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AIR UNIVERSITY

AN OFFSET FOR AFSOF:

COMBINING ADDITIVE MANUFACTURING AND AUTONOMOUS SYSTEMS WITH SWARM EMPLOYMENT

By

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ABSTRACT

Air Force Special Operations Forces require unique technological solutions tailored to the unique missions and tactics used to accomplish those missions in order to provide them a third offset. Additive manufacturing, autonomy, and swarm employment are three technologies that can potentially provide that offset. This paper will use an evaluation framework to address the research. Additive manufacturing can produce complex designs, including integrated electronic components, with minimal waste. Autonomous systems reduce the risk to service members by removing them from the hostile environment. Swarm technologies and employment use a larger number of simple, relatively low cost, inherently redundant agents to accomplish a task. Each of these technologies on its own presents the possibility of a technological offset, however when combined that potential is expanded. Combining these technologies would provide future commanders the ability to deploy with a force that has been specifically created for the task at hand rather than piecing a force together from the forces available, or more simply put, going to war with the forces you want not the ones you have.

INTRODUCTION

"The third offset is meant to give United States Forces a technological overmatch against future adversaries."[1] When discussing the third offset strategy it is important to understand what is meant by offset, and that it is an advantageous capability gap, driven by technology, between two competing organizations. The third offset is the United States' and it's allies' strategy to do this for the third time since World War II.

Special Operations Forces (SOF) execute missions in hostile, denied, or politically or diplomatically sensitive areas. They employ unique tactics to conduct missions significantly different than conventional forces often described as high-risk/high reward and no fail.[2] These missions can be covert, clandestine, low visibility, or involve a higher degree of risk accomplished by small units operating with small footprints far from large bases.[34] To continue to do this in the future SOF require unique equipment and technology that facilitate their unique nature and provide a third offset.

This paper will explore two potential third offset technologies, additive manufacturing and autonomy, and an employment method that is enabled by technology, swarming. Additive manufacturing and autonomy are two advanced technologies that are essential to providing a SOF a third offset. Additive manufacturing has many advantages over conventional manufacturing methods. Some of the many advantages include creating finished products directly from digital designs, reduced waste, and the ability to create objects that would be difficult or impossible to create with conventional methods.[5] Autonomous systems provide many advantages as well. They reduce the risk to manned forces by reducing exposure to hostile forces, can reduce the time required to respond critical events, and provide persistence that cannot be accomplished with manned platforms.[6]

While the technology is vital, equally important is the method of employment. Swarming is unique in that it is a tactic or strategy that is enabled by specific technology and is the potential next evolution of our current form of conflict. "A swarm consists of disparate elements that coordinate and adapt their movements in order to give rise to an emergent, coherent whole."[7] Swarming employment takes advantage of the unique benefits provided by increasingly advanced multi agent systems to do this.

Additive manufacturing and autonomy technologies combined and employed as a swarm will contribute to the Air Force Special Operations Forces (AFSOF) third offset by providing commanders the ability to produce forces that are tailored, in both capability and capacity, to the specific needs of the situation. AFSOF is small when compared to the conventional force and being small cannot afford to design and develop technologies specific to each of the numerous possible future conflicts they will be involved in. Therefore it is more prudent to look to technologies, systems, and processes that will be adaptable to the majority of those conflicts.

The question this paper answers is what future/advanced technologies would provide Air Force Special Operation Forces a third offset. The underlying research problem that drives this question is what capabilities and/or advances in technologies need to occur to ensure United States' Special Operations Forces (USSOF) maintain a technological advantage over our adversaries?[8] This problem and question was derived from the 2016 Special Operations Research Topics "A2" topic and adapted for the purposes of this paper.

BACKGROUND

Third Offset

An offset is a technological asymmetry in capability between two competing organizations. For the purpose of this paper it will be in reference to any favorable technological gap between the United States and our allies versus our adversaries. The first offset was the initial nuclear advantage over the USSR. As the nuclear technology gap narrowed the United States started developing the second offset which was characterized by stealth and precision guided munitions.[9] As near peers are developing these technologies or finding ways to mitigate the effect capability gap, the United States has determined the need for a third offset. "But the Defense Innovation Initiative (DII) and the third offset strategy, or strategies, are much more than just technology. They're about increasing the competitive advantage of our American forces and our allies over the coming decades."[10] Third offset strategy is different, the nation is no longer facing a known enemy. It will be an iterative process deliberately developing a range technologies, and there is no single silver bullet or cookie cutter solution.[11]

Special Operation Forces

Special operations are conducted in hostile, denied, or politically sensitive areas to achieve military, diplomatic, informational, or economic effects using forces and tactics that do not exist in the conventional forces. Often these forces use techniques and tactics that are covert, clandestine, or low visibility. These operations apply across the scope of military operations, and can be conducted in conjunction with or independently of conventional forces.[12]

Special Operations Forces have a number of characteristics that differentiate them from conventional forces. All of these characters may not apply to every element of the SOF community however the majority of the characteristics apply to the majority of SOF as a whole and Air Force Special Operations Forces specifically. The traits listed below are not all inclusive but rather are tailored to be applicable to AFSOF and the technologies and their implications discussed in this paper. A complete listing and thorough explanation of each can be found in Joint Publication 3-05.

SOF are inherently joint. This is because of the required integration and interdependency established among Army Special Operations Forces (ARSOF), Naval Special Operations Forces (NAVSOF), Air Force Special Operations Forces (AFSOF), and Marine Special Operations Forces (MARSOF) in order to accomplish their missions.[13]

When called, SOF deploy and employ with its command and control structure intact. This facilitates integration into the applicable joint force using established command relationships. It retains SOF cohesion and leverages established enduring relationships. This..."provides a supported JFC [Joint Forces Commander] with the control mechanism to address specific special operations concerns and coordinates its activities with other components and supporting commands."[14]

SOF Deploy rapidly and provide a tailored response.[15] The reason for this is threefold. The first is that SOF are limited in number and cannot afford a majority of resources responding to a single event. Second, the supported Joint Forces Commander (JFC) requires a force able to address the specific conditions present. And third, the forward staging bases often have limitations and the footprint of the SOF element needs to accommodate those limitations.

