

Enabling Technologies for Small Unmanned Aerial System Engagement of Moving Urban Targets

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The DoD has a mission need to engage moving targets in an urban setting in clear and adverse weather conditions. To address this mission need and overcome the limitations associated with conventional airborne targeting and weapon platforms, APL embarked on an independent research and development (IR&D) effort to weaponize a small unmanned aerial system (UAS) that is capable of cooperating with currently fielded small UASs to execute the entire kill chain (find, fix, track, target, engage, and assess). The main objectives of the IR&D effort were to plan a mission using a UAS simulation environment, demonstrate the enabling technologies that would allow a group of cooperating small UASs to execute the entire kill chain in a complex aerodynamic environment, and demonstrate the lethality of a small UAS-compatible warhead. The accomplishment of these IR&D objectives led to a successful demonstration of the cooperative hunter/killer UAS concept performing convoy protection at the Joint Expeditionary Forces Experiment 2010 (JEFX 10) at the Nevada Test and Training Range.

INTRODUCTION

Need

The DoD has a mission need to engage moving targets in an urban setting in clear and adverse weather conditions. Unfortunately, there are issues that prevent this capability from being realized with conventional airborne targeting and weapon platforms. The first issue is an inability of conventional ground-based and

airborne intelligence, surveillance, reconnaissance, and targeting systems to reliably maintain custody of the moving target track identification (ID) throughout the kill chain. As was demonstrated in a recent kill chain analysis by APL,¹ vertical urban obstructions and low cloud ceilings prevent these systems from reliably main-

taining a continuous, unobstructed sensor line of sight to moving targets from the time that initial positive combat ID is established through the time the target is hit. These obstructions, coupled with the high density of similar moving vehicles and erratic ground vehicle motion in the target area, cause an unacceptably high probability of sensor-to-track misassociations when the track is handed off between the targeting sensors and the weapon seeker. In addition, conventional systems cannot execute the kill chain fast enough to handle time-critical moving targets. The window of vulnerability for time-critical targets in urban environments is often measured in a few minutes or even in seconds. APL interviewed Marine Corps unmanned aerial system (UAS) operators who conducted operations in Iraq. They stated that they had very little capability to engage the insurgents that they saw with the UAS. The insurgents would typically scatter before support units arrived at the scene. According to an analysis of Army UAS stakeholders conducted at the U.S. Military Academy, a majority of the stakeholders felt that close air support was available and effective less than 50% of the time.² Finally, conventional systems cannot destroy the target without unacceptable probability of collateral damage in dense urban environments. The lethal radii of our Joint Direct Attack Munition and Joint Standoff Weapon unitary warheads are too large to provide the warfighter with the selective killing capability needed in the urban environment. This is also true of the Small Diameter Bomb and the Hellfire missile, which is designed to destroy tanks.

Concept

To address this mission need and overcome the issues associated with conventional airborne targeting and weapon platforms, APL investigated the concept of weaponizing a small UAS [human-portable with a gross takeoff weight of less than 20 lb (9 kg)] that is capable of cooperating with currently fielded small UASs to execute the entire kill chain (find, fix, track, target, engage, and assess). This concept provides a precision strike capability that is used by and under the control of the local commander (thus, it would be an organic asset of the local commander). The APL concept involves the use of multiple “hunter” UASs whose mission objectives and associated priorities are set by the local commander. APL’s Mission-Level Autonomy (MLA) software³⁻⁵ enables the autonomous cooperation and allows each UAS to decide locally how it can best achieve the mission objectives. The hunter UASs execute the find portion of the kill chain by conducting an autonomous search of the commander’s area of responsibility. As soon as one of the hunter UASs finds a target, the UAS operator uses the cursor to select the target in the ground control station video stream.

The target selection action initiates computation of the target’s location (the fix portion of the kill chain). Video feature tracking, which directs the path of the UAS and the pointing of the UAS’s imaging sensor, keeps the target in the UAS field of view (track). The location of the target attracts the other hunter UAS, as specified in the mission objectives and priorities. (Note that there could be a single hunter UAS or multiple hunters, depending upon the UAS operator’s rule set.) The multiple hunter UASs observe the target from different vantage points, which improves the probability of target ID and the accuracy of geolocation. Once the operator has determined that the target is a threat, the local commander has the option of launching a “killer” UAS. Using MLA, the killer is attracted to the threat location. When the target appears in the killer UAS video, it is compared with the target in the hunter UAS video. After the operator confirms that the target in the killer video is the same target, the local commander can make the decision to engage by using the killer UAS. By maintaining the target track, the hunter UASs monitor the engagement and provide immediate battle damage indication to the UAS operator so that he or she can assess the success of the engagement, completing the kill chain. In this concept for moving target engagement, track custody and ID are maintained throughout the kill chain; the kill chain is shortened through use of autonomy and organic assets; and the use of a small, visually guided UAS allows precise delivery of a small-yield warhead, minimizing the probability of collateral damage.

