as distinguishing between warships and merchant vessels, or narrow classification, such as identifying fishing vessels, tankers, general cargo ships, dredgers, etc. The ultimate goal trains the machine to identify specific vessels or warship classes. Through this method, the machine receives raw data from the images and discovers the representations needed for detection and classification (LeCun et al., 2015). Traditional machine learning, according to the research by LeCun et al. (2015), is limited in feature extraction for pattern recognition and classification. Multi-layer neural networks have been designed for machine learning analysis of two-dimensional data such as images and video (Arel, Rose & Karnowski, 2010). To implement the regimen of cycles described, the research by LeCun et al. (2015), showed that the machine uses a multi-layer deep learning architecture that develops increasingly complex representations for detecting and learning features within the images. The multi-layer deep learning enables the detection of minute differences between images with increasing complexity at each level, allowing for greater differentiation and classification (LeCun et al., 2015).

2. Image Analysis

The computer vision relationship with the camera system is the same relationship between the human brain and the human eye (Nixon & Aguado, 2012). This research showed that both the human eye and the camera system capture data and send it to the human brain or computer vision system respectively, for processing and analysis. Nixon and Aguado (2012) computer vision conducts image analysis at multiple levels. Their work found that multiple layer analysis is necessary to extract the full range of features needed for complete analysis. This research shows that low-level feature extraction is basic feature detection without accompanying shape information. Low-level features include edge detection, which reproduces the line drawing, and corner detection, the point where lines bend sharply (Nixon & Aguado, 2012). The research by Nixon and Aguado (2012) found that edge detection uses vertical changes in contrast intensity to detect horizontal edges and horizontal changes in contrast intensity to detect vertical edges. Research by Szeliski (2010) complements these findings through determining that image contrasts naturally occur around the boundaries of images or objects. Nixon and Aguado (2012) determined that detecting contrast aids in identifying the boundaries of features and objects in an image. Addition findings by Nixon and Aguado (2012) in their research determine that corner detection or curvature consists of edge direction rate of change. This research shows that curvature ranges from edge direction changing rapidly, such as corners, to more gradually or non-existent change such as contours or straight lines. Based on this research, Nixon and Aguado (2012) determined that computer vision commonly calculates curvature through determining the angular change along the curve's path. Alternatively, changes in image intensity can determine curvature within an image (Nixon & Aguado, 2012).

While low-level feature extraction focuses on merely determining boundaries within an image, high-level feature extraction involves identifying actual shapes and objects within images (Nixon & Aguado, 2012). The same study determined that high-level feature extraction uses low-level features of points, lines and edges to define objects with greater complexity. High-level feature extraction, according to Nixon and Aguado (2012) research, seeks high levels of invariance to enable computer vision to find shapes and objects reliably regardless of varying conditions. Invariance, according to their study, involves finding and identifying objects within an image regardless of position, orientation, size, scale or illumination within the image. Nixon and Aguado (2012) found that identification of edges, contours and points enable matching between objects regardless of orientation or scale. Further findings showed that invariance is necessary to progress from mere detection to actual extraction. Through this study, Nixon and Agaudo (2012) determined that detection of an object only implies knowledge of its existence within an image. Further research determined that object extraction requires developing a description of a shape computer vision can recognize regardless of the circumstances of capture for the object within the image. This involves developing a template for the object we are trying to find and matching that template to objects within an image (Nixon & Aguado, 2012). For example, we know what a ship looks and how they are generally shaped, but from the work of Nixon and Agaudo (2012), we know difficulties can arise from rotational and scale invariance. Developing a template enables computer vision to detect and extract the ship object from its background, whether that be the ocean, a pier, etc, and conduct analysis to classify and identify the specific vessel.

3. Metrics

We must develop a feedback system to determine the viability and performance of the machine. This involves creating measurements or metrics for objective observation and determination of system performance. The purpose of metrics is threefold and includes 1) determining how well the system works and what the system is worth; 2) making an existing system perform better; and 3) designing and preparing future systems so they will function better and more efficiently (Raisbeck, 1979). With these criteria, we are able to determine whether the machine provides a satisfactory solution to our problem (Sproles, 2002). Metrics are divided into two viewpoints: measures of effectiveness, which focus on external output, and measures of performance, which focus on internal operation (Sproles, 2002). Measures of effectiveness establish how well computer vision achieves it intended purpose of improving MDA and contributing to a decrease of illegal maritime activities (Sproles, 2002). Measures of performance detail the efficiency and precision of the system in accomplishing its desired tasks (Sproles, 2002).

We judge the effectiveness of the system by its ability to provide an adequate solution for the desired problem (Sproles, 2002). It must be determined that the added ability to detect, identify and track vessels through satellite imagery will improve the ability to reduce undesired activity (piracy, smuggling, IUUF, human trafficking, etc.).

Further, historical data must be presented in a “before” and “after” fashion to demonstrate a correlation between reduction in undesired activity and employment of computer vision in conjunction with SeaVision. Partner nations’ usage of SeaVision and computer vision must increase their ability to find and track vessels of interest. Information sharing through SeaVision must support the ability to view these statistics and measure whether SeaVision increases a partner nation’s capabilities for MDA. We can also determine, if at any given time, partner nations are able to, with greater accuracy, pinpoint the whereabouts and pattern of life for personally-vested vessels of interest versus sometime in the past. SeaVision must demonstrate the ability to consistently detect and track vessels of interest while the vessels in question are not radiating AIS and demonstrating intent to evade detection and identification. These measurements fall within the scope of determining the effectiveness of coupling SeaVision with computer vision and determining whether this system meets the needs of countries for improving MDA (Sproles, 2002).

The performance of the system lies in the internal efficiency of the system (Sproles, 2002). Performance focuses on ensuring that when we receive an output, that output is as accurate and correct as possible (Sproles, 2002). Performance criteria include the ability to detect a ship within an image and determining the probability that the system will detect the vessel’s presence in said image. Machine learning feeds into the performance, ensuring the system increases the probability of determining the presence of a ship within an image (LeCun et al., 2015). The training of the machine must ensure the presence of weather, atmosphere, shore features or other elements within the image that may degrade image quality or obfuscate the presence of a vessel and does not unduly reduce the probability of detection (LeCun et al., 2015). This necessitates the presence of a feedback system to indicate that a vessel was present but not detected by the system. The system must accurately classify detected vessels into predetermined vessel classes. These classes, as discussed earlier, may start broad and, as machine learning evolves, classification narrows to become more specific (LeCun et al., 2015). From this, we can determine the probability of classification and establish a benchmark for acceptability probability for system classification. Classification then leads to identification. We must measure the probability of identification from detected ships and classified ships. We must also determine if the system will identify a vessel even if unable to classify that same vessel. The scope of this thesis focuses primarily on measures of performance or the output internal to the system (Sproles, 2002). This involves consistently and accurately detecting, classifying and identifying VOIs from the dataset of the UN-sanctioned vessels list compiled into a working image library.