SOF are often required to gain access to hostile, denied, or politically and/or diplomatically sensitive areas. This is done to prepare the operational environment for future operations and develop options, both conventional and SOF, for addressing potential national concerns.[16]

SOF "Conduct operations in austere environments with limited support and a low-profile."[17] Because of the nature of special operations this is often the case. Many concerns may contribute to this, to include, but not limited to, political sensitivities, space available, forces available, compressed timeline, or capabilities.

SOF execute their missions using nonstandard organic equipment.[18] Today, on one extreme, this is C-130 aircraft modified into AC-130 gunships or MC-130 transports, or the other extreme being as simple as uniforms modified to more closely match those of the indigenous forces.

"SOF are not a substitute for CF[Conventional Forces]."[19] This is a vital point that is often overlooked. SOF are meant to compliment conventional forces not replace them. The role of SOF is specific, not the one size fits all tool in every situation. Since it generally takes significantly longer to train SOF than CF tasking them against conventional takings has the potential to squander assets that are significantly more difficult to replace.

“Simply put, the term “special operations” is often associated with two types of concepts: special mission areas and capabilities. Special operations differ from conventional operations in the operational techniques and small size of the friendly force (compared to the enemy), degree of physical and political risk, relative independence from friendly support, mode of employment, reliance on detailed and perishable intelligence, extensive use of indigenous assets, and preference toward detailed planning and rehearsals."[20]

In addition to the characteristics listed above that are common across the majority of SOF, AFSOC has core missions that it executes daily, across the globe, and will continue to be expected to perform for the foreseeable future. These core missions combine the unique characteristics of SOF with the capabilities of the United States Air Force and are listed below.

Agile Combat Support (ACS) is effectively supporting AFSOC assets, material and manpower across the spectrum of conflict, at a self-determined speed. ACS aims to be agile, robust, technologically superior, responsive, and integrated with operations in order to enable AFSOC operational mission areas.[21]

Aviation Foreign Internal Defense (AvFID) is conducted by combat aviation advisors (CAA) who assess, train, advise, and assist foreign aviation forces. To goal is to enhance the security and stability of the partner nation in order to reduce the need for US airpower.[22]

Battlefield Air Operations (BAO) are conducted by battlefield Airmen (combat control (CCT), pararescue (PJ), special operations weather (SOWT), and tactical air control party (TAC-P)) who synchronize, integrate, and control air and space assets to achieve national objectives.[23]

Command and Control (C2) is the exercise of authority and direction of forces by a designated commander in order to execute joint/combined special operations.[24]

Information Operations (IO) are predominantly nonkinetic capabilities including, but not limited, to influence operations, electronic warfare operations, and network warfare operations to influence, disrupt, corrupt, or usurp adversarial decision making while enabling our own.[25]

Intelligence, Surveillance, and Reconnaissance (ISR) is designed to provide actionable intelligence and operational environment awareness by synchronizing and integrating platforms and sensors for the planning, direction, collection, processing, exploitation, analysis, and dissemination of information.[26]

Precision Aerospace Fires execute close air support, air interdiction, and armed reconnaissance by using integrated capabilities to find, fix, track, target, engage, and assess (also known as find, fix, and finish).[27]

Military Information Support Operations (MISO) are planned operations to favorably influence the behavior of target governments, groups, or individuals by conveying selected information to affect emotions, motives, or objective reasoning. This includes the broadcast of radio and television signals and delivery of leaflets.[28]

Specialized Air Mobility (SAM) is the conduct of rapid, global infiltration, exfiltration, and resupply of personal and equipment in hostile, denied, or politically sensitive areas. Operations may be clandestine, low visibility, or overt using specialized systems both manned and unmanned.[29]

Specialized Refueling is the refueling of vertical lift assets either airborne or using forward arming or refueling points (FARP) using specialized systems and tactics. As with specialized air mobility, missions may be clandestine, low visibility or overt in hostile, denied, or politically sensitive areas. [30]

While not all inclusive the list of missions above highlights the broad range of tasks AFSOF are expected to perform. Couple that with the small number of overall forces and the global responsibility and it presents a unique problem set that conventional solutions cannot solve.

Additive Manufacturing

The first technology evaluated will be additive manufacturing. 3D printing is a term often used interchangeably with additive manufacturing however it actually is a subset of the technology. Additive manufacturing is a term that describes any one of a number of techniques used to convert a computer-generated design to a finished structure by assembling materials incremental using an additive method.[31]

Additive manufacturing techniques build structures layer-by-layer adding the base material rather than removing excess from larger pieces of material in a subtractive process found in current machining. Today, additive manufacturing can create objects from a variety of materials, including plastic, metal, ceramics, glass, paper, and living cells. The materials can come in a variety of forms as well, from powders, filaments, liquids, and sheets to living cells. Techniques vary, and depending on the process, can produce a single object printed in multiple materials and colors, and a single process can produce parts with interconnected moving parts.[32] Figure 1 illustrates the variety of techniques and the processes they use. A more complete description of each technique can be found in Appendix II. Additionally the technology exists to incorporate and embed electronics within the part as it is being built. Three companies teamed up to produce a smart wing made of thermoplastic incorporating circuits, sensors, and antenna in the design.[33] "The idea is that such technology would allow lightweight drones that can be customized for specific missions and printed on demand."[34] This is significantly different than current mainstream technologies that remove materials to create products or use molds to shape them.

