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Operating Low-Cost, Reusable Unmanned Aerial Vehicles in Contested Environments

Preliminary Evaluation of Operational Concepts

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Preface

Wargames and analyses of future conflict scenarios involving China and Russia reveal disquieting trends in the military balance of power. Both countries are fielding military capabilities and postures that, in wartime, would make it extremely challenging for U.S. forces to project power and defeat large-scale aggression. This realization is a key motivation behind the 2018 National Defense Strategy, which calls on components within the U.S. Department of Defense to turn priority attention to developing innovative capabilities and concepts for confronting these challenges.

The United States Air Force has responded to this direction by redoubling its efforts to explore the demands of warfare in highly contested environments, such as those that could be created by modern Chinese or Russian forces, and to devise and evaluate new approaches to defeating aggression in those environments. One intriguing approach is to employ large numbers of relatively low-cost, *attritable*—low-cost, reusable, and ultimately expendable—unmanned aerial vehicles (UAVs) to perform a variety of tasks in support of joint force defensive campaigns. If such an approach proves feasible, it could allow land-based forces to generate and sustain airpower without relying on fixed base infrastructure, such as runways and maintenance facilities. The implications of such an approach for the resiliency of forward-based forces and for their effectiveness in the opening days of a conflict could be profound.

This report summarizes early thinking and analysis about how the Air Force might employ a force of attritable UAVs and what effects such a force might achieve in the most demanding conventional warfighting scenarios. This research was commissioned by the United States Air Force's Warfighting Integration Capability (AFWIC) and conducted by RAND Project AIR FORCE as part of a fiscal year 2019 project Analytic Assistance to the Air Force Warfighting Integration Capability (AFWIC).

RAND Project AIR FORCE

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Summary

The U.S. approach to conducting large-scale military power-projection operations is being rendered untenable by adversary states that are fielding a range of new air, sea, land, space, counterspace, cyber, and electronic-jamming capabilities. Large inventories of accurate, conventionally armed ballistic and cruise missiles pose a particular challenge to forward forces and bases. In wargames featuring such threats, "Blue" teams are consistently confronted with the challenge of generating combat power while under attack and reaching into the contested zones created by the adversary capabilities and then trying to locate, engage, and damage or destroy attacking forces at sea and on land during the opening days of a conflict.

One promising approach to addressing this need is the proliferated employment into the contested battlespace of small, inexpensive, unmanned aerial vehicles (UAVs) to perform a variety of functions, including intelligence, surveillance and reconnaissance (ISR); position, navigation, and timing (PNT); communications; and strike. The low-cost attritable aircraft technology (L-CAAT) concept aims to provide one means for realizing this approach. This report describes such an approach, evaluates its possible effectiveness, and identifies topics for further analysis.

If U.S. and allied forces can make large numbers of small vehicles work together, and if these platforms can overwhelm or otherwise evade enemy defenses and countermeasures, they have the potential to transform potentially vulnerable "kill chains" into a "targeting mesh." The metaphor is apt because unlike a chain—which can be rendered useless by the failure of one link—a mesh can retain structural integrity even when multiple elements fail.

In addition to supporting the targeting mesh concept, the L-CAAT and related unmanned systems offer the means to generate and sustain air combat power without reliance on runways and with a significantly smaller forward logistics footprint than conventional manned and unmanned platforms. Like reusable target drones, the L-CAAT is designed to be launched from a mobile trailer and can be recovered using parachutes and airbags that allow it to land on any flat surface. This feature severely complicates enemy efforts to keep U.S. air forces on the ground and provides a means for fighting the enemy without drawing on scarce assets, such as bomber aircraft, to get the UAVs to the fight.

Preliminary development activities, analysis, and gaming have shown the following:

- Air vehicles with useful range and payload performance can be launched and recovered without the use of runways and can be fielded at costs that would support their employment in wartime in large numbers (thousands).
- Affordable, lightweight sensors can support target identification in cluttered and contested environments if such sensors can be employed in large numbers, can share information, and if the data they produce can be processed on the collection platforms.

- Millimeter-wave radios for intramesh communications appear to be an attractive means of defeating even powerful standoff jammers.
- Squadron-sized units (on the order of 900 personnel or less) should be able to launch and recover approximately 1,000 L-CAATs or smaller “kittens” (small UAVs) daily.

Considerably more analysis is called for in areas that include sensor performance in the face of enemy countermeasures, force size and launch rates required to overwhelm and exhaust enemy surface-to-air and air-to-air threats, the susceptibility of the targeting mesh to cyberattacks on sensor fusion artificial intelligence, and the vulnerability of L-CAAT ground operations and support infrastructure to enemy special operations forces and other threats. We must also consider the possibility of enemies developing mesh capabilities of their own. However, the overall concept of employing reusable, runway-independent UAVs as a key part of joint force operations to blunt enemy aggression appears sufficiently promising that it seems prudent to begin field experiments with prototype systems.

Acknowledgments

The authors would like to thank the leaders and staff of the Air Force Warfighting Integration Capability (AFWIC) for allowing us to be a part of the work they are doing to devise and evaluate new operational concepts for the very challenging conditions that will characterize future large-scale warfare. We are particularly indebted to Major General Michael Fantini, the commander of AFWIC, and to his deputy, Brigadier General Clinton Hinote.

AFWIC's leaders have recruited an exceptional staff of airmen and civilians to carry out the organization's mission, and a number of them have been instrumental in helping the RAND Corporation's project team to shape our work in useful ways. Key players include Colonels Carmelo Giovanco and Tim Welter; Lieutenant Colonels Aaron "Vandal" Gibney, Don "Stryker" Hayley, Ryan LeBlanc, Todd Morin, Kevin Treat, Sean "Wiki" Williams, and Eric Saunders; Major Kim Sloan; Nicole Misita; and Mark Svetska.

Several RAND colleagues have provided valuable insights as the work has progressed. They include Jeff Hagen, Jim Chow, Bill Stanley, Dan Norton, David Orletsky, and Ted Harshberger. Jacob Heim and Mike Nixon also merit special mention in this regard for their careful and expert reviews of an earlier draft. Rachel Ostrow deftly edited the manuscript.

Abbreviations

AI	artificial intelligence
AFWIC	Air Force Warfighting Integration Capability
ATR	automatic target recognition
CCD	camouflage, concealment, and deception
CONOPs	concept of operations
db	decibel
ELINT	electronic intelligence
EO/IR	electro-optical/ infrared
GHz	gigahertz
ISR	intelligence, surveillance, and reconnaissance
J/S	jamming-to-signal ratio
L-CAAT	low-cost attritable aircraft technology
nm	nautical miles
PAA	primary authorized aircraft
PNT	position, navigation and timing
SAR	synthetic aperture radar
SFC	specific fuel consumption
TE	tank-equivalent
UAV	unmanned aerial vehicle

1. Introduction and Overview: Employing Attritable Unmanned Aerial Vehicles En Masse

The proliferation of accurate ballistic and cruise missiles has created serious challenges for U.S. power projection operations. Fixed land bases and surface ships are increasingly vulnerable to attack by these weapons, large salvos of which can overwhelm currently available active defenses. And while passive protection measures, deception, decoys, dispersal, and other tactics can be cost-effective ways to raise the "price" of an adversary's attack, such measures are generally unable to fully ameliorate the effects of attacks.[1]

This reality has prompted planners, operators, technologists, and analysts in and associated with the U.S. Air Force to explore new approaches to projecting power in highly contested environments. In the future, one can expect the Air Force to pursue a number of complementary approaches to addressing the vulnerability of its forward bases. In addition to investing in a variety of base-resiliency measures, steps are warranted to increase the lethality and capacity of the bomber force and to explore the potential of air vehicles that can be launched, recovered, and serviced without reliance on runways and other fixed infrastructure. This report explores concepts relating to the latter approach: generating and sustaining airpower with attritable (that is, low-cost, reusable, and ultimately expendable) unmanned aerial vehicles (UAVs).