C. SOUTHEAST ASIA: SEACAT AND UN SANCTION VESSELS

The SEACAT exercise occurs annually under the guidance of CTF-73 (Commander, Task Force 73, 2017). The proposal was set forth to utilize the SEACAT maritime exercise as an opportunity to implement the SeaVision and Computer Vision pairing within a controlled environment. SEACAT participants include numerous countries from the SCS region that experience many of the maritime challenges previously mentioned. Limited resources, impediments to information finding and sharing as well as sociopolitical challenges within the region act as impediments to tackling these challenges. CTF-73/COMPACFLT possess stakes in helping to build and maintain a collective MDA presence in the South China Sea that can be enjoyed by all participating countries. SeaVision is one tool that CTF-73 can offer to these countries to promote information sharing and improve their capabilities for VOI location and tracking. The SEACAT exercise, among other priorities, works to assist in improving nation's MDA capabilities through VOI location of a target vessel (CTF 73, 2017). SeaVision capabilities would be utilized within this capacity to assist and improve MDA ability.

Further analysis of MDA within SEA brought an additional viewpoint to the picture. C7F possess a strong interest in maintaining cognizance of North Korean vessels involved in questionable or nefarious activities within their AOR (U.S.-Indo Pacific Command, 2019). Vessels of particular interest are those found on the UN Sanctions List. These vessels actively attempt to disguise their locations and movements, keeping their AIS transponders in a non-transmitting state. SeaVision coupled with Computer Vision proposes the viable solution of detection, identification and tracking of these vessels while they are engaged in illegal or questionable activity. SeaVision would be able to detect these vessels without AIS, determine who they are, what they are doing and develop a pattern of life profile. This information would be useful to not only the Seventh Fleet and subordinate commands, but also provides valuable information to allies operating in the Southeast Asia region.

D. CONCLUSION

Maintaining MDA in and around SEA and the SCS is a priority. While serving as maritime hub for global economic trade, the region also suffers from illicit maritime activity and regional geopolitical conflict. This requires the collection, analysis and dissemination of information to enable nations in the region to take appropriate action for rectifying these concerns. The information sharing requirements suggests that the sharing platform should be an unclassified web-based medium. This enables the widest availability and dissemination of information to allied partners. Resource availability differs by nation. A system or platform that is accessible and shared by all reduces the disparity in resources, engenders teamwork and trust, and decreases redundancy in resources dedicated to information gathering.

SeaVision operates as a web-based COP, accepting inputs from AIS, radar and satellite imagery. The COP allows each participant to access and analyze the information provided by the system. Computer vision allows expansion of the injected information, with the intent of detecting and identifying vessels not actively identifying themselves through AIS or other means. Computer vision develops three-dimensional models of VOIs and uses them to classify and identify vessels detected in satellite imagery. Computer vision learns to recognize these vessels through the process of machine learning. The training occurs over several cycles, improving the machine's capability to recognize and identify vessels with each iteration. Machines use various identifying features for analysis and image recognition during machine learning. These features develop a template for detecting, classifying and identifying vessels. The overall capability of system is determined by developing metrics to measure to performance of the system. These metrics measure both the internal efficiency and performance of the systems, as well as determine the intended external output of the system. The SEACAT exercise, an annual maritime exercise in the SCS, exhibits the capabilities of Computer Vision and SeaVision together as a COP. Injecting the UN Sanctions vessels list and corresponding imagery and information allows observance of external effects of the additional information availability and sharing.

III. RESEARCH METHODOLOGY

Our thesis research builds upon the work and research of our predecessors who designed a scenario that would be implemented during SEACAT 2018. This multi-year project started with research by Wreski and Lavoie (2017) to establish a CONOPS to provide a COP with shareable information for partner nations. The research project continued with the designing of an operational experiment by Stevie Greenway and Coey Sipes (2018) that would be implemented during SEACAT 2018. The scenario developed in the preceding thesis was based upon the rising tensions in the SCS due to increased piracy, EEZ encroachment, trafficking, and weapon smuggling (Greenway & Sipes, 2018). The plan for our thesis research was to implement the designed scenario into the SEACAT 2018 exercise, adding an element to the boarding operations, and to test the proof of concept that CV will enhance MDA. After determining the scenario was outside the constraints of the exercise, our attention changed from conducting the experimental exercise to focusing on UN-sanction vessels. This involved finding and collecting available information and images for the sanction vessels, then collaborating with Progeny and SeaVision for using the information within the MDA tools.

A. COLLECTION

We received a copy of the UN-sanction vessels from the CTF 73 MDA Advisor with input from Commander, Naval Forces Korea N2 (S. Miller, personal communication, April 12, 2018). UN Security Council Resolution (UNSCR) 1718 established the baseline for the sanctions of DPRK individuals and entities and was superseded by UNSCR 1874 (United Nations, 2018). Follow-on resolutions by the United Nations Security Council (UNSC) add or subtract vessels from the list. All resolutions and updates are uploaded to the UN website, creating a comprehensive sanctions list. The list received via correspondence on April 12, 2018, was compared against the UNSC sanctions list on the UN website, and verified for completeness and currency.

After verification of the sanctions list, we developed an image library for the target vessels. This entailed gathering as many images as possible of each VOI, attempting to find images with views from multiple angles, including an overhead shot, to aid in construction of the vessel three-dimensional model. The three-dimensional model would have later been used to identify vessels located in satellite imagery by CV. CV imported these identified vessels as tracks into SeaVision, for information sharing in support of MDA and the COP. Images of vessels on the sanctions list were retrieved from unclassified, open-sourced AIS websites. These websites were comprised of www.marinetraffic.com, www.vesselfinder.com and www.shipspotting.com. Figures 4 and 5 are images of websites we used for our initial search for photographs of the UN-sanctioned VOI. An image search of these websites produced an accumulated 476 total images for the image library, which included images for 62 of the 97 vessels on the sanctions list.