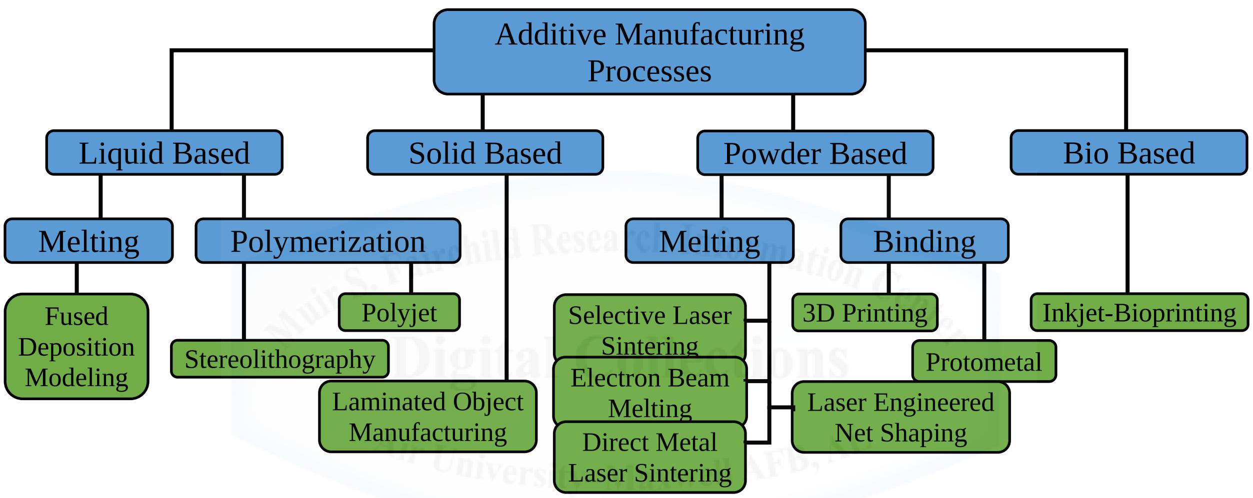

Figure 1 Additive Manufacturing processes[35]

Autonomous Systems

Automation has been employed for decades in the aviation industry, an early example would be a simple attitude hold autopilot. The intent being to have machines perform simple tasks to enable the human perform other more complex tasks. Autonomous systems take idea an order of magnitude further.

What is autonomy?

"Autonomy is a capability (or a set of capabilities) that enables a particular action of a system to be automatic or, within programmed boundaries, “self-governing.”"[36] Automation has been used to describe a variety of systems and generally includes the application of software to provide logical steps or operations to be performed, and can be defined as that in which “the system functions with no/little human operator involvement: however, the system performance is limited to the specific actions it has been designed to do.”[37] Automation applied to aircraft systems has included the introduction of flyby-wire flight control systems, data fusion, automation for guidance and navigation, and systems for automated recovery of aircraft in danger of an impending collision with terrain.[38]

Autonomy "involves the use of additional sensors and more complex software to provide higher levels of automated behaviors over a broader range of operating conditions and environmental factors, and over a wider range of functions or activities." Autonomy is often measured in terms of the capability to achieve tasks or goal independently, with uncertainties, compensate for degraded systems, over extended periods of time, with limited or no communication, without external intervention. To achieve this autonomy incorporates capabilities that let is respond to dynamic situations and self-direct behavior. Software solutions may extend beyond logic/rule based process into computational intelligence and learning algorithms. Autonomy is a significant extension of automation allowing complex commands to be executed in dynamic environments. [39]

Autonomy can be utilized at multiple different levels. It is often assumed that autonomy occurs at the vehicle level, the unmanned aircraft or self-driving car, however this is not always the case. There may be multiple autonomous systems working on a single platform. For example one system may manage the enroute navigation, another the mission sensors, and a third the vehicle's power. Autonomous systems software use similar programming, organization, and testing regardless of whether the end result is executed in the real world by hardware, or in the virtual world by software.[40]

Current status of autonomous systems

The armed forces of nations around the world have eagerly accepted unmanned systems. They provide advantages in persistence, endurance, and cost less to develop and field. These advantages have ensured that unmanned have become an established part of military operations and will play an ever-increasing role.[41] At this point the advances and applications of autonomy with the most impact have been on the ground and in the air.[42] The most extensive use of autonomy has been at vehicle or platform level of control. Even with the ever widening acceptance of autonomous systems applications have not taken full advantage of proven technologies and the autonomous capabilities available are not consistently applied across platforms.[43] Figure 2 illustrates the current status of aerial autonomous systems identifying areas that are underutilized or needing technical development.

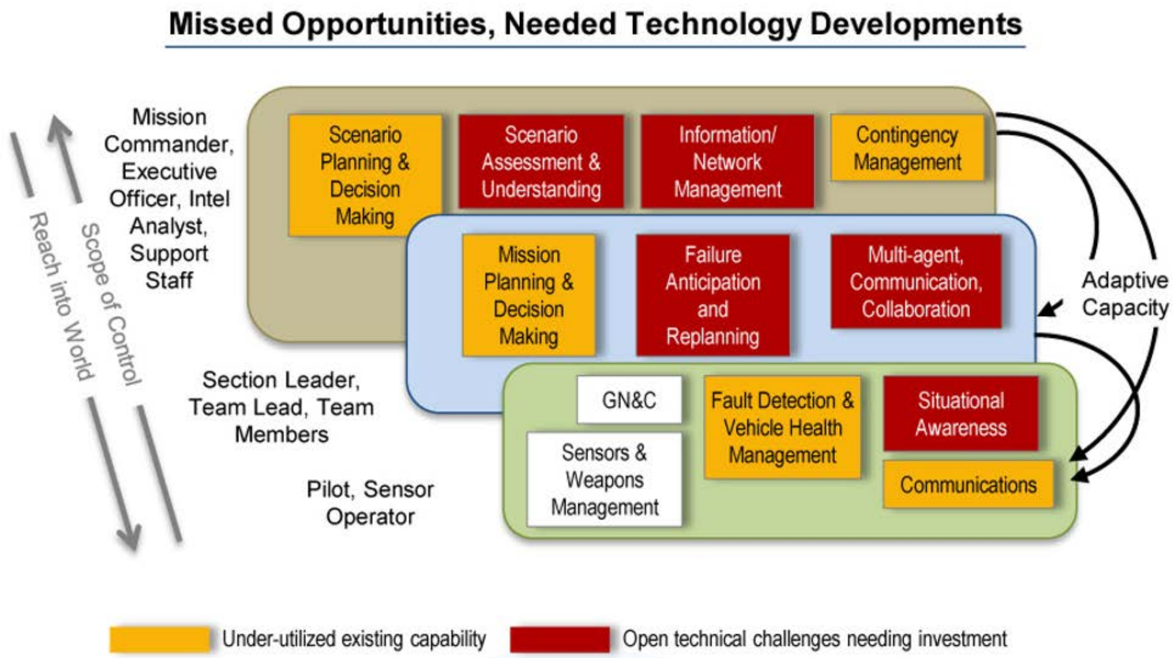

Figure 2: Status of Technology Development and Remaining Challenges[44]

Swarm Employment

Swarming employment is unique in that it is a strategy or tactic that is enabled by technology. While it has been demonstrated by military forces in the past it gets its name from insect behavior. Neither of these examples accurately exemplify the swarms described below. Multi agent swarms being developed today represent a leap forward and are possible because of advances in communication and autonomy technology.