The report addresses the following five aspects of the employment of this class of air vehicle:

- key characteristics of two classes of UAV
- their employment in contested zones to create a *targeting mesh*—a net of UAVs that work together
- how UAVs communicate with one another and with incoming weapons
- UAVs' susceptibility to adversary jamming
- concepts for operating UAV launch and recovery teams in forward areas.[2]

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[1] For an overview of the RAND Corporation's analyses of advanced threats to airbases and strategies for mitigating those threats, see Brent Thomas, Mahyar A. Amouzegar, Rachel Costello, Robert A. Guffey, Andrew Karode, Christopher Lynch, Kristin F. Lynch, Ken Munson, Chad J. R. Ohlandt, Daniel M. Romano, Ricardo Sanchez, Robert S. Tripp, and Joseph Vesely, *Project AIR FORCE Modeling Capabilities for Support of Combat Operations in Denied Environments*, Santa Monica, Calif.: RAND Corporation, RR-427-AF, 2015. Numerous assessments of base resiliency have been conducted using these tools, shedding light on the cost and utility of investments in active and passive material soluitons to a wide range of kinetic threats.

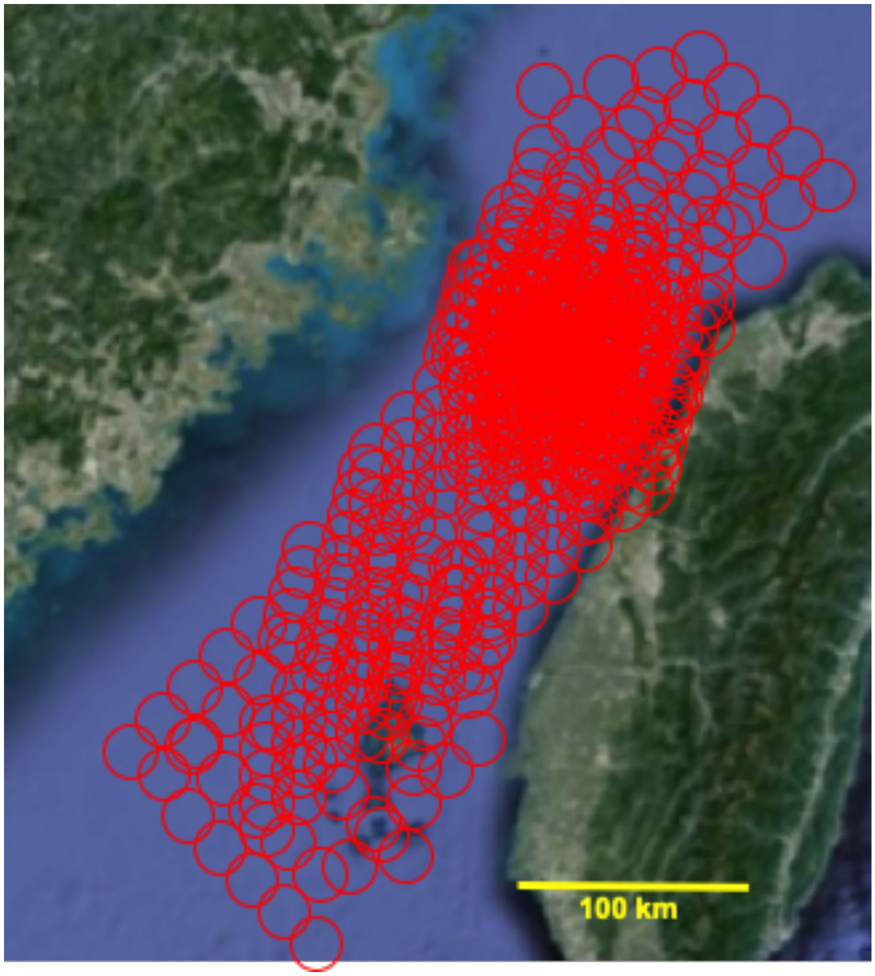
[2] For a more-detailed examination of requirements for manning and logistically supporting large-scale operations by attritable air vehicles, see James A. Leftwich, *Low-Cost Attritable Aircraft Technology: Logistics Concept of Support for Deployment and Employment*, Santa Monica, Calif.: RAND Corporation, forthcoming, Not available to the general public.

The targeting mesh concept could support the employment of many types of long- and short-range weapons. This report does not discuss specific weapons for engaging enemy forces, other than to observe that they must be able to communicate with the targeting mesh during their approach to their targets. The report also does not address in detail physical threats to the UAVs. This is an important issue. The UAVs will, in general, be quite vulnerable to certain types of enemy fires. The general answer to this class of threats is to put enough small UAVs into the battle space to saturate or exhaust the defense. Although this approach will be effective against existing threats, such as surface-to-air missiles and air-to-air missiles, it might be vulnerable to radically different future threats, such as enemy mesh. Ongoing work is evaluating the dynamics of a variety of potential “mesh-on-mesh” scenarios.

2. Creating an Intelligence, Surveillance, and Reconnaissance and Targeting Mesh

Figure 2.1 illustrates the coverage that around 500 small UAVs, flying at medium altitude, could provide in one potential conflict zone: the Taiwan Strait. The red circles depict the range of sensors on each UAV, which is typically about 10 km. Although each UAV has small, lightweight, and inexpensive sensors capable of detecting and observing targets over a very limited area, the aggregate capability of hundreds of small UAVs can cover a large area with considerable redundancy, meaning that any point within the area covered by the mesh can be observed simultaneously by multiple independent platforms. In Figure 2.1, most of the UAVs are concentrated in the area where the bulk of the invading fleet is located. The analysis presented in this report primarily concerns the ability of this concentrated force to support attacks on the invading fleet. The outlying UAVs provide situational awareness. If additional threats are located, the UAV fleet can rapidly concentrate, within minutes, at any point.

Figure 2.1. Coverage Provided by Sensors on 500 Small UAVs over the Taiwan Strait



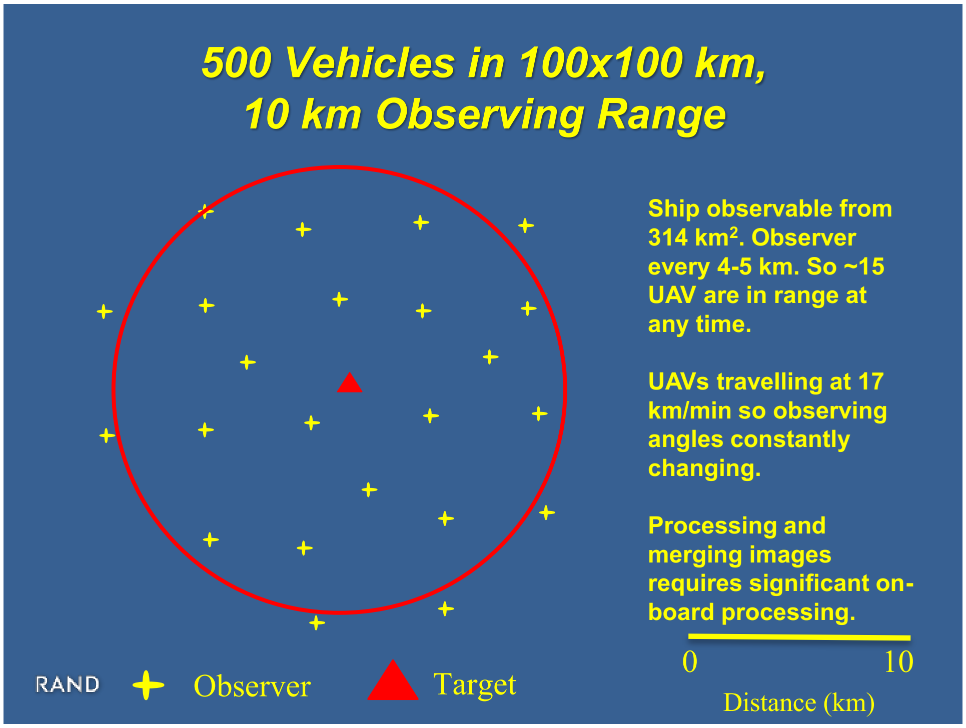
The avionics carried by the small UAVs would include a variety of capabilities. For this assessment we assume that they include simple electro-optical/infrared (EO/IR) sensors, synthetic aperture (SAR) radars, and electronic intelligence (ELINT) detectors, including time difference of arrival capability. All UAVs would also carry low-power, short-range directional radios operating at frequencies in the tens of gigahertz (GHz) range. Just as Link-16 does today, such radios are capable of using the measured propagation delay of radio signals within the mesh to generate a local position, navigation, and timing (PNT) solution, which can be used to locate targets and guide weapons. Some of the UAVs would carry longer-range radios for communicating long distances, including with satellites orbiting in space. However, these longer-range systems would not be essential to the operation of the mesh.