Objectives of the Independent Research and Development Project

The purpose of the independent research and development (IR&D) project described here, “Weaponized Small UAS for Engaging Moving Urban Targets,” was to develop technologies that enable a small UAS to overcome the previously described issues associated with engaging a moving target in an urban environment and to conduct field demonstrations of the end-to-end capability. The main objectives were to plan a mission using the UAS simulation environment (Refs. 6 and 7, and see also the article by McGrath et al. in this issue) to demonstrate the enabling technologies, including the ability of a group of cooperating small UASs to execute the entire kill chain in a complex aerodynamic environment and to demonstrate the lethality of a small UAS-compatible warhead.

Challenges

Although the cooperative hunter/killer (CHK) UAS concept overcomes some of the issues associated with conventional airborne targeting and weapon platforms,

different challenges are associated with using small UASs for this mission. Existing small UASs currently do not lend themselves to autonomous operation within complex, highly variable aerodynamic environments. A detailed understanding of the urban airflow characteristics is needed to reduce the high risk of failure associated with low-altitude, urban UAS missions. This detailed understanding of the aerodynamic environment can be built into the UAS mission planning software, can be measured by the UAS during flight, or both. Not only do urban “canyons” create a complex aerodynamic environment, they also make it difficult to maintain reliable communications with and between UASs, and they increase the dilution of precision of the Global Positioning System (GPS) navigation solution. Even with nominal GPS accuracy, it would be difficult and sometimes impossible to navigate between the buildings. In an urban environment, the buildings also make it difficult to maintain line of sight between the UAS and the target. To mitigate this issue, the UAS must loiter directly above the target, which can alert the target to the UAS’s intentions and can prompt the target to take countermeasures. For the killer UAS, the challenge is to build a warhead small enough to be carried by a small UAS, lethal enough to eliminate personnel and disable lightly armored vehicles, and accurate enough to minimize collateral damage. Target engagement is subject to the same issues as navigation in the urban canyon, making accurate warhead delivery a challenge.

APPROACH

The IR&D team took an evolutionary approach to demonstrate the ability of a group of CHK UASs to execute the entire kill chain against a moving target. The initial demonstration involved partnering with Procerus Technologies to execute the entire kill chain with research UASs (Procerus Unicorns and a Procerus Miracle) in a benign, noncluttered, rural environment at Camp Roberts, California. The second demonstration had similar objectives but was conducted at the McKenna Military Operation on Urban Terrain (MOUT) facility at Ft. Benning, Georgia. That demonstration used a Prioria Maveric UAS hunter and a surrogate killer UAS carrying the Procerus video processing unit, which enables onboard video tracking and engagement processing. The MOUT facility is the closest thing to an urban environment in controlled airspace that is available for UAS operation. Recognizing the limitations of the MOUT facility, the IR&D team also developed a UAS simulation environment to accurately depict the urban environment, including airflow, sensor, and communications behavior.

In addition to proving the concept of CHK in demonstrations and simulation, the IR&D team developed

or obtained and assessed the performance of technologies that address the challenges associated with CHK operation in the complex and cluttered urban canyon. These technologies included an optical wind sensor, MLA software, a mobile ad hoc communications network, vision-based guidance and navigation, and a small UAS-compatible warhead. Because these technologies had different levels of maturity, some were assessed on the UAS, some were assessed in laboratory experiments, and some were evaluated in simulation.

The final demonstration was a teamed exercise with the Army Aviation and Missile Research Development and Engineering Center and used three Army RQ-11B Ravens as hunter UASs. This demonstration was sponsored by the Air Force Global Cyberspace Integration Center (GCIC) and the Navy Second Fleet. Participation in the Joint Expeditionary Forces Experiment 2010 (JEFX 10) at the Nevada Test and Training Range represented the next evolutionary step. In that experiment, CHK was demonstrated in an operationally realistic scenario using military UAS platforms and real-time video connectivity to the local command and control (C2) node.

OVERVIEW OF SMALL UAS COMPONENTS AND ASSOCIATED ENABLING TECHNOLOGIES

Airframe

For the purposes of this article, the term “small UAS” is a Group 1 UAS as defined in the *Office of the Secretary of Defense Unmanned Systems Integrated Roadmap (2009–2034)*.⁸ Group 1 UASs have a maximum gross takeoff weight of less than 20 lb (9 kg); they normally operate below 1200 ft (366 m) above ground level and fly at speeds less than 100 knots (51 m/s). A small UAS can either be fixed wing or rotorcraft. One of the most significant characteristics of the small UAS is that it is human-portable, meaning that a dismounted soldier can carry and launch it. The fixed-wing UASs are hand, tube, or bungee launched.