What is a swarm?

There are two elements to the swarms being described, the first is a technological element. Swarming, or multi-agent coordination, is a term that applies to accomplishing a task that distributed over multiple systems. Systems may be robot or software and each system is considered to have a degree of autonomy. The groups' actions are coordinated either by interacting with each other (distributed coordination) or as directed by a controller (centralized coordination). Also it is assumed that the individual agents have an understanding of their own capabilities and limitations, the other agent's capabilities and limitations, and the overall progress toward the goal. The coordination and distribution of activities must adapt and react to a dynamically changing environment in order to achieve the designated task.[45]

The second element is the tactical or strategic element. To understand the swarming tactic there needs to be an understanding of the evolution of organization and employment of forces throughout history. Arquilla and Ronfeldt identify four types of organization and employment: melee, mass, maneuver, and swarm, each more sophisticated than the last.[46]

In melee combat soldiers fought as individuals, not as a coordinated whole. Prehistoric conflicts up to and including those of the Sumerians and Arkkadians would be melee engagements. An example of melee combat in the air would be the dogfights of the First World War[47]

Figure 3: Melee vs Mass[48]

Mass engagements are characterized by geometric formations designed to mass forces and firepower against an objective, often in waves. The mass employment was enabled by increased training, communication, and ability to command and control. Greek phalanxes are examples of early massed formations. In the air, the bomber formations of World War II and Vietnam exemplify mass tactics.[49]

Figure 4: Mass vs Maneuver [50]

Maneuver warfare is characterized by complex, synchronized movements of large forces. The intent is to move forces rapidly to achieve a local superiority in mass on strategic objectives. Maneuver warfare has been demonstrated throughout history, to include Alexander and Genghis Kahn, but the German blitzkrieg of World War II, with its integrated air support, is a textbook example of maneuver warfare. Additionally the United states currently trains and fights in the maneuver warfare regime. The key enabling technology has been electronic communication, radio initially, and now beyond line of sight digital data communication. [51]

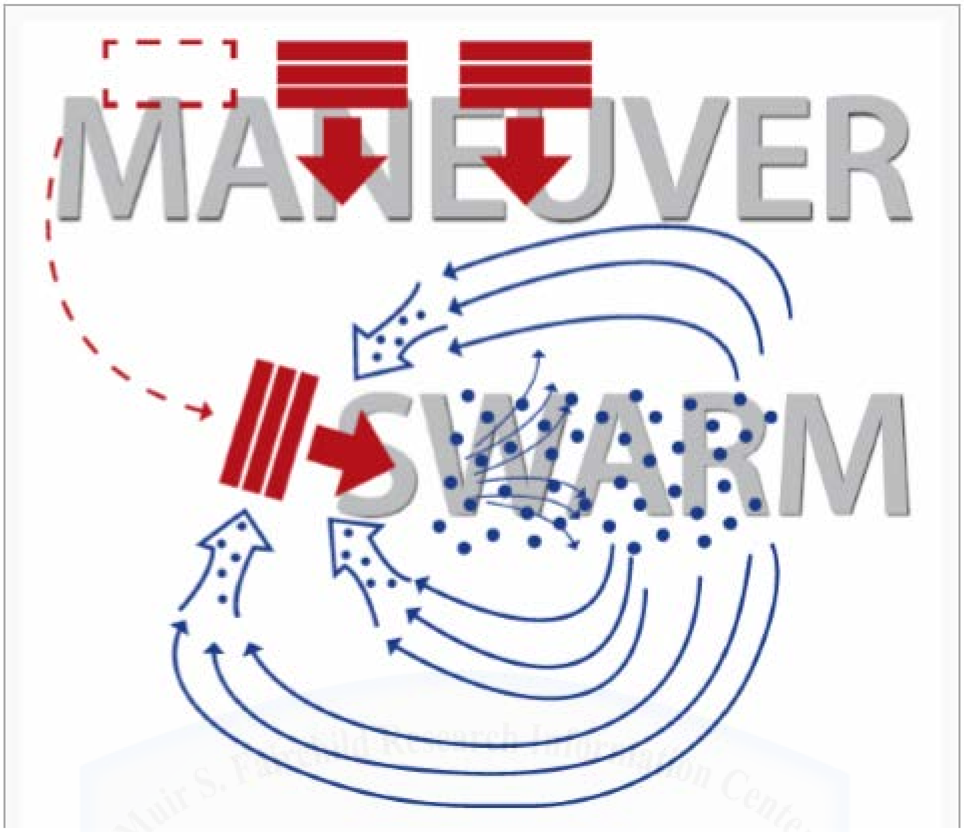

Figure 5: Maneuver vs Swarm[52]

Swarming is characterized by numerous autonomous units engaging in a convergent attack against a common objective. It requires complex organizational, communication, and information processing capabilities. The intent is to disperse units in deployment to reduce risk of engagement, converge from multiple directions for the attack, and then disperse again in preparation for follow on attacks.[53] "Swarming is seemingly amorphous, but it is a deliberately structured, coordinated, strategic way to strike from all directions, by means of a sustainable pulsing of force and/or fire, close-in as well as from stand-off positions."[54]

Currently there are a number of different methods for employing multi agent swarms. They are characterized by coordination schemes. The scheme describes the organization (Strongly centralized, weakly centralized, or distributed), coordination method (strong, weak, or not), the agents knowledge of other agents (aware or unaware), and cooperation (explicit or implicit).[55] Unaware agents do not know the presence, status, or goal of the other agents in the systems. These are modeled off insect colonies or bacteria and are best suited for low-cost high-volume homogeneous agents with simple behaviors in communications denied environments.[56] Weakly coordinated aware systems are those where the agent is aware of the presence of other agents but not aware of the other agent's intent. These systems often do not communicate between systems but rather have a set of rules that define behavior based on the behavior of the other agents in the system and the goal. The Defense Advanced Research Project Agency (DARPA) has recently demonstrated the capabilities of a few weakly aware systems.[57] Strongly coordinated distributed systems are systems in which agents with heterogeneous roles must be tightly coordinated to accomplish a goal in a dynamically changing environment. This is a very active area of research and exemplified by the robot soccer league, a competition where teams composed of autonomous robot players compete in games of soccer.[58] Strongly coordinated centralized systems are similar to the distributed systems but coordinated by a central controller. That central controller can either be geography separated from the swarm or it can be a designated agent in the swarm, another current area of focus. The drawback is the potential single point of failure and the communication requirement for geographically separated controllers. To offset this, the controller could be one of the agents with multiple potential backups contained within the swarm.[59] The benefit is a leader directing the action of the system of agents. The bottom line is that there are multiple technical schemes in development to employ swarms depending on the desired effects.