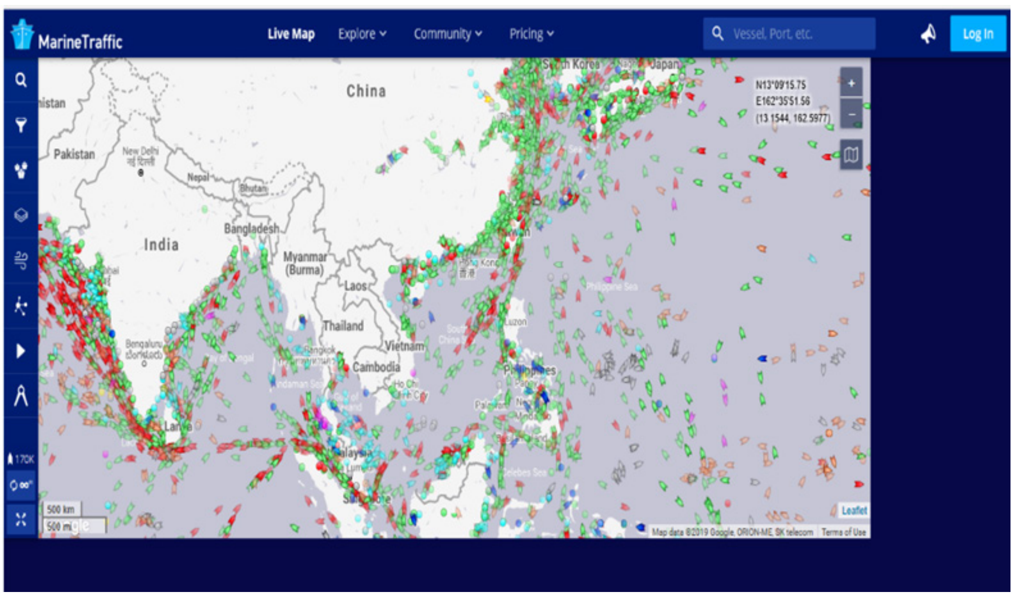

Figure 4. Image of MarineTraffic Website. Source: MarineTraffic at www.marinetraffic.com (2019).

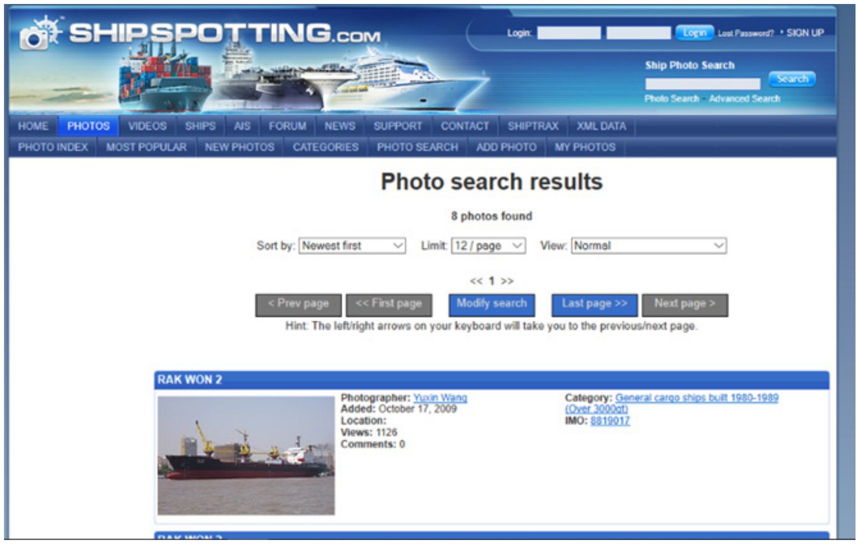

Figure 5. Image of ShipSpotting Website. Source: ShipSpotting at www.shipspotting.com (2019).

Library images were crosschecked with information from the website database to determine the dates and locations of each image of the vessel. Progeny requested this information to create a tentative historical timeline for each vessel's movements and port calls (S. Miller, personal communication, September 20, 2018). Creating a historical timeline assists in finding initial overhead satellite imagery of vessels in the DigitalGlobe database for creating a complete three-dimensional model. The timeline for vessels in the image library ranged from 2001 to 2018. Vessels were found in 78 different locations or ports, covering a broad geographic area across Southeast Asia, from Russia to Australia. Latitude and longitude information was inconsistently labeled; however, we were able to retrieve what appeared to be accurate information for several vessels that were not captured in port. We consolidated the images, along with corresponding accurate locations and dates, and sent the information to the Progeny point of contact. We discarded any inaccurate location information. Images without corresponding locations were included in the image library, but notated for missing location information.

Progeny, after receipt of our original information, requested verified locations and dates for as many vessels as possible, to assist in retrieving overhead images. We used www.vesselfinder.com, an AIS database, to find dates where sanction vessels broadcasted AIS showing their location in port. We were able to find five vessels, through www.vesselfinder.com, that broadcasted AIS while in port on various dates. The dates for the locations were all within a six-month range. We specifically searched for vessels with recent dates, less than six months old, to increase the probability that satellite imagery, for the desired date and location, would be in the DigitalGlobe database. Figure 6 shows an image of the vessel finder website we used for our secondary, and more refined, search of the UN sanctioned VOI. Of the vessel locations we discovered, three broadcasted from six different ports in China, one from Inchon, Korea and one from two different ports in the Philippines. Each vessel broadcasted their position in port on multiple dates, increasing the likelihood that Progeny could locate satellite imagery for an overhead view. This information was compiled in a similar format to the original information and sent to Progeny for review and implementation.