It is important to note that although the concept involves the simultaneous employment of a large number of small UAVs, this is not a “swarm” in the sense of a group of objects coordinating their tactical movement. The UAVs are spreading out to cover the required area. They are continuously communicating with one another to ensure that they are not all concentrated in one area, but they are not otherwise attempting to coordinate their behavior. The UAVs are autonomous in the sense that their flight paths are not being controlled by an entity external to each platform. They are directed at launch to fly to a specified target area and to maintain separation from other UAVs. Every few seconds, they are randomly turning so that their precise path cannot be predicted by the enemy.

The core function of each UAV in the mesh is to observe potential targets in its area of regard and communicate the results of those observations to other, nearby UAVs in the mesh. Through this intramesh communication, each UAV will, in principle, “know” everything. The mesh will use the information from the observations to determine optimum targets for each weapon as it becomes available. This will require significant onboard processing on each UAV, yet the overall computing capability required will be modest by modern standards—certainly less than that of a contemporary smartphone. The system is only keeping track of the position and rough description of a few hundred objects. Weapons could become available as they enter the area of mesh observation from launch locations far away. Alternatively, weapons could be employed from larger UAVs or other platforms operating near or inside the area occupied by the mesh.

Figure 2.2 gives a sense of the density and functioning of sensors in the mesh. It portrays a representative portion of the mesh, a 20 km by 20 km square. For reference, the red circle has a radius of 10 km, the baseline range of the sensors. (In practice, the sensors would often have a longer range against large targets.) This depiction assumes that 500 UAVs are operating within an area 100 km by 100 km square. It assumes also that the sensors, flying at an altitude of 30,000 feet, have a useful range of ten km and that the UAVs are separated from one another by three to five km. (30,000 feet is a typical search altitude; however, the sensors could descend to lower altitude for closer looks at particular targets in specific situations.) Under these conditions, a target anywhere within the area under observation could be “seen” by the sensors onboard approximately 15 UAVs.

Figure 2.2. Illustrative Density of UAVs in Targeting Mesh



The observers are not stationary, but flying around at high subsonic speed. The modeling presented later in this report assumes that the sensors on each of the UAVs will have limited effectiveness. Many of the systems that could potentially observe a target will fail to do so in practice in specific situations. The concept is that the system has a high degree of redundancy; even a high failure rate of individual observations will not result in an overall failure of the mesh to perform its key function of target identification and location.

3. Characteristics of the UAVs

Table 3.1 summarizes key technical parameters of two possible types of UAVs. The larger design is intended to be comparable in size to the Kratos XQ-58, which recently had its first two flight tests, demonstrating the feasibility of operation without runways. The smaller vehicle is a similar design but one-tenth the weight. The Air Force Research Lab funded the XQ-58 as part of the low-cost attritable aircraft (L-CAAT) initiative. The smaller aircraft, a concept developed during RAND's work with the Air Force Warfighting Integration Capability (AFWIC), has been dubbed the "kitten." The specific numbers referenced in Table 3.1 are for the point designs referenced in this document; that is, we have used these numbers to calculate estimated capabilities for the purposes of analysis. Although we believe that these numbers are realistic, they do not precisely match any existing aircraft. For example, we assess that a modern kitten-sized engine could have a specific fuel consumption (SFC) superior to 1.1. Nevertheless, we have used 1.1 in our analysis, because it is a fuel efficiency typical of small turbojet engines of the past. Note, also, that we have not calculated detailed mission profiles in estimating range or duration. What we call *raw* cruise range is simply the distance the aircraft can cruise when carrying a full payload without considering such concerns as safety reserves. Raw cruise range is close to the aircraft ferry range and, of course, much longer than an operational mission radius.

Table 3.1. Characteristics of the L-CAAT and Kitten Air Vehicles

	L-CAAT	Kitten
Maximum takeoff weight	6,000 lbs	600 lbs
Payload	1,200 lbs	60 lbs
Fuel	1,800 lbs	240 lbs
Cruise range (raw)	5,055 nm	3341 nm[a]
Mission duration	8.9 hrs	5.9 hrs
Cruise speed	487 kts (M .85)	487 kts (M .85)
Empty fraction	.5	.5
Lift divided by drag	15	15
SFC (lb/lb-hr)	.515	1.1
Fuel fraction	.3	.4
Wingspan (ft)	~36	~18
Aspect ratio	~10	~10
Wing loading (lb/ft^2).	~46	~19

SOURCE: See Garrett Reim, "Payload Tests for XQ-58A Set for Early 2020," *Flight Global*, September 18, 2019; and "Kratos XQ-58 Valkyrie (XQ-222): Unmanned Combat Aerial Vehicle," *Military Factory*, January 29, 2020.
[a] The range and duration numbers are maximum theoretical values for the listed fuel consumption and lift-to-drag ratio. These numbers do not include, for example, emergency reserves. However, because of the relatively modest cost of the loss of a single unit, operating reserves likely would be smaller than for a crewed aircraft.
NOTE: lbs = pounds; nm = nautical mile; hrs = hours; kts = knots.

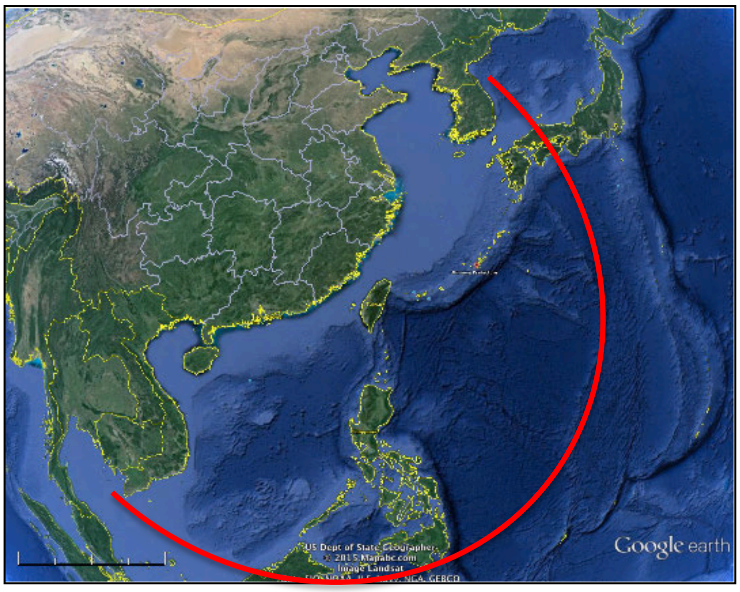
The smaller UAV has a shorter range than the larger UAV. This is a direct result of the relatively poor fuel efficiency of small jet engines. However, even with such an inefficient engine, the small UAV has sufficient range to make it practical to reuse it if basing can be found within about 1,000 nm of the operating area.