METHODOLOGY & EVALUATION CRITERIA

This paper will use an evaluation framework to address the research question. First the current status of the technology will be described, where and how is it being used in both the civilian and military arenas. Next any of the technology traits that are especially applicable to AFSOF specific characteristics or core missions will be identified. Additionally the paper will identify unique abilities that have the potential to mitigate risk to mission or to force. Finally the paper will summarize the technologies potential as a third offset technology, its advantages, disadvantages, and challenges moving forward. The criteria above were chosen to focus the research on technological traits that AFSOF can leverage to expand overall capability, decrease the cost of fielding forces that are tailored to the specific conflict, and increase the probability of mission success while reducing the overall risk. The overall intent is not to propose a single way forward but rather to highlight the potential of these technologies individually as well as synergistically.

RESULTS OF EVALUATION

Additive Manufacturing

Additive manufacturing has the potential to radically change how the military as a whole implements logistics, and the impact will eventually be transformational. It can reduce footprint, transportation requirements, waste, cost, improve speed-to-field, and streamline the supply chain.[60]

Applicability to AFSOF specific characteristics and Core Missions

The first core mission that additive manufacturing is especially applicable to is Agile Combat Support. The ability to manufacture a variety of "things" only limited by the availability of the digital designs and materials needed would significantly enhance the Agile Combat Support mission. The amount of bench stock could be reduced as items could be created as they are needed. This is especially applicable to AFSOF due to the vast range of environments, both political and physical, they are tasked to operate in as well as their overall small force size. Additionally as the technology matures it will likely shrink in size. Replacement parts could be produced when needed rather than a large inventory kept on hand, or reliance on an extended untimely logistics line. This could lead to much simpler rapid deployment plans, instead of a large package of supplies designed to support a range of contingencies, a few additive manufacturing plants could potentially replace a large portion of the equipment required.

Another unique area that additive manufacturing could support is AvFID. Additive manufacturing could be used to produce cheap simple systems to support the security and stabilization of a nation. A forward deployed additive manufacturing plant could produce a wide variety of items that would be otherwise unavailable to a struggling nation. The items produced could range from water purification and sanitation equipment to limit the spread of disease, to the production of simple unmanned aerial systems to secure the borders.

Potential to mitigate risk to mission or risk to force

AFSOC uses highly modified systems that have capabilities not found in the conventional forces. This leads to a small number of weapons systems that have been highly modified often with one of a kind systems. Additionally those systems are kept in service longer than their conventional counterparts due to the cost to replace them. Due to the relatively small number of weapons systems, they are often deployed in small numbers, potentially a single aircraft. Combine this with the no fail nature of many special operations missions and it becomes imperative to keep the weapons systems fully mission capable. This is a daunting task with the small number of available spare parts spread across the globe. Having the capability to manufacture replacement parts at a forward location can significantly reduce the risk to mission by reducing the time to repair those systems. "Additive manufacturing can be leveraged to repair and sustain aging systems faster and cheaper than traditional processes."[61]

Potential as a third offset technology

Additive manufacturing has the potential to revolutionize all facets of manufacturing. The process can create lighter, more complex designs, complete with embedded electronic components with little to no waste. With most technological revolutions there will be resistance. For additive manufacturing, that resistance will stem from the immense infrastructure in place that supports the current manufacturing processes.[62] The inertia generated by a large industry will be difficult shift. This is where AFSOC can take advantage of its smaller size relative to the conventional Air Force, and the proportionally smaller in place infrastructure, to adapt and incorporate additive manufacturing technologies more rapidly than the larger conventional force.

Autonomous Systems

Autonomous systems are an active area interest in the Department of Defense and that can expand the capabilities of current and future unmanned systems. There are many programs already in place, and the idea of human machine cooperation is becoming more and more accepted.

Applicability to AFSOF specific characteristics and Core Missions

Leaflet delivery is an often overlooked or marginalized mission. Often referred to by air crews as "littering in anger" leaflet delivery in support of Military Information Support Operations is an important mission that faces unique obstacles. One of those is risking low density high demand weapons systems, MC-130s for example, for their delivery. Desired areas for delivery are often contested and the altitude and lateral offset required for effective employment is usually in the enjambment zone of multiple hostile weapons systems. An inexpensive autonomous platform could alleviate this obstacle. The vehicle would be smaller and more difficult to detect. Additionally a relatively cheap unmanned platform is more palatable to risk than a manned platform with multiple crewmembers. Along the same lines as leaflet delivery, aerial resupply in hostile, denied, or politically sensitive areas could be accomplished by autonomous systems. Simple unmarked non-attributable platforms could be used in clandestine situations reducing the possibility of exposure in sensitive environments.

Potential to mitigate risk to mission or risk to force

Automation has already been used in aircraft to reduce the crew compliment required to execute a specific mission set. Reducing the number of aircrew on combat aircraft numerically reduces the number of lives in harm's way, reducing risk to force. It follows that as autonomous systems expand in capability they will fill more roles further reducing the number of United States service members in those hostile, denied, or politically sensitive areas, further reducing the risk to force.

In addition to reducing the risk to force, autonomous systems can reduce the risk to mission by reducing the number of individuals exposed to those hostile environments. A downed aircraft is often mission cancel criteria while recovery of the downed crew is accomplished. This recovery is not needed with an unmanned an autonomous system. Additionally a captured service member is a powerful asset that an adversary can exploit for propaganda or political gain, which can be potentially devastating to the overall mission in that region. Reducing the number of forces exposed diminishes the vulnerability of capture, and the risk to mission is decreased as a result.