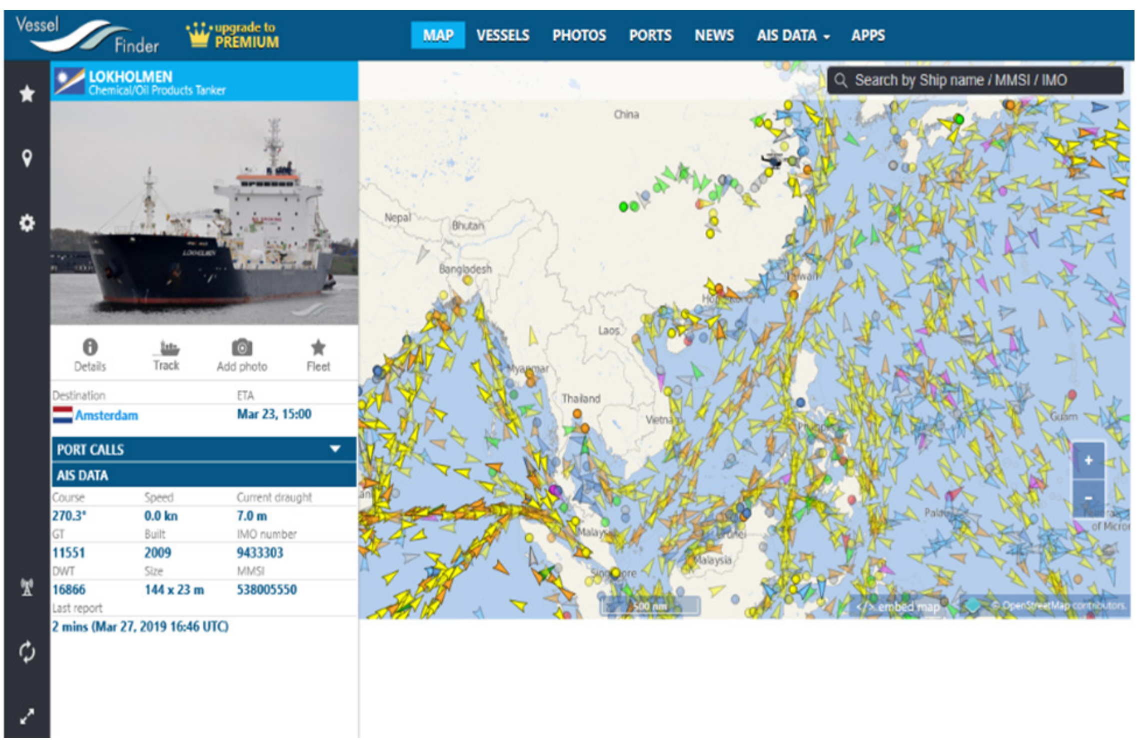

Figure 6. Image of Vessel Finder Website. Source: Vessel Finder at www.vesselfinder.com (2019)

B. DETECTION AND METRICS

Progeny would combine overhead imagery of VOIs with respective images from the image library to create the three-dimensional model. This image library compares the models with newly acquired unclassified imagery to find matches. SPOTR ingests the unclassified satellite imagery from the DigitalGlobe imagery database and runs detection and identification algorithms, comparing the images to the three-dimensional models. CV would be used to conduct the search of the database to detect and classify vessels. Figure 7 is an image of the DigitalGlobe home page of its website. When SPOTR discovers a match, it sends the data to SeaVision, creating a track in the SeaVision system. These created tracks will fall under one of three categories in SeaVision; 1) detected, 2) classified, or 3) identified. A ship is detected when an image matches the criteria used to determine the presence of a maritime vessel, but not enough information is available to classify or identify the vessel. Classification is when a type of ship is recognized, such as an oiler, a cargo ship, or even a warship. The algorithm can determine what the type of ship is, based on the comparison between the three-dimensional model and the newly acquired image. However, there does not exist sufficient feature matching to identify a specific vessel. Identification is when the VOI matches the criteria being looked for and the exact vessel is found. A positive identification match provides multiple hits over time. Identification is the toughest category to place a vessel. Many vessels look the same and have similar designs and markings. Warships, for example, are tough to identify, but easily classified. Finding overhead images of a United States destroyer will allow the algorithm to classify the vessel, as possibly a Flight IIB, but the exact vessel, or hull number, will be unknown.

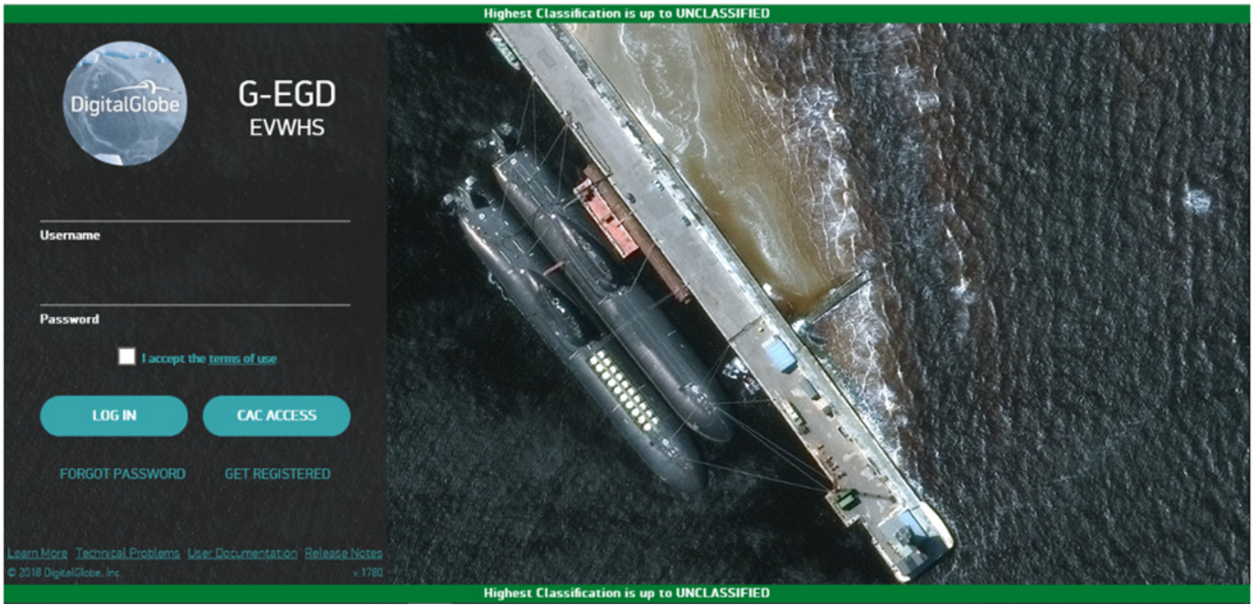

Figure 7. Image of DigitalGlobe Website Login Page. Source: DigitalGlobe at evwhs.digitalglobe.com/myDigitalGlobe/login (2019).

The DigitalGlobe database has imagery dating back to 2014 allowing for analysis of historical movements and development of pattern of life for VOIs. The frequency of these hits, such as days, weeks, or months, demonstrates the efficacy of the process. Detecting and tracking targets every few days is useful for developing pattern of life information. Detecting and tracking a VOI every few months has limited usefulness and provides little information regarding the vessel's conduct and habits. False positive identification of VOIs would further limit usefulness or skew the historical data. The SPOTR false target rate is low, meaning the detection of a target is generally trustworthy and accurate (Boger & Miller, 2018). False identification rate, however, is a phenomenon that requires further study. Determining the occurrence of false positive identification determines the veracity of the developed three-dimensional model, indicating whether enough data has been collected to build a model detailed enough to consistently identify targets with a high probability.

The efficiency of the SPOTR, along with the accuracy of the model, must be considered to ensure the functionality of the entire feedback loop. The following discussion highlights areas for verification of system performance. Developers have already reduced the occurrence of false targets to acceptably low levels (Boger & Miller, 2018). Users can trust that, when the system indicates the presence of a target, the indication is legitimate. There is no method, however, to determine failure of the system to detect a target's presence. A possible solution would be an alternative CV system capable of detecting missed targets. This raises two issues; First, this assumes the hypothetical alternative system is better at detection than SPOTR, which would beg the question why we are using SPOTR versus this hypothetical system; Second, this system uses excessive resources. Two redundant CV systems are operating concurrently to accomplish a single purpose. The alternative is to view the false negatives as an acceptable loss ratio. Based on training during machine learning, Progeny would adjust and improve the algorithms until the percentage of vessels that would not be detected falls below a predetermined acceptable level and use this percentage as an operational constraint.