These UAV designs have substantially more range than many small UAVs that have been employed in the past. This range is desirable because it enables the user to recover and reuse the UAV platforms at significant distances from the operating area, making them far more cost-effective over time than systems that are expended after a single use. This longer range is achievable because the air vehicles feature a higher aspect ratio wing than that commonly used on small UAVs. This longer—although not heavier—wing is feasible because the UAVs are designed to be launched from the ground and recovered on the ground. They do not need to fit with large launching aircraft. However, by using the larger wing we give up the ability to pull high-gravitational force (high-g) loads.[3]

[3] The general shape of the airfoil and its aerodynamic characteristics are similar to those of most commercial transport aircraft. We confirm that the design is scalable in this size range by calculating the Reynolds number, which, for the kitten, is approximately 6,000,000. (A *Reynolds number* is the ratio of drag due to air's inertia to drag

Air vehicles with these characteristics could fly useful missions from areas up to 1,000 nautical miles from the operating area. For example, if the kitten were launched from such a distance, it could dwell for up to two hours in or near the target area and recover to its launch point with a modest fuel reserve. Figure 3.1 shows how this mission profile would apply to a conflict in the Taiwan Strait. This compares favorably with the unrefueled radius of many manned fighter aircraft.

Figure 3.1. Representative Mission Radius for the Kitten



due to air's viscosity. It is bigger for larger, faster fliers. Aircraft performance deteriorates rapidly if the Reynolds number is less than about 200,000. That is why small slow fliers have much shorter ranges.

4. Functions and Performance of Short-Range Sensors

Kill chains against mobile targets are often described as having four segments: finding, identifying, weaponeering and guiding, and engaging. The short-range intelligence, surveillance, and reconnaissance (ISR) capabilities provided by the mesh are primarily important in the middle two steps—target identification and weapon selection and guidance.

Short-range sensors can find targets, but so can a variety of other sensors, including those in space or on stand-off airborne platforms, or surface-based acoustic systems.

Identifying targets, and particularly discerning whether detections are of high priority targets or other objects—including decoys—is a more difficult challenge. The mesh concept uses simultaneous observations from multiple independent platforms, often using different detection phenomenologies, integrated through appropriate artificial intelligence (AI) algorithms, to determine the probability that a set of detections actually reflect the presence of a priority target.

We use the term *AI* to mean the integration of a small number of detections—maybe ten—from different platforms to form a common description of a possible target defined by a particular location. In this scenario, we are looking for large metal objects floating in the ocean. This is relatively simple problem compared with those being addressed by cutting-edge AI applications. Also, note that inherent to the mesh concept is the allocation of resources to the best target. The mesh continuously observes every point and thus every potential target in the area of operations. If a particular point is not providing a good solution at a particular time, perhaps because the signals are contradictory, the mesh will allocate weapons to the targets that are identified with high confidence as being of the highest priority.

Once a target is identified, another challenge is determining the best available weapon and attack profile for engaging it. Finally, the weapon must be guided to the optimum aimpoint on the correct target. The precision of this guidance can be modelled as a function of the time between the last sensing and guidance update and weapon impact. In a jamming environment, sending updates to the weapon as it gets close to the target will be more robust if the updating emitter is in close proximity to the weapon. This communication function is provided by the mesh platforms closest to the engagement.

It is important to be clear that the two key tasks to be performed by computer technology are intentionally not relying on future, or even recent, advances in technology. The type of automated target recognition envisioned has been a part of weapon designs for decades. Its reliability has been historically limited. Our proposed concept of operations (CONOPs) does not postulate improvement. Our baseline model, described in the next section, assumes a reliability for any single observation of 20 percent, assuming optimal geometry but problematic weather. Our CONOPs deals with this inherently low reliability by employing substantial sensor redundancy. We envision multiple sensors of different types in different locations making a series of observations over a period of tens of minutes. This allows for reliability rates that are far lower than would be demanded of a single automatic target recognition (ATR) system fixed to the weapon it was guiding.

Similarly, the resource-allocation algorithm uses mature technology. For many people, the obvious analogy is Uber or similar companies that allocate taxi rides in an automated fashion using consumer need and resource availability. However, such automated algorithms have been used for many years for many industrial-control purposes. Much of the mathematics was developed by AT&T, a telecommunications firm, in the 1950s, to efficiently allocate a limited supply of long-distance telephone circuits to a large, shifting demand for long-distance phone calls.

We have constructed a simple spreadsheet model for assessing the effectiveness of the targeting mesh. Again, we use a Taiwan Strait scenario in which the enemy fleet is assumed to be in a known 10,000 square km area to illustrate the case. (This area is roughly the size of the area of UAV concentration shown in Figure 2.1. We do not explicitly model how the UAVs locate the enemy fleet's general area. This could be done by small UAVs themselves, space-based assets, undersea acoustic detectors, or other systems.)

The objective is to disable as many high-value targets (large amphibious ships) as possible with a given level of effort by the defender (in this case, 1,000 Harpoon-class weapons). We assume that the enemy has a total of 1,550 ships in the Taiwan Strait, composed of the following types:

- 50 high-value ships (large amphibious vessels with a capacity of 50 tank-equivalents [TEs] each)
- 500 lower-value ships (including commercial cargo vessels)
  - 250 commercial cargo vessels, each with a capacity of ten TEs
  - 250 small amphibious vessels, each with a capacity of four TEs
- 1,000 ships with no value that serve as decoys.

The specific numbers above are arbitrary—chosen to produce an illustrative case—but are consistent with a large-scale amphibious operation that would be undertaken in anticipation of significant enemy resistance.[4] The assumption that Blue has a limited number of Harpoon-class weapons is important. If Blue had an unlimited weapon supply and the ability to employ them, ISR would be less important.

We assume that sensors on platforms in space and on standoff airborne platforms are able to detect the presence of these and other ships in the Taiwan Strait, but not identify them reliably. On detection of a large invading fleet, the defender launches large numbers of stand-in UAVs which, by providing multiple observations of the same individual targets and correctly fusing

[4] David Shlapak, David T. Orletsky, Toy I. Reid, Murray Scot Tanner, and Barry Wilson, *A Question of Balance: Political Context and Military Aspects of the China-Taiwan Dispute*, Santa Monica, Calif.: RAND Corporation, MG-888-SRF, 2009.

their collective sensor data, support target recognition and aimpoint selection. The UAVs closest to the target provide target-position updates to incoming weapons as they approach the Taiwan Strait.

The target and aimpoint identification and selection are provided by the mesh acting as a unit. In principle, all available information is available to all parts of the mesh at all times, although in practice, only the nearby UAVs will provide useful information to incoming weapons. The mesh would still be effective if individual parts were cut off from one another. These disconnected parts would function as smaller meshes. They could function effectively, as long as each part was large enough to support its mission.

We assume that the sensors aboard any single L-CAAT or kitten have a probability of accurately identifying a ship within a range of ten km with a single observation of .2, given that the ship is within range of the UAV's sensors at the time of observation. This value is intended to account for the presence of cloud cover and obscurants in large parts of the operating area. The probability that the mesh accurately identifies a target increases as multiple observations are made of that target and the results of those observations are shared.[5] Multiple observations also increase the probability that the mesh is able to identify the optimum aimpoint on the target vessel. We further assume that the Harpoon has a 40-percent chance of disabling a high-value ship if it is guided to the ship at its most vulnerable point. (Technically, we have assumed that the weapon has an 80-percent chance of disabling the ship if it works perfectly and hits the optimum point, but that all of our weapons have an additional 50 percent failure rate because of equipment failure or enemy point defenses.)