Potential as a third offset technology

"When it comes to autonomy, the third offset is as much about software, or organizational culture and concepts, as it is equipment. Any discussion of autonomy must capture and leverage this insight. An important inference is that leaders, decision makers, and planners will lead *and* follow; they must become comfortable in both roles as humans guiding and following autonomous systems."[63]

One of the biggest challenges for autonomous systems has little to do with the technology itself but rather the humans utilizing the systems. To fully realize the potential of these systems the end user must trust the system. In addition to the standard barriers to trust like competence and integrity, there are additional barriers to human-machine trust. Those barriers include a lack of analogical thinking, low transparency, limited self-awareness or environmental awareness, and low mutual understanding of common goals of the team.[64] "Autonomous machines, like people, offer greater potential with increased latitude in determining their own course of action. The challenge with men or machines is trusting their judgment in a complex and contested environment. In this final regard, we hold a significant advantage. Western militaries have a long history of devolved command responsibility."[65]

Swarm Employment

Swarming involves many relatively low cost systems or agents of limited capability cooperating to achieve a desired effect opposed to the current model that focuses of few high cost very capable systems.

Applicability to AFSOF specific characteristics and Core Missions

Swarm technology and employment can be applicable across the vast majority of AFSOC mission sets, limited only by technological development and the operators' imagination. For example a swarm robots could be airdropped into a remote location to evaluate and prepare a remote landing zone. Using onboard sensors the robot team would evaluate the surface, identify obstacles, mark out a desert landing strip, and monitor for hostile activity in preparation for the arrival the mobility platforms and their cargo.

Another example could be the preparation and penetration of hostile nation's airspace. A swarm of airborne agents could be dropped in advance of a penetrating flight of specialized air mobility platforms, currently MC-130s or CV-22s, outside of the hostile nation's radar coverage. Some of the swarm may be decoys, some radar jammers, some or all with a kinetic terminal destructive ability. The swarm could communicate effects, adjust tactics to the dynamically changing threat environment, and report results to the follow on force.

Potential to mitigate risk to mission or risk to force

The potential for swarms to mitigate risk to force is twofold. Anytime you remove a human from the force it reduces risk to force. By removing some of the aircrew from danger, or some of the battlefield Airmen from hostile environments you instantly reduce the risk to the human force. Additionally you remove the risk of capture and political exploitation.

By using a swarm you can reduce risk to mission with inherent redundancy. A greater number of systems can be employed with redundant capability. What is currently a force of one or two, be it a fires, ISR, or mobility platform would be replaced with tens or hundreds. Now a single loss of an aircraft in a no fail role is mission failure, with a swarm it is just degradation of desired effect, and the other agents can be re-tasked as required.

Potential as a third offset technology/employment method

Swarming technology and tactics present many advantages. Some of those include increased coverage, decreased costs, redundancy, and specialization.[66] Swarms of unmanned agents can provide persistent coverage, over a larger target area, using multiple sensors, from multiple locations. Multiple low cost agents could deliver the same effects as a single high cost asset for an overall lower investment. As mentioned above, multiple agents provide redundancy, this may be in the form of a small swarm of tens of agents, where the burden of the loss of a single agent is shared between the remainder of the swarm. It may also be in the form of a swarm of hundreds or thousands into an area where attrition is expected to be high. Most may be destroyed but some will get through, and some may be all that is needed. Finally by using multiple agents to accomplish a task we can allow them to specialize. For example one agent could be the communicator and controller, another could a sensor agent, and a third type could be a refueling agent. By having specialized agents their individual designs are simplified and optimized for their specialty, reducing agent design complexity and agent production cost.[67]

To fully embrace Swarming, and the advantages it presents, there would need to more than significant changes to the military organization. What that organization looks like is impossible predict at this point, but would likely involve the restructuring the majority of the established formations as well as their command and control. Additionally it would require the development and implementation of an entirely new logistical infrastructure.[68]

RECOMMENDATIONS

Additive Manufacturing

Initially AFSOC should identify specific programs that can exploit the advantages that current additive manufacturing processes possess. This could be creating parts that are complex shaped and small in number. Applications could include selected legacy aircraft replacement parts that have a limited supply or identified items that civilian or conventional equivalent exist but their form or function is less than ideal for AFSOF purposes. Members of the command can be asked to identify equipment, either military or civilian, that they have been issued and subsequently modified to better suit mission requirements. Applicable objects could be found across the spectrum of mission sets from special tactics to aviation foreign internal defense. These items could be then produced using of the shelf additive manufacturing technologies. This will introduce the command to the technology and begin to establish the infrastructure for the technology. After the initial integration of the technology has been introduced programs need to be identified that can benefit from the technology and introduced to industry. This will help drive the technology in a direction desirable to the commands overall objectives. An example program for this could be small battlefield unmanned aerial systems. Having the capability to manufacture complete man portable systems could present unique opportunities.

Autonomous Systems

As conventional forces implement advances in their legacy unmanned systems with additional autonomous systems AFSOC needs to coordinate and implement those upgrades as appropriate. MQ-1s and MQ-9s are a perfect example, the demand for these systems capabilities is driving increased implementation of autonomy. AFSOC must be part of the process, ensuring unique SOF mission requirements are accommodated.

In addition to incorporating applicable autonomous technology from the conventional force AFSOC must identify SOF specific mission sets that can take advantage of autonomous systems. Once identified, those programs must have a deliberate process designed to develop and deliver the proposed systems. Initial programs could include MISO leaflet delivery or resupply as previously mentioned, but could expand to include many of the AFSOC core missions.

Swarm employment

The recommendations for autonomous systems are also applicable to the technological aspects of swarm employment. Additionally AFSOC will need to begin to develop a framework, or frameworks, for swarm employment. These frameworks should be designed in cooperation with industry leaders in swarming technology. The intent would be a flexible architecture that can be applied to SOF specific mission sets, or provide effects that support those mission sets.

Many elements of the development of swarming technology is linked to that of autonomous systems. It is imperative that as these technologies progress that commonality and coordination continue. Development of multi agent swarming software needs to be in concert with that of autonomous system development to enable future interoperability. Autonomous systems fielded as single unit systems could be upgraded to be included in future swarms provided there is forethought in their development.