Following detection, SPOTR compares the target against feature sets developed for each type of vessel, enabling classification into one of eight categories (Boger & Miller, 2018). Results from classification should ensure the system can accurately and consistently label the category of detected vessels. Analysis of system output would have determined the probability that vessels detected are unable to be categorized. The analysis would also have determined what the leading cause for failure to classify, such as inconclusive information in the target image or lack of matching features. The determination must be made whether identification, without any level of reliable probability, is possible without classification. Based on the functions of the system, identification is unlikely if the feature information is unavailable to provide classification. This could lead to a low probability identification, where the system determines the identity could be one of several vessels, with low probability of varying degrees. Therefore, we would have established a base probability standard to be 0.95 confidence level, for the system to attribute positive identification. Any confidence level from 0.75 to 0.949 would have received a probable identification label. Confidence levels less than 0.75 would have received a possible identification label. Detection, classification and identification provide the three pillars for system functionality. The accuracy of system performance ensures the effectiveness of its implementation

C. CONCLUSION

We developed an unclassified image library from the UN sanction vessels list using open sources for the VOIs that had information available. Approximately two thirds of the sanctions list were included in the image library. We further narrowed the list to vessels that broadcasted AIS with port and date information. This enabled Progeny to retrieve overhead images for creating a full three-dimensional model of the selected vessels. This reduced the list of VOIs from the original 97 on the sanctions list to five specific vessels. Progeny's three-dimensional models of these VOIs would have been used to demonstrate the efficiency of the CV system for detection, classification and identification of targets. This demonstration would have established accuracy and functionality of the CV system before determining system effectiveness in implementation.

IV. RESULTS

A. CHALLENGES

Our thesis research changed from implementing a fictitious operational scenario in order to test a proof of concept to utilizing a list of actual VOI. These VOI, derived from the UN sanction vessels list, would be the subjects of this process of using CV with commercial imagery to detect, classify, and identify vessels when the vessels aren't broadcasting AIS data. Several challenges were faced with the execution of this research and include:

- Designed scenario unattainable
- Competing priorities
- Participating nations unable to meet requirements
- Limited to UNCLAS images
- Large amounts of data.

1. Designed Scenario Unattainable

The operational scenario designed by our predecessors appeared too ambitious to be implemented during SEACAT 2018. It became clear, as we attended the IPC and spoke with many of the participants of the exercise, that conducting the operational scenario would be unattainable. According to CTF-73, the use of computer vision to track VOI was too forward leaning for the partner nations to grasp and be able to execute (Boger & Miller, 2018). The designers of the SEACAT exercise contract Military Sealift Command (MSC) vessels to be implemented into the scenarios as VOI for boarding exercises.

Even though the designed scenario wasn't able to be implemented during the SEACAT exercise, another effort to track a VOI was attempted. We wanted to try to track a known VOI in the background of the SEACAT exercise using CV while not interfering with the execution of the boarding scenarios. Tracking a known VOI would require an advanced notice of the vessels that would be contracted for use during the exercise to give plenty of time for the image collection and delivery. The collected images would be delivered to Progeny Systems Corporation employees assisting us in this research area, who would use the images to create a three-dimensional model of the vessels. Unfortunately, the vessels being used during the SEACAT 2018 exercise weren't contracted quickly enough for the execution of our research.

The change in focus to UN-sanction vessels would be much more time-consuming for locating images, as the VOI increased from three to the 97 vessels mentioned on the UN-sanction list. While searching for images of the 97 vessels, we discovered that many of the vessels changed names over the years. The different names used for each vessel made the search a little more difficult, but even though the names might change, the International Maritime Organization (IMO) number never changed. Our searches started focusing on the IMO number instead of searching for the name of a particular vessel. The list of UN-sanctioned vessels, and the images gathered, would be used in our research in place of contracted vessels in order to test the ability to use CV to detect, classify, and identify VOI.

2. Competing Priorities

Priorities vary greatly, not only between nations, but in organizations also. With nine countries participating in the SEACAT exercise, the priorities among them never aligned. Each nation had its own agenda and goals to accomplish, so differences in priorities were to be expected. Some nations were more troubled with piracy, while others were more concerned with smuggling, trafficking, or illegal fishing. Differences in agendas and priorities among partner nations reduce collaboration and overall MDA in the SCS region.

The three-dimensional model being built by employees from Progeny Systems assisting in our research would be used as part of the CV process. Unfortunately, our research project wasn't the only thing Progeny had going on, and it was a project that the employees working with us would be doing on the side. Other projects the company had undertaken took precedence over what we were asking them to do for us. Communication between both ends, us and Progeny employees, got delayed on several occasions. It took time for Progeny to figure out what exactly it was that we were looking for and how it was going to get accomplished. The two gentleman we worked with from Progeny, Tim and Karsten, would travel a lot (and overseas) for their company, which made for difficulties in catching them, and it would take time to respond to e-mail correspondence. We sent Progeny more than 475 photos of UN-sanctioned vessels we downloaded from different sources. The first set of photos, of just the UN-sanctioned vessels, were delivered to Progeny. Once received, we were asked to find the dates and locations where the photos were taken. Having to find the dates and locations of the photos delayed our research. This included returning to the photos' website sources to search for additional dates and port location data. Eventually, we completed the new list of photos with the associated dates and locations. While incomplete, it provided a new list for Progeny to work with in looking at historical data through SPOTR. The historical data could be used to find the areas the VOI normally operate and where they have been detected.

Several of the photos collected were taken many years ago, which didn't provide much help to Progeny. We were asked to find dates and locations of sanctioned vessels that were more recent. Another search was conducted, using unclassified AIS databases, to find VOI broadcasting AIS in a more recent timeframe. We were able to find only five of the UN-sanctioned vessels that broadcasted their AIS data and get the dates and locations of when and where they broadcasted. This data was then sent to Progeny to be used to search DigitalGlobe to find an overhead image of the vessels to complete the three-dimensional models. The back-and-forth communication and discovery of requirements took several months and went beyond the timeframe of the SEACAT exercise. Once we delivered the images, along with dates and locations, we needed to wait for Progeny to have time between other projects to develop a three-dimensional model from the images received. Due to higher priorities at Progeny, the three-dimensional model was never created or tested.