Figure 4.1 shows the relationship between the number of UAVs in the mesh and the lethality of 1,000 anti-ship weapons, given these assumptions and inputs. Given the high percentage of low-value targets in the battlespace, when ISR is poor, most of the 1,000 weapons committed to the defense are wasted on low-value ships. The chart shows the presence of a "critical mass" effect when the number of UAVs in the mesh is between 200 and 400. This jump in munition effectiveness reflects the value of having multiple sensors observing the same target area and collating the data from them to improve the accuracy of the picture. In an operating environment with lots of decoys and low-value targets, *when weapons can be guided to the targets of greatest value and, then, to the optimal aimpoint of each of those targets, the number of weapons required to kill the desired targets is greatly reduced. Specifically, without any small UAVs at all, relying exclusively on space and long-range ISR aircraft, in this model it would require 10,000 Harpoon class weapons to destroy 72 percent of the invading flotilla's TE capacity.* By

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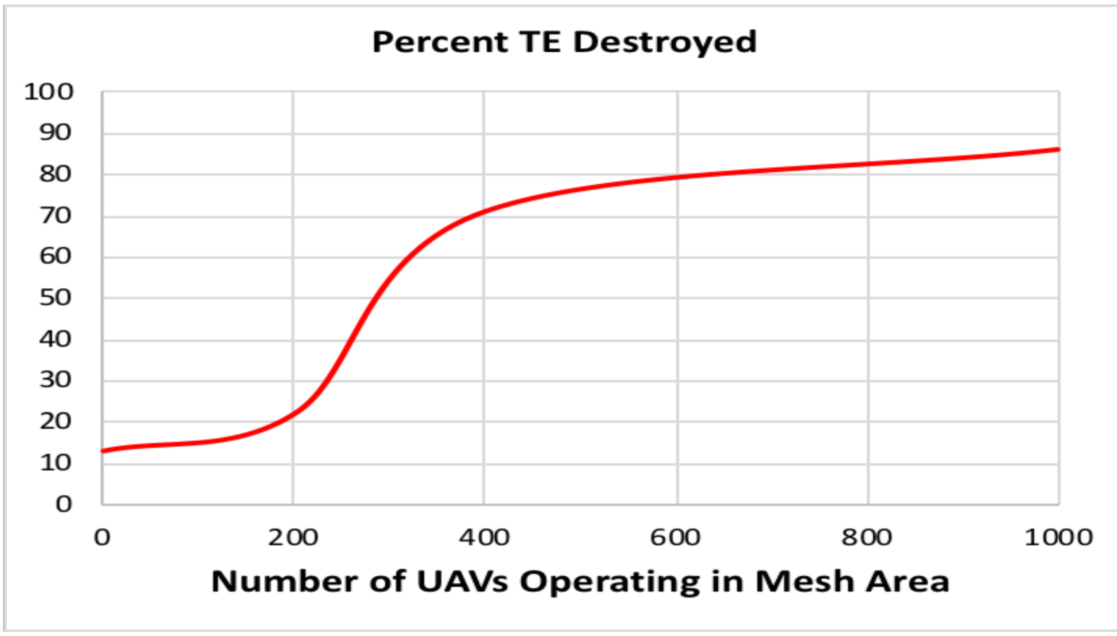
[5] The formula used for determining the cumulative probability of an accurate identification is $P_{ID} = 1 - (1- P_{ID})^n$ where P_{ID} is the probability of any one detection making a successful identification, here 0.2, and n is the number of independent detections. A key assumption here is that each attempted detection is an independent event. (A fine point is that the model specifically assumes that the P_{ID} for one detection would be 0.4 in perfect weather, but is degraded to 0.2 because of cloud obscuration. This is typical of the high level of aggregation throughout the model.)

contrast, when supported by a targeting mesh of 600 or more UAVs, 1,000 weapons can destroy upwards of 80 percent of the TE.

The flattening of the curve above 600 UAVs in Figure 4.1 reflects that essentially all of the weapons are being properly guided and the overall effectiveness of the forces is constrained by the number of weapons available.

Figure 4.1. Increased "Sensor Density" Enables Increased Lethality



5. Threats to the Mesh

Kinetic Threats

If these UAVs, as part of a joint and multidomain force, can produce these sorts of effects, an adversary will have strong incentives to neutralize it. In our concept, the UAVs are typically flying at 30,000 feet and will be visible to ground-based and airborne radars. They likely will not be capable of high-*g* evasive maneuvers, so considerable attrition must be expected. The idea is to saturate and, ultimately, exhaust the enemy's on-hand inventory of interceptor missiles.

It might be worth exploring the utility of putting jammers, high-speed anti-radiation missiles, or both onto some of the UAVs to counter the enemy's integrated air defenses. However, preliminary analysis conducted by RAND suggests that if the cost of the UAVs, including launch, can be kept low enough, it will be possible to pursue a strategy of pure saturation, replenishing the mesh at a rate faster than the enemy can attrit it, until the enemy exhausts its on-hand inventory of interceptor missiles. This approach maximizes the number of weapons that the mesh can bring to bear against the invasion force. Insights regarding the number and types of attritable UAVs appropriate for future conflicts, and the value of giving some of them defense suppression capabilities, will be the subject of further research.

Furthermore, although a saturation strategy appears likely to be successful against current and near-term kinetic threats, there is the possibility that an adaptive enemy will develop its own fleet of small UAVs, a sort of anti-mesh mesh. This is clearly an important area for future work. However, forcing the enemy to develop a completely new integrated air defense system concept, particularly if it makes large parts of the enemy's force relatively obsolete, can be an effective form of strategic competition.

Jamming Threats

The success of the mesh concept depends on the ability of the UAVs participating to communicate with one or more nearby UAVs. This requires communication ranges on the order of 5 km at an altitude of 30,000 feet. Mesh operation requires continuous communication. The mesh elements constantly exchange information to maintain the mesh; for example, determining what elements are active in the mesh, synchronizing their clocks, and using signal propagation delay to determine their precise positions relative to each other. The mesh also distributes tactically relevant information concerning the targets the mesh has located, and the weapons that the mesh might guide.

If these communications can be jammed, this concept can be defeated. However, likely locations for high-powered ground-based jammers are a considerable distance from the individual UAVs—in a Taiwan scenario, between 50 to 100 km. This means that jamming can be defeated by using radio frequencies, such as those in the tens of GHz, that experience relatively high levels of atmospheric absorption.