Combining additive manufacturing, autonomy and swarming

Each of these technologies, additive manufacturing, autonomous system, and multi agent swarms, can provide significant advantages on their own however the real potential of these third offset technologies is realized when they are integrated. Combining these three technologies presents an array of possibilities. Individual agents could be designed to be produced by additive manufacturing technologies, tested in small numbers and as a swarm, and then have that design saved to a database available for production when the need arises. Additive manufacturing facilities could initially be established at larger military instillations, and eventually as the technology develops, design and field deployable additive manufacturing facilities with the database of tested designs. A small number of predesigned swarms could be kept in reserve for rapid contingency response. The majority of the remainder of the swarm force would be stored as digital designs and raw materials ready to be produced at the onset of a crisis. This would cut down on the cost required to maintain the force, and reduce the waste of systems built but never used. Additionally the force fielded would be tailored to the JFC's needs providing the force the situation needs rather than the force that is available.

CONCLUSIONS

There is the world that you would want, the world that you program to, and the world that actually happens…Every time we've tried to predict the world in the last century, we've been wrong.

Lieutenant General George J. Flynn
Director for Joint Force Development, The Joint Staff J-7
Address to the Air War College, 14 November 2012

Additive manufacturing and autonomy technologies combined and employed as a swarm will contribute to the Air Force Special Operations Forces third offset by providing commanders the ability to produce forces that are tailored, in both capability and number, to the specific needs of the situation. The relatively small size of AFSOC prevent the design and development of systems that could be needed in the numerous potential future conflicts and there for it is imperative the command look to technologies that will provide the most adaptability.

SOF conduct missions significantly different than conventional forces using unique tactics and equipment to do so. These missions are often high risk/reward or no fail. [69] To continue to accomplish these missions AFSOF will need unique third offset technological solutions tailored to their unique nature. Third offset technologies are technologies that provide an advantageous technological capability gap against future adversaries, and are the focus of the third offset strategy. [70]

The first technology is additive manufacturing. Additive manufacturing techniques can create complex finished products from digital designs and creates less waste then conventional methods. [71] The second technology is autonomy. Autonomous systems reduce the risk to manned forces and provide persistence that manned platforms cannot. [72] The last technology is swarming, and it is also a method of employment, and the potential follow on to the maneuver scheme of war currently employed. Swarms disperse on deployment, converge and attack as a coherent whole, then disperse in preparation for follow on attacks. [73]

Air Force Special Operations Forces require solutions from future advances technologies tailored to their unique characteristics and mission set to provide a third offset. One answer is combining additive manufacturing and autonomous systems with swarm employment.

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APPENDIX I: ADDITIVE MANUFACTURING TECHNIQUES

Fused deposition modeling (FDM)	A filament of plastic resin, wax, or another material is extruded through a heated nozzle in a process in which each layer of the part is traced on top of the previous layer. If a supporting structure is required, the system uses a second nozzle to build that structure from a material that is later discarded (such as polyvinyl alcohol). FDM is mainly used for single- and multipart prototyping and low-volume manufacturing of parts, including structural components.[74]
Stereolithography (SL)	A laser or other UV light source is aimed onto the surface of a pool of photopolymer (light-sensitive resin). The laser draws a single layer on the liquid surface; the build platform then moves down, and more fluid is released to draw the next layer. SL is widely used for rapid prototyping and for creating intricate shapes with high quality finishes, such as jewelry.[75]
Polyjet	This is an additive manufacturing process that uses inkjet technologies to manufacture physical models. The inkjet head moves in the x and y axes depositing a photopolymer which is cured by ultra violet lamps after each layer is finished. The layer thickness achieved in this process is 16µm, so the produced parts have a high resolution. However, the parts produced by this process are weaker than others like stereolithography and selective laser sintering. A gel-type polymer is used for supporting the overhang features and after the process is finished this material is water jetted. With this process, parts of multiple colors can be built.[76]
Laminated Object Manufacturing (LOM)	A sheet of material (paper, plastic, or metal) is fed over the build platform, adhered to the layer below by a heated roller, and a laser cuts the outline of the part in the current layer. LOM is typically used for form/fit testing, rapid tooling patterns, and producing less detailed parts, potentially in full color.[77]

Selective laser sintering (SLS)	In this technique, a layer of powder is deposited on the build platform, and then a laser “draws” a single layer of the object into the powder, fusing the powder together in the right shape. The build platform then moves down and more powder is deposited to draw the next layer. SLS does not require any supporting structure, which makes it capable of producing very complex parts. SLS has been used mostly to create prototypes but recently has become practical for limited-run manufacturing. General Electric, for example, recently bought an SLS engineering company to build parts for its new short-haul commercial jet engine."[78]
Electron Beam Melting (EBM)	A process similar to SLS is electron beam melting (EBM). This process is relatively new but is growing rapidly. In this process, what melts the powder is an electron laser beam powered by a high voltage, typically 30 to 60KV. The process takes place in a high vacuum chamber to avoid oxidation issues because it is intended for building metal parts. Other than this, the process is very similar to SLS. EBM also can process a high variety of prealloyed metals. One of the future uses of this process is the manufacturing in outer space, since it is all done in a high vacuum chamber.[79]
Direct metal laser sintering (DMLS)	DMLS is similar to selective laser sintering but deposits completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications.[80]
Laser Engineered Net Shaping (LENS)	In this additive manufacturing process, a part is built by melting metal powder that is injected into a specific location. It becomes molten with the use of a high-powered laser beam. The material solidifies when it is cooled down. The process occurs in a closed chamber with an argon atmosphere. This process permits the use of a high variety of metals and combination of them like stainless steel, nickel based alloys, titanium-6 aluminium-4 vanadium, tooling steel, copper alloys, and so forth. Alumina can be used too. This process is also used to repair parts that by other processes will be impossible or more expensive to do. One problem in this process could be the residual stresses by uneven heating and cooling processes that can be significant in high precision processes like turbine blades repair.[81]