Two tools that would be used in this research project are SPOTR, a product of Progeny Systems, and SeaVision, a product of the United States Department of

Transportation (DOT). These two projects would collaborate to ensure tracks would be ingested from SPOTR, when images matched the three-dimensional model being built, into SeaVision. The tracks being ingested into SeaVision would provide the COP for users, and the tracks would be created once VOI have been detected, classified, or identified by the use of UNCLAS imagery. Members from SPOTR and SeaVision assured us that the ability to ingest tracks from SPOTR to SeaVision was feasible, however, it would take time and collaboration between the two entities to make it work. Misunderstandings occurred; while SeaVision waited for SPOTR to ingest the tracks into their system, SPOTR needed tracks from SeaVision to validate their approach and ensure the tracks being ingested into SeaVision were in the proper format (Boger & Miller, 2018). Both Progeny and the members from SeaVision, needed to compete with other priorities of their respective organizations and the integration between the two products remains incomplete.

3. Participating Nations Unable to Meet Requirements

Sharing information is critical in order to use CV to detect, classify, or identify VOI and enhance MDA in the SCS. The continuous sharing of information among nations in the Asia-Pacific region can be a tough task. Many nations appear hesitant to want to share information with others and typically require consistent pressure to continue sharing information to achieve the goal of improving MDA in the region (Boger & Miller, 2018). Continuous sharing of information among ASEAN partners requires a culture shift because of historical relations and tensions to create cooperation among them. This will help them to achieve their common objective of increased MDA.

A lack of available resources among the ASEAN partners became a challenge for implementing our research into a real-world scenario. The U.S. DoD has an abundance of resources available to execute many military missions or exercises. Resources readily available to the DoD include personnel, ships, equipment, finances, and technology. Working with other nations can become complicated when there is a lack of resources in any of the areas mentioned. Compared to the United States, the ASEAN countries do not have as many naval assets or personnel available to them for exercises. The amount of money spent on defense of the ASEAN nations pales in comparison to the amount spent on defense by the United States. The approximate amount spent on defense, in United States Dollars (USD), by the United States is $716 billion, while the amount spent by the nations participating in the SEACAT exercise comes to a total of approximately $35 billion (Global Firepower, 2019). The $35 billion spent on defense by participating nations in SEACAT comes from eight nations combined. Singapore is the largest contributor, spending approximately $9.7 billion on defense (Global Firepower, 2019). While money being spent on defense may not determine one's military strength, it most certainly provides the personnel and resources being used to carry out a country's priorities. Resources available differ, not just with United States, but among ASEAN partners also, creating challenges with how much information and resources are being provided by participating nations.

An easy way to share information among partners working together is to establish a web-centric enterprise, where all participants can collaborate. Our research planned to use CV and inject tracks into the SeaVision COP for all users to be able to provide and receive information needed to conduct operations and make operational decisions. A major challenge we faced with attempting to use this technology with our research is that most of the countries participating in the SEACAT exercise did not have Internet access onboard their ships. Not having Internet connectivity aboard the naval vessels became a major issue, as the participating ships could not access the information available to them. Some of the countries participating in the exercise had heard of SeaVision, and used the resource in some capacity, but there was also a lack of active accounts to access the information. Prior to the start of the SEACAT exercise, SeaVision accounts would need to be created, but with the lack of Internet connectivity on the ships, the need for account creation became moot.

Another requirement unable to be met by the participants of SEACAT was implementing the idea of Pattern of Life (POL). POL is a term used in the military to determine behaviors and habits of people through surveillance over time and can be used to predict future movements and actions (Craddock, Watson, & Saunders, 2016). The use of CV, combined with SeaVision, could produce a POL of particular VOI. A historical search of vessels could show where ships have been, ports frequently visited, how long typical port visits last, and typical routes the vessels take between ports. SeaVision account users only have access to the past 90 days of historical logs, making POL assumptions more difficult. Unfortunately, the concept of POL seemed too difficult for the ASEAN nations, as they each have very little experience in this area or have little desire to attempt pattern of life analysis.

4. Limited to UNCLAS Images

To ease the ability to share information among partners, we limited our research to only UNCLAS information. The photos we collected, along with the information on location and dates, all were taken from UNCLAS sources readily available to anyone with Internet access. SeaVision is a tool, available to all registered users, on UNCLAS networks; it allows users to enter and share information and detection of vessels among each other. Using only UNCLAS sources limited the number of photos and information on VOI for our research. Having access to, and using, classified sources would increase the number of photos collected, along with additional satellite images, dates, and locations. Classified sources would allow us to expand our search and increase the probability of finding information to aid in building the three-dimensional models of the VOI. Not every country participating in the SEACAT exercise has access to the same classified information, nor does every nation want to share what classified information they each have with one another.

5. Large Amounts of Data

According to Bernard Marr (2018), 2.5 quintillion bytes of data is created each day and 90 percent of the data generated in the world has been done so in the past two years. These statistics are taken from 2018 and, at the rate data is generated, the number of bytes of data created each day is probably even higher than 2.5 quintillion. This is a large amount of data being produced each day. While having lots of data may be a good thing, it is only useful if one knows how to make sense of the data and gather what might be beneficial to them. As multiple countries input data into SeaVision for all users to see, it could possibly flood the COP with too much information to be useful. Each nation would need to sort through the data that is helpful to them to clear up their individual COP. Sorting through massive amounts of data being inserted by partners can become time-consuming and the information can quickly become irrelevant. The main challenge being faced here is how to find relevant data and make use of what is being shared by partner nations.

B. ACTUAL RESULTS

The goal of using SPOTR to create tracks for SeaVision did not come to full fruition during this period. However, valuable lessons were learned that can be implemented going forward. Keeping these things in mind can improve the process and yield actionable results. The following are factors that affect the results of the project moving forward.

Completion of this project requires a concerted level of prioritization and coordination among the entities involved. The current priority for the SeaVision and SPOTR teams seems more of a side project. As of this writing there was no confirmation that SPOTR had fully fused with SeaVision to provide track data in a readable format. Progeny, the Department of Transportation Volpe Center, and DigitalGlobe continue to iron out the details to establish a system for feeding satellite imagery into SPOTR and converting the images into track data that can be piped into SeaVision. The process should include an automated method to feed imagery from the source into SPOTR for maximum efficiency. Manually locating and feeding images into SPOTR is time consuming and resource intensive. With increased focus on interoperation and implementation of all the system components, potential exists for a useful and valuable product.

The DigitalGlobe image repository has inherent limitations with satellite imagery as its source. Satellite revisit times provide a ceiling on how many photos can be captured of an area of interest within a specific timeline. The swath area of the specific satellite limits the geographic area captured on each revisit. Cloud cover and weather interference further reduce the number of satellite images available. This is an inherent limitation on satellite imaging and, based on cursory investigation of the DigitalGlobe database, this will affect the ability to gather source images for vessel detection and identification. Satellite imagery should be supplemented by other image sources, such as aerial or maritime imagery with accurate date and location metadata. Satellite imagery provides a good starting point for demonstrating a proof of concept with SPOTR. Evolution of the system should allow for using other image sources to increase the chances of detecting and identifying VOIs.