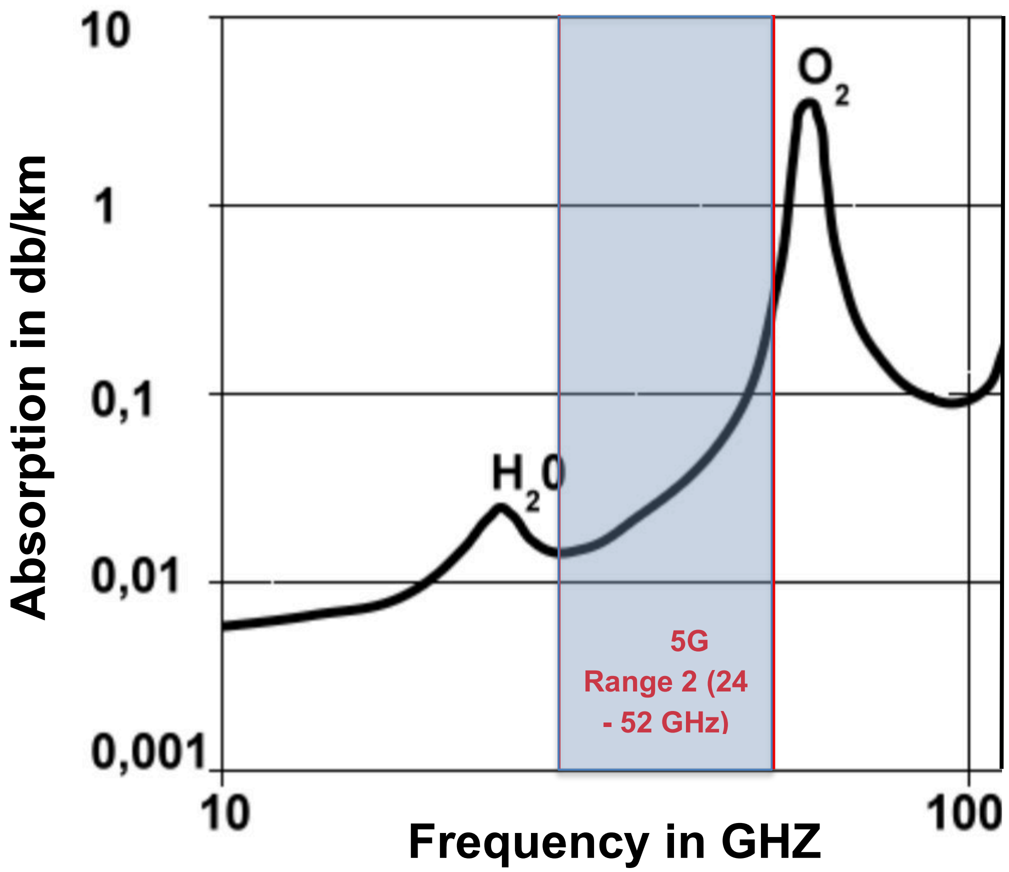
This high-frequency signal will only be useful over short distances, but this will be sufficient for communication among the UAVs. UAVs at considerable distances from each other will be able to communicate through a chain of relays. Communication with the entities outside of the mesh, such as command and control nodes, could be established with a chain of relays extending to a distance either free from Red jamming or to jam-resistant systems, such as a ground station connected to a terrestrial fiber network.

In practice, some UAVs could be equipped with a variety of long-range and satellite communications equipment, some of which is likely to work. As mentioned previously, the effectiveness of the mesh depends only on the short-range, high-frequency links, which can be made robust by the appropriate choice of frequency.

Figure 5.1 shows the atmospheric absorption of radio waves as a function of frequency at ground air pressure. The large absorption feature at 60 GHz is a result of radio wave absorption by oxygen molecules. This is a function only of the density of the air. It does not depend on temperature, wind, water content, or any other weather-related effect. It is therefore entirely predictable.

Modern radios can select their operating frequency. This will allow the UAVs to choose communications frequencies at which the radio's effective range is limited to the requirements of the particular link. Figure 5.1 highlights the frequency range that the cell phone industry has designated as 5G Frequency Range 2, often called millimeter wave. Commercial firms are investing heavily in very compact radios operating in this frequency band. Many observers predict that smartphones operating in these frequencies will become very common in the next few years.

Figure 5.1. Radio Wave Absorption as a Function of Frequency



NOTE: db = decibel.

The following case provides an example of the extent to which atmospheric absorption at the rates characteristic of 5G Frequency Range 2 can attenuate radio waves.

Assume that the adversary deploys a communications jammer that is 100,000 times as powerful as the signal it is attempting to jam; a megawatt jammer against a 10-watt radio. Assume the intended receiver is 10 km from the transmitter and the jammer is 100 km away. In free air with no atmospheric absorption, the signal strength drops as the square of the distance from the source. In such a case, with no absorption, the jamming-to-signal ratio would be 1,000:1. However, the situation is quite different when there is atmospheric absorption of one db/km, as is the case at 52 GHz in Figure 5.1 At a range of 100 km, the extra 90 km of distance produces additional signal loss of 90 db. The jamming-to-signal ratio (*J/S*) is now one part in a million. The *J/S* has dropped by a factor of a 10^9, or one billion. No conceivable ground station could overcome that much absorption. (A ground station that could burn through that much oxygen would require more than the total electrical generating power of the entire earth.)[6] A shipborne jammer might get closer to the mesh but would still have severe range restrictions. However, a shipborne jammer could jam the communications link to a weapon being guided into the ship itself. We have considered this as part of a ship's terminal defenses. We estimate that even if the weapon lost external guidance in the last ~10 km of flight, a large ship would not be able to change position in the ~40 seconds of weapons flight time remaining. The weapon would use inertial guidance and onboard sensors, if available, to engage, using the last available information.

Another approach Red could take would be the deployment of large numbers of coaltitude jammers, part of an anti-mesh mesh. Because of the large amounts of spectrum available in a millimeter-wave regime and the relatively low quantity of data to be transmitted, coaltitude jammers might require considerably more power than the radios they are designed to jam. This would make them larger and more expensive. It might make more sense for a coaltitude mesh to destroy kittens with kinetic weapons than for it to fly close enough to jam them. This is clearly a subject for future study.

The enemy could also employ jamming systems and laser weapons in efforts to disrupt SAR, ELINT, and EO/IR sensors in the targeting mesh. Ongoing analysis is exploring these questions.

Camouflage, Concealment, and Deception

Red will naturally wish to employ camouflage, concealment, and deception (CCD) to prevent the mesh from detecting and identifying valuable targets. The techniques that would work against the mesh are generally similar to those that would be effective against any radar and EO/IR sensors. The fact that the mesh will have the advantage of multiple platforms at a variety of geometries will make Red's task challenging. The mesh can also respond to particular situations dynamically. For example, if a particular target appears potentially important but is difficult to identify, the mesh could concentrate additional small UAVs in its vicinity, possibly flying very close to the potential target. A target could destroy such a UAV, but the information gained by the mesh could well be worth the cost if it supports the destruction of a target worth far more than one small UAV.

We envision a dynamic process in which Blue constantly tests the mesh and its software against possible Red target sets, including various Red CCD CONOPs. In practice, this could include machine learning, but this is not necessary. What is necessary is continuous realistic field tests. Such testing will be necessary to develop and validate software against a constantly evolving threat.

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[6] This effect is one of the attractions of millimeter-wave frequencies to mobile phone operators, who can use it to prevent inadvertent self-jamming and achieve better frequency reuse throughout their systems. Indeed, the whole mesh design is similar to a 5G mobile phone system.

Cyber Threats

The mesh concept requires reliable software and hardware to operate. If, for example, a threat were able to penetrate the supply chain for key UAV computer hardware, the threat likely could sabotage its operation. Alternatively, one could imagine malicious software being inserted during routine maintenance. One particular issue, common to AI systems, is maintaining the integrity of the machine learning training data.

We do not assess that the mesh has any unique strengths or vulnerabilities in this area. We do note that the mesh is designed to be a closed system. It does not depend on interactions with the larger world. As long as it can find targets, communicate with itself, and communicate with weapons, it can do its job. It should not, therefore, be vulnerable to disruptions from outside its isolated universe. Nevertheless, it is essential that procedures for maintenance, testing, and upgrades to the system software be secure.

6. Launch and Recovery Operations

RAND has made initial estimates of the manpower, equipment, and consumables that would be required to generate and sustain L-CAAT and kitten sorties. Using information gained during discussions with the manufacturer of the XQ-58, and from experience with the base operating support needs of traditional flying units, we assess that a squadron of approximately 900 personnel, properly equipped and trained, could launch and recover 300 L-CAATs every six hours, for a total of 1,200 sorties per day, on a 24 hours a day, seven days a week, continuous basis.[7] As discussed in the paragraphs that follow, a smaller squadron of 504 personnel could launch and recover 1,200 of the smaller kittens per day. This could include up to 600 kittens at one time, generating two such surges per day. It is not envisaged that deployed units operating attritable UAVs would perform maintenance on the air vehicles. If a vehicle were found to be defective during preflight inspection, it would be put aside and replaced by another.[8] This approach, which treats the air vehicles more like expendable articles (such as a munition) rather than as a platform allows for a smaller base operating support "footprint" than would be the case for a more-conventional platform.