3 Dimensional Printing (3DP)	3DP process is a MIT-licensed process in which water-based liquid binder is supplied in a jet onto a starch-based powder to print the data from a CAD drawing. The powder particles which is a medical grade PC. The main advantages of this process are that no chemical post-processing required, no resins to cure, less expensive machine, and materials resulting in a more cost effective process. The disadvantages are that the resolution on the z axis is low compared to other additive manufacturing process (0.25mm), so if a smooth surface is needed a finishing process is required and it is a slow process sometimes taking days to build large complex parts. To save time some models permit two modes; a fully dense mode and a sparse mode that save time but obviously reducing the mechanical properties.[82]
Prometal	Prometal is a three-dimensional printing process to build injection tools and dies. This is a powder-based process in which stainless steel is used. The printing process occurs when a liquid binder is spurt out in jets to steel powder. The powder is located in a powder bed that is controlled by build pistons that lowers the bed when each layer is finished and a feed piston that supply the material for each layer. After finishing, the residual powder must be removed. When building a mold no post processing is required. If a functional part is being built, sintering, infiltration, and finishing processes are required. In the sintering process, the part is heated to 350◦F for 24 hour hardening the binder fusing with the steel in a 60% porous specimen. In the infiltration process, the piece is infused with bronze powder when they are heated together to more than 2000◦F in an alloy of 60% stainless steel and 40% bronze. The same process, but with different sintering temperatures and times, has been used with other materials like a tungsten carbide powder sintered with a zirconium copper alloy for the manufacturing of rocket nozzles; these parts have better properties than CNC machined parts of the same material.[83]

Inkjet-bioprinting	Bioprinting uses a technique similar to that of inkjet printers, in which a precisely positioned nozzle deposits one tiny dot of ink at a time to form shapes. In the case of bioprinting, the material used is human cells rather than ink. The object is built by spraying a combination of scaffolding material (such as sugar-based hydrogel) and living cells grown from a patient's own tissues. After printing, the tissue is placed in a chamber with the right temperature and oxygen conditions to facilitate cell growth. When the cells have combined, the scaffolding material is removed and the tissue is ready to be transplanted.[84]

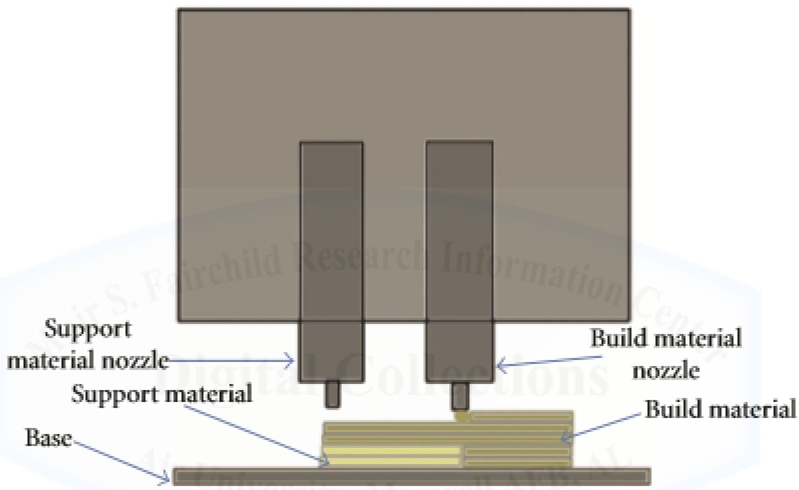

Figure 6 Fused Deposition Modeling[85]

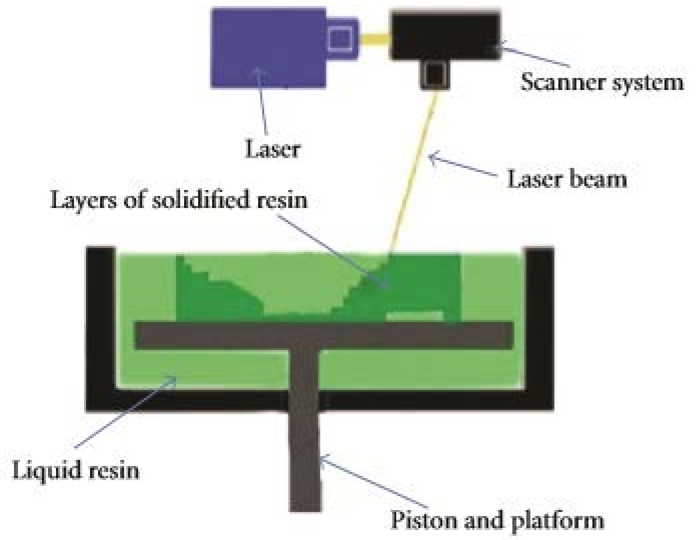

Figure 7 Stereolithography[86]

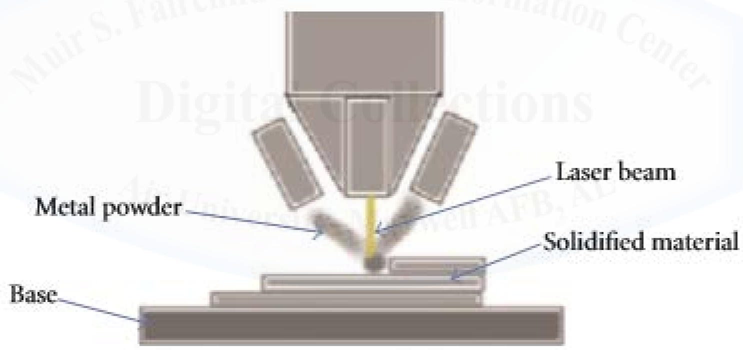

Figure 8 Laser Engineered Net Shaping[87]

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APPENDIX II: ACRONYMS

3DP – Three dimensional printing

ACS – Agile Combat Support

AFSOC – Air Force Special Operations Command

AFSOF – Air Force Special Operations Forces

ARSOF – Army Special Operations Forces

AvFID – Aviation Foreign Internal Defense

BAO – Battlefield Air Operations

C2 – Command and Control

CF – Conventional Forces

DARPA – Defense Advanced Research project Agency

DMLS – Direct metal laser sintering

EBM – Electron Beam Melting

FARP – Forward Arming and Refueling Points

GN&C – Guidance Navigation and Control

IO – Information Operations

ISR – Intelligence, Surveillance, and Reconnaissance

JFC – Joint Forces Commander

LENS – Laser Engineered Net Shaping

LOM – Laminated Object Manufacturing

MARSOF – Marine Special Operations Forces

MISO – Military Information Support Operations

NAVSOF – Naval Special Operations Forces

SAM – Specialized Air Mobility

SL – Stereolithography

SLS – Selective laser sintering

SOF – Special Operations Forces

USSOF – United States' Special Operations Forces

FDM – Fused deposition modeling