Building an image library from unclassified sources poses a unique challenge. Only five of the 97 original VOIs had recent location data while in port from unclassified sources. Gathering photos of these vessels from the indicated location assists in obtaining an overhead vantage for creating the three-dimensional model and developing pattern of movement for the VOI. Finding identifying photos and building subsequent three-dimensional models from unclassified sources can be challenging for uncooperative VOIs. VOIs, such as those on the sanctions list, are attempting to evade detection. This increases the likelihood they will not participate in such transportation reporting projects such as, MSSIS or VTS, since they want to shield their behavior and location. The greater the level of effort in ensuring that SPOTR would detect the vessel, the greater the occurrence of diminishing returns. The next step is determining whether the level of effort required to collect and develop the inputs matches the output received. This will depend on how many hits SPOTR generates on the given VOIs. The number and frequency of hits must be enough to generate historical tracking or pattern of life.

Four of the five vessels were in China or Korea. Little imagery on the unclassified realm is available for these regions. The ports reported for these vessels could not be located on the DigitalGlobe unclassified image database. Using classified imagery may solve the problem, but defeats the purpose of creating an unclassified COP. Other unclassified satellite image sources besides DigitalGlobe may possess images of this region. Image sources other than satellite imagery are possibilities, however, it is likely that the sources providing these images would have to declassify them before use. VOI will operate and reside in sensitive areas where it may be difficult to obtain unclassified imagery of that region.

Starting from the original list of 97 vessels, we set out to develop an image library with photos of each of the vessels. Searching the unclassified image sources yielded photos for 62 of the 97 ships. Progeny requested location information for each of the photos discovered. This requirement reduced the number of ships to 51 that had location and date information for their photos. Of those 51, 41 of the ship's photos were dated inside the DigitalGlobe database date range of 2014-present. Seeking to restrict the search to the most recent photos, we sorted the results to show only those photos from 2018. Of the 41 ships, only nine had photos from 2018. We searched the entire list of 62 ships that had images to see if any of them had broadcast AIS data in port in 2018. We found five ships from that list that had broadcasted. We cross-referenced these five against the ships that had images in the image library from 2018. Only one ship had both images from 2018 as well as broadcast AIS data in port during that same time span. These numbers are shown in Figure 8, where each requirement yields decreasing numbers of eligible vessels.

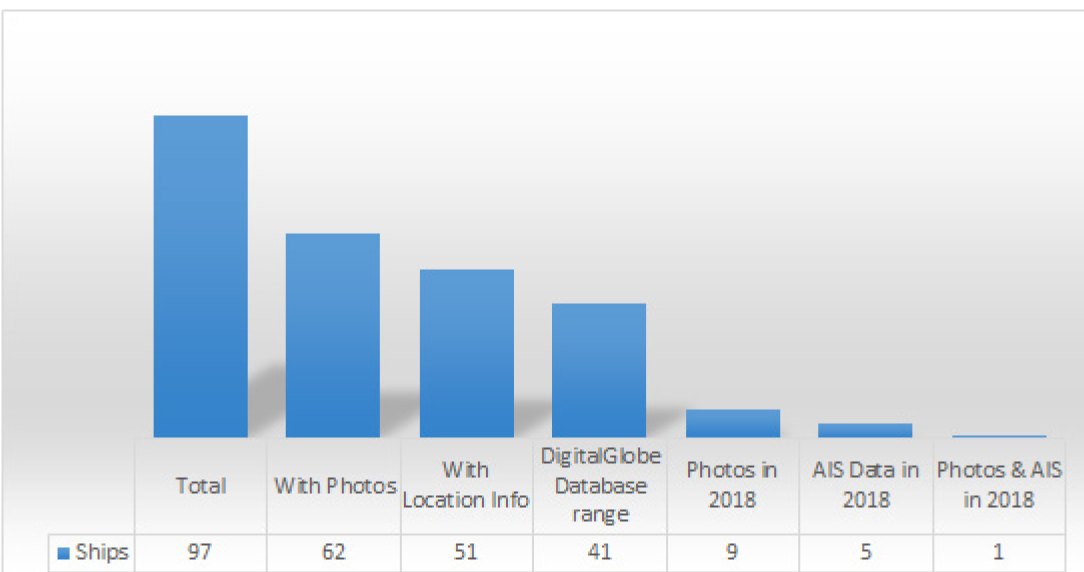

Figure 8. Number of Eligible Ships at Each Requirement Level.

The fact is unsurprising that as requirements become more stringent, fewer entities exist to meet those requirements. What was surprising was how restricted the results were after meeting all requirements. Table 1 demonstrates the breakdown of percentiles with each successive requirement. The list dwindled from 97 to 62 with the requirement of finding photos, less than two thirds of the original number. The restriction of appending location and date information to photos further reduced the number of eligible ships to 51, almost half the original number. Restricting the ships to those that had photos within the date range for DigitalGlobe's database reduced the number to 41, less than half of the starting amount. Focusing on ships with photos from the past year left less than ten percent of the original list. AIS data was only available for five of the 62 ships with photos in the image library. Cross-referencing those five leaves us with one percent of the original list meeting all requirements, as shown in Figure 8. Failure to find an overhead image for developing the three-dimensional model for that single ship negates all the effort required to get to that point. The requirements need to expand to cover the entire time span, starting from 2014, instead of restricting to only 2018. Data of uncooperative vessels isn't readily available from unclassified sources. Increasing the time window for gathering historical data, within the tolerances provided, increases the likelihood of finding useable and actionable information. Expanding the requirements increases the number of ships that will provide potential for developing a three-dimensional model and decreases the likelihood that the search yields no results.

Table 1. Percentage of Ships Meeting Specific Requirements.

	Num	% Total	% Photos	% Location
Total Ships	97	100%		
Ships w/ Photos	62	64%	100%	
Ships w/ Photos & Loc	51	53%	82%	100%
Ships in 2018	9	9%	15%	18%
Ships in 2017	9	9%	15%	18%
Ships in 2016	25	26%	40%	49%
Ships in 2015	16	16%	26%	31%
Ships in 2014	8	8%	13%	16%
Ships w/ Photos in DigitalGlobe Date Range	41	42%	66%	80%

We were assigned to look for VOI that work hard to remain undetected. There are types of ships that ASEAN countries might also consider VOI, such as smuggler and illegal fishing ships. Applying these techniques to that class of ship type might reveal better results.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The goal of our thesis project was to conduct an MDA experiment within the SEACAT 2018 exercise. The experiment was designed to test the ability to track VOI that are not broadcasting AIS data with the use of unclassified MDA tools, such as SeaVision and SPOTR. Unclassified photos of VOI were collected and used to create a three-dimensional model. Imagery, from unclassified sources ingested into SPOTR, was to be compared with the use of CV to the three-dimensional models to find a match. SeaVision would create tracks in its system, when there was a detection, classification, or identification of a VOI. These tracks would create a COP for all partner nations in SEA to use. This exercise would also test partner nations' ability to share information, which is important for the successful enhancement of MDA. COPs are designed to assist the decision-maker in making intelligent operational decisions. As nations share information among one another, more tracks would be implemented into SeaVision creating a clearer picture for decision-makers. This experiment would also test the likeliness of detecting, classifying, and identifying VOI with the use of unclassified MDA tools.

1. Results

The operational scenario, designed by our predecessors, was not implemented during the SEACAT 2018 exercise. Although there is a high level of interest in MDA in the Asia-Pacific region, our focus of research never became a high enough priority in the area. The operational scenario would provide a platform to test the use of CV to detect VOI not broadcasting AIS data. This scenario would be conducted, using contracted vessels in a controlled environment, to test the ability and reliability of detecting, classifying, and identifying VOI. Once we concluded that the experiment would not be conducted during the SEACAT 2018 exercise, our focus shifted from using contracted vessels to using vessels from the UN-sanctioned list. By adding UN-sanction vessels to this research experiment, we increased the number of test subjects, from three to 97, and added a real-world element to the experiment. Unfortunately, the information required to build the three-dimensional models (i.e., images from different angles, including overhead images) limited our searches from 97 ships to five.

Employees from Progeny Systems would use the information and images gathered, through our research, to build the three-dimensional models. These three-dimensional models, with the use of algorithms, would be compared with newly acquired images to detect a VOI. Once a detection, classification, or identification of a VOI occurred, information would get ingested into SeaVision, creating a track. This three-dimensional model, to our knowledge, never got created. SPOTR, a tool from Progeny Systems, collects and processes data. This processed data gets compared with the three-dimensional model and the information is sent to SeaVision for track creation. The process of sending information to SeaVision, and creating tracks for the COP, requires integration between the two systems and two organizations. The integration, between Progeny and SeaVision, never came to full fruition during our window of research, further limiting the ability to test the use of CV to detect VOI and enhance MDA.

2. Challenges

Throughout our research and implementation of the operational scenario, we faced many challenges, ultimately leading to a failure in conducting an operational test. Challenges faced with our research include the designed scenario being unattainable, competing priorities among entities, participating nations unable to meet the requirements, the image library being limited to only unclassified photos, and a large amount of data being produced and shared. Our objective was to implement a way of sharing information among partners to increase the MDA in the region. We attempted to do this by limiting our usage of photos to the unclassified level, which allows for ease and timely sharing of information. With the change in focus to UN-sanction vessels, unclassified photos were tougher to find, along with information required to conduct testing, such as dates and locations of retrieved photos.

The participating nations in the SEACAT 2018 exercise were mostly unable to meet the requirements to successfully test the use of CV with SeaVision, to detect VOI. In order to access SeaVision to view a COP with updated tracks, Internet connectivity, along with account access, is required. A lack of resources, particularly the absence of Internet connectivity among ships, aided in the unsuccessful testing of the operational scenario.

Priorities among the countries participating in SEACAT varied greatly. Some countries were more concerned with piracy, while others were more concerned with illegal fishing, smuggling, or trafficking. Competing agendas among nations made cooperation and sharing information more difficult. The Progeny Systems employees assisting us in our research had other projects they were working on. These projects took precedence over our area of research, and communication became delayed between the two sides with our competing schedules. Ultimately, the differences in priorities among all participating organizations made the successful testing of CV to enhance MDA a difficult task.

B. RECOMMENDATIONS

Demonstrating the proof of concept for SPOTR and SeaVision would have a better chance of success with greater controls over the test environment. The test scenario should implement a constrained geographic area of travel for the test VOI. Limiting the geographic search area uses less time and resources during the testing scenario. In order to place this restriction on the VOI, the target should be a vessel under control of the researchers. This control enables researchers to gather images of the requisite angles required to create the three-dimensional image and build a historical timeline for the vessels' location. The vessel movements can then be constrained or directed as needed, depending on where geographically the tests will be conducted.

The requirements for creating three-dimensional models must be clearly defined in order to allow for the accurate and complete collection of the necessary data for model creation. The requirements should state the date, location details, and image angles that are needed to streamline the information process. The information needed should attempt to answer the questions of who, what, when and where for each VOI.

More data sources must be identified for developing information on target vessels. Data sources during this research were limited to unclassified open-source data repositories. While these sources provided valuable information, there is an inherent risk of error or misreporting that exists due to the open-source nature of the data. There is also the risk of information gaps. The information gaps can manifest themselves through limited images of a vessel, resulting in incomplete modeling through CV, spans of time where no images or vessel movement information is recorded, and incomplete or missing biographical data on vessels such country of origin or ownership. Expanding the data sources will likely decrease the number of data gaps for VOIs.

More data sources are required for creating source imagery. Data sources can include other satellite imagery providers besides DigitalGlobe, aerial imagery from MPA, ISR and maritime reconnaissance and surveillance footage from ports and docks. DigitalGlobe is limited by the coverage of their constellation and the corresponding revisit times. Additionally, weather and atmospheric interference limit the number of usable images captured during those revisit times. A single source of data increases the chance that images of specific place at a specific time will not be available.

C. FUTURE RESEARCH AND DEVELOPMENT

The use of unclassified applications with CV can be implemented into other areas in the future upon successful testing in a controlled environment. This process can be integrated onto naval warships, Maritime Patrol Aircraft (MPA), UAVs, and even sail drones (a type of USV). Our CONOPS focused on the maritime domain, detecting VOI not broadcasting AIS information. Naval warships, along with MPAs and UAVs, could implement the use of commercial imagery to locate vessels to meet mission requirements. Detecting vessels that are not broadcasting AIS data isn't limited to just vessels conducting piracy, illegal fishing, or smuggling. Commercial imagery with CV can locate and detect ships operating in territorial waters that are not their own, or locate other military vessels, whether in port or out to sea.

UAVs and other drones are already being utilized by the U.S. Navy to support its missions. These UAVs can be used to provide imagery to feed the proper applications that are being used with CV to detect vessels. With equipment installed onboard naval vessels, the imagery feeds can provide real-time or near real-time locations of VOI and provide clearer information for decision makers.

While our thesis focused on unclassified imagery with commercial applications, this process can be further developed to include classified imagery. The use of classified imagery will limit the number of countries with access to them. Although the limited access to classified images may hinder some countries' ability to use the information, it will provide a greater number of images to those countries with access. The greater number of images available from classified sources can create a better product by producing more options of pictures to create three-dimensional models. Creating more three-dimensional models and having more available sources of receiving images can enhance the ability to detect VOI

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