Figure 6.1 provides an illustration of how a launch and recovery element for attritable UAVs might operate in the field. This element includes approximately 15 kitten UAVs and launchers plus any accompanying attrition reserve vehicles, roughly twenty people, and transport equipment to distribute approximately 7,000 pounds of fuel per day.

Sticking with our Taiwan Strait scenario, we show a deployment area in an region of cultivated fields on the edge of a mountain range in the southern Japanese island of Kyushu. The particular area was picked at random using GoogleEarth.

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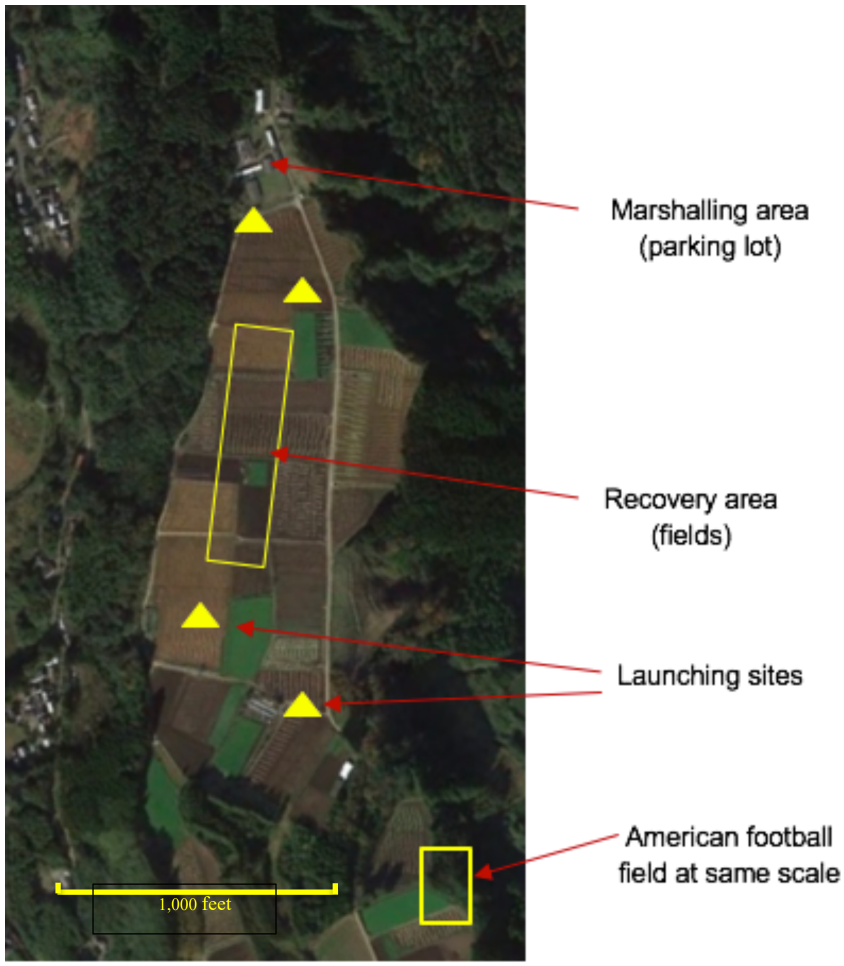
[7] Leftwich (forthcoming) goes into more details on the manpower, logistics, and sustainment aspects of employing attritable UAVs.

[8] Maintenance during peacetime operations would be done at a maintenance depot or by contractors.

Figure 6.1. Illustrative UAV Element Deployment Area



The area features a flat, cleared area the size of several U.S. football fields (one of which measures 300 by 160 feet). This area is accessed by paved roads and is only a few minutes' drive from small towns that would have a variety of services, including diesel fuel and provisions for personnel. A few shed-type buildings are visible. We envision that the element could set up four launchers outside the main landing area. An element travelling in two trucks for equipment and smaller vehicles for personnel could set up in an area such as this in a matter of hours.

These particular fields are surrounded by low, wooded hills. It would be difficult for an airborne platform orbiting outside Japanese airspace to see into the valley to observe UAV operations. Even if the site could be located, there is little at the site that would justify the expenditure of a long-range weapon. If the site were attacked, it could easily be abandoned, with surviving personnel and equipment moving to another, similar site, perhaps a few hundred meters away.

There are many similar areas nearby, as shown in Figure 6.2. The area depicted is approximately 20 km by 40 km, or about two percent of the land area of Kyushu. The area shown in the Figure 6.1 is outlined in red in the left half of the picture in Figure 6.2. Another 19 areas of similar farmland are marked in yellow. This could represent the spacing of 20 launch and recovery elements. The Japanese Defense Forces' Nyutabaru Airbase is shown in the orange box at the bottom center. Equipment could be stored there or at some other location in the area and deployed to operating sites as required. Again, the road network on the island is well developed, facilitating rapid deployment and redeployment with wheeled vehicles.

Figure 6.2. Possible Deployment Areas for 20 UAV Elements

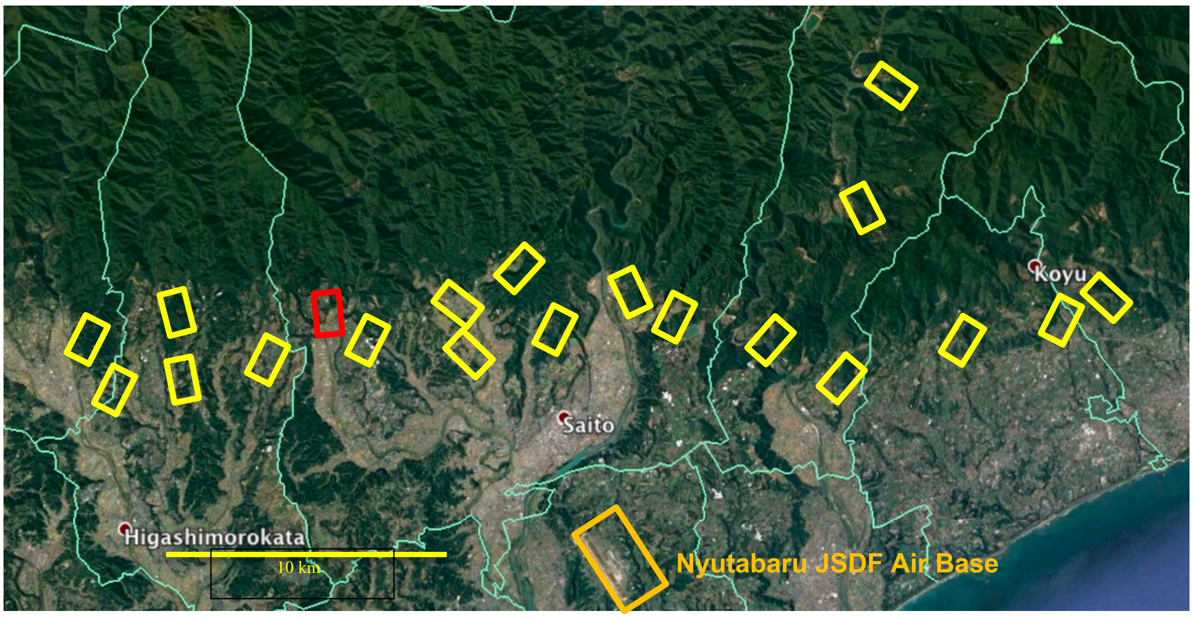
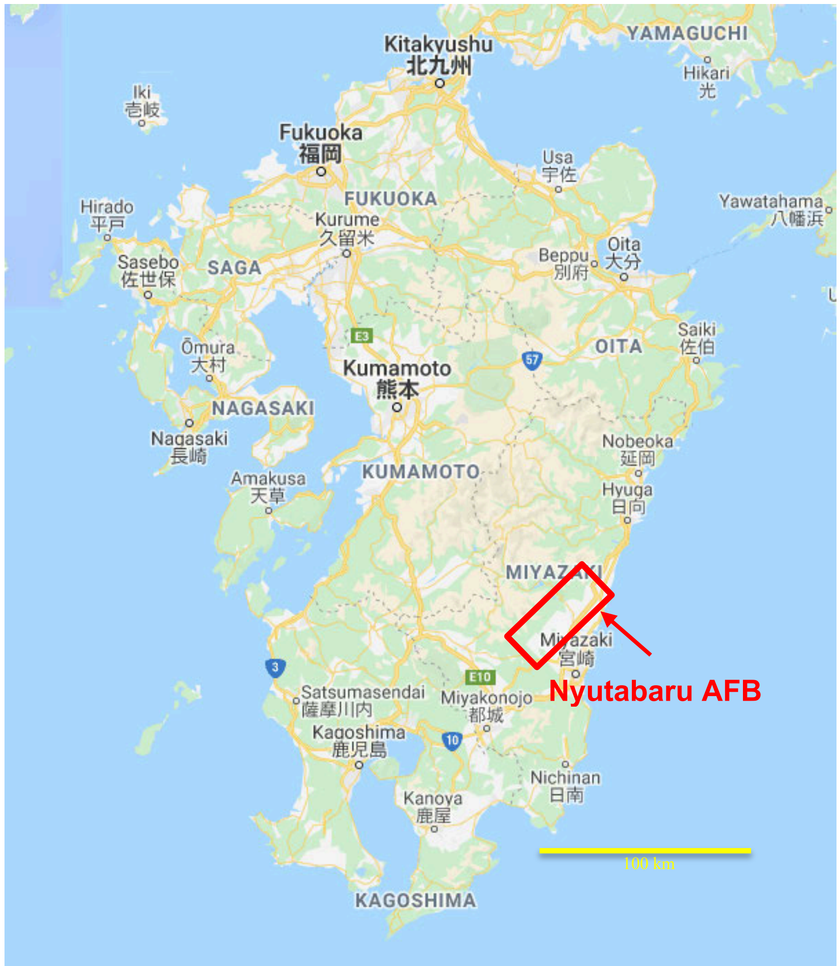