The first IR&D demonstration used two different fixed-wing research platforms with capabilities similar to those of the fielded fixed-wing UASs. The second and third demonstrations used the Prioria Maveric and the AeroVironment Raven UAS, respectively, which are in operation with the Canadian and U.S. forces, respectively. The following subsections provide additional detail on each of these systems. Their key specifications are listed in Table 1.

To assess the capability of small UASs to engage moving targets in an urban setting, a high-fidelity simulation environment needed to be developed. With good reason, the Federal Aviation Administration does not allow operation of small UASs in urban areas. The

Table 1. UAS specifications

	Procerus Unicorn	Procerus Miracle	Prioria Maveric	RQ-11B Raven
Standard payloads	Forward and side-looking electro-optical (EO) camera, or retractable gimbal EO camera	Forward-looking EO camera	Forward EO, side-looking EO or IR camera, or retractable gimbal EO camera	Forward and side-looking EO or IR camera
Range, mi (km)	5 (8)	5 (8)	3.1 (5) (without high-gain antenna at ground station)	6.2 (10)
Endurance, min	30–60	12	45–90	60–90
Speed, knots (m/s)	25–50 (12.86–25.72)	25–50 (12.86–25.72)	26–55 (13.4–28.3)	17–44 (8.75–22.6)
Typical operating altitude, ft (m) above ground level	50–500 (15.24–152.4)	50–500 (15.24–152.4)	50–500 (15.24–152.4)	100–500 (30.48–152.4)
Wing span, ft (m)	5 (1.5)	3 (0.9)	2.46 (0.75)	4.5 (1.37)
Length, ft (m)	1.83 (0.56)	3.0 (0.91)	2.2 (0.67)	3.0 (0.91)
Weight, lb (kg)	4 (1.8)	3 (1.36)	2.5 (1.13)	4.2 (1.9)
Power	Electric battery	Electric battery	Electric battery	Electric battery
Launch/recovery method	Hand launch/belly skid	Hand launch/belly skid	Hand launch/deep stall	Hand launch/deep stall

UASs described in the following sections are typically operated in a benign environment above the buildings or in rural areas. UAS performance in the urban canyon is largely unknown; thus, a synthetic environment was required for development of the enabling technologies and assessment of airframe performance. An overview of the UAS simulation environment developed and utilized during the IR&D effort is provided in the *UAS Environment Simulation* section.

Procerus Unicorn

The Procerus Unicorn UAS (shown in Fig. 1) is the primary platform we used in this research. It is an expanded polypropylene plastic foam flying wing with a pound of extra payload capability. The foam structure and extra payload capacity make it easy for the researchers to integrate test payloads. In addition, the Unicorn is rugged, reliable, low-cost, and has specifications similar



Figure 1. The Procerus Unicorn, which typically has a 5-ft (1.5-m) wingspan.

to those of fielded small UAS platforms; thus, research conducted on the Unicorn is relevant to the fielded platforms. The Unicorn specifications⁹ are outlined in Table 1.

Procerus Miracle

The Procerus Miracle UAS (shown in Fig. 2) is APL's surrogate killer UAS and is also a reasonable surrogate for fielded small UASs. Its design was optimized for robustness rather than endurance, and so its endurance is much less than that of the other UASs shown



Figure 2. The Procerus Miracle, which has a 3-ft (0.9-m) wingspan.

in Table 1. The Miracle has a traditional fixed-wing configuration and control system. Like the Unicorn, it is made of expanded polypropylene plastic foam, which makes it a rugged and reliable surrogate. Although its airframe is simple, the Miracle carries a sophisticated electronics suite. The Miracle has a 5-megapixel digital EO camera. It also uses the Procerus video processing unit, which enables OnPoint video target tracking and engagement processing on board the plane. The video processing unit was added to the Miracle in 2009, so the tracking and engagement processing was done on the ground station during the 2007 experiments that are described later in this article. The Miracle's specifications are outlined in Table 1.

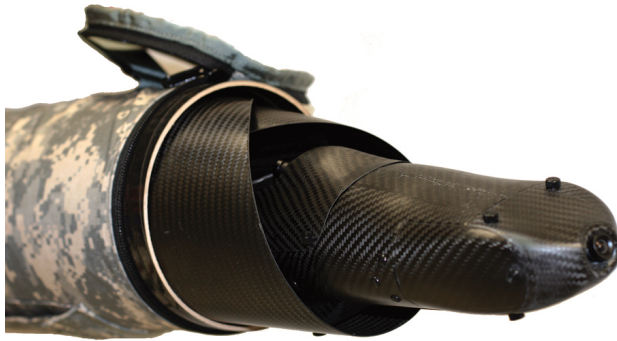


Figure 3