Figure 6.3 shows the location on the Japanese island of Kyushu of the area shown in Figure 6.2. This is the operating area of one squadron when it is dispersed.

Figure 6.3. Possible Location of Kitten Squadron in Kyushu



7. Kitten Squadron Size

Table 7.1 summarizes one possible size for a kitten squadron that would operate in the area described in Chapter 6. This squadron would perform launch and recovery operations and combat-support operations such as refueling and flight checks. Launch and recovery personnel are assumed to work one 12-hour shift for each 24 hours during combat operations. Mission planning would be performed elsewhere, likely at a higher headquarters. The proposed squadron would not have a field maintenance capability. Damaged UAVs would be discarded and immediately replaced from the substantial attrition reserve, which would be located at the unit.

Table 7.1. Kitten Squadron Size

Squadron Element	Number
Total personnel	504
Operators	400
Operators each shift	200
Total turns per 24 hours	1,200
PAA vehicles (kittens)	300
Attrition reserve	300

Launchers are compact and inexpensive. Every kitten air vehicle—both primary authorized aircraft (PAA) and reserve—would have its own launcher. In a surge, all 600 air vehicles could be launched at once, although such an effort could only be made once every 12 hours. If the squadron had time to set up the equipment, it could launch 600 vehicles simultaneously, but in sustained operations, the squadron is sized to turn 50 vehicles per hour. (The terms *vehicle* and *launcher* refer to the kitten and its launcher, respectively—a total of about 500 pounds of equipment, unfueled. The vehicles and their attached launchers would be stored together in peacetime in shipping containers, and moved by trucks to their operating areas during a conflict.)

In our baseline Taiwan Strait scenario, the enemy might destroy large numbers of kittens in the air over the battlespace (upwards of 1,500). Although our analysis suggests that operating approximately 500 kittens in a battlespace of this size might lead to a favorable result, prudent planning would call for the deployment of many more. If we assume that we want to employ as many as 3,000 kittens simultaneously, the structure described here would require the employment of five squadrons.

Roughly estimating the hardware cost, including launch and recovery equipment, at roughly $500,000 per kitten, the air vehicle hardware cost per squadron is roughly $300 million. This estimate assumes that each kitten would have its own launcher, an object resembling a small boat trailer, perhaps weighing between 100 and 200 pounds. The kitten would be stored mounted on its launcher. The launcher would have wheels and rails for physically carrying the kitten and pointing it into the air. It would not be self-propelled or necessarily include any electronics. The trailers and kittens could be moved around by physical labor, but it would likely be convenient to have small tractors assigned to the unit, perhaps one for every five PAA kittens. That would imply 60 tractors to support 50 launches per hour. We have chosen this launcher concept because it is simple and inexpensive. Other concepts would be consistent with the basic CONOPs. We have estimated the cost of the air vehicles themselves as $300,000 each and the total cost of the launch an recovery equipment at $200,000 per vehicle, considerably more than just the cost of the launcher. There would be additional costs for fuel trucks, general purpose vehicles to move personnel, and so on. Personnel cost for 504 people at $100,000, annually, would be $50 million per year. It is important to note that this is only the employment cost per unit. The development of the software will involve extensive and expensive testing in peacetime. Another way to look at it is that the cost per unit is the marginal cost of adding additional kittens. A low marginal cost per additional unit means that the fleet can be expanded easily in response to changes to the threat. In any case, these are obviously very rough ballpark estimates.

8. Conclusion

Considerably more analysis is called for into topics that include sensor and communications performance in the face of enemy countermeasures, force size and launch rates required to overwhelm and exhaust enemy surface-to-air and air-to-air threats, and the vulnerability of L-CAAT ground operations and support infrastructure to enemy special operations forces, among other threats. Attention will need to be paid to the problem of ensuring the integrity of the computer hardware and software aboard the air vehicles. And, as noted previously, we will want to understand the dynamics of a conflict in which both sides employ large numbers of these aircraft as platforms for sensing, air-to-air, air-to-surface operations, or some combination thereof. However, the overall concept of employing reusable, runway-independent UAVs as a key part of joint force operations to blunt enemy aggression appears sufficiently promising that it seems prudent to begin field experiments with prototype systems.

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RAND PROJECT AIR FORCE

There are disquieting trends in the military balance of power. Both Russia and China are fielding military capabilities and postures that, in wartime, would make it extremely challenging for U.S. forces to project power and defeat large-scale aggression. The 2018 National Defense Strategy called on the U.S. Department of Defense to turn priority attention to developing innovative capabilities and concepts for confronting these challenges.

The U.S. Air Force has increased its efforts to explore the demands of warfare in highly contested environments, and is devising and evaluating new approaches to defeating aggression in those environments. One intriguing approach is to employ large numbers of relatively low-cost, attritable—low-cost, reusable, and ultimately expendable—unmanned aerial vehicles (UAVs) to perform a variety of tasks in support of joint force defensive campaigns. This could allow land-based forces to generate and sustain airpower without relying on fixed base infrastructure, such as runways and maintenance facilities. The implications of such an approach for the resiliency of forward-based forces and for their effectiveness in the opening days of a conflict could be profound.

The authors of this report summarize early thinking and analysis about how the U.S. Air Force might employ such a force, and what effects it might achieve in the most-demanding conventional warfighting scenarios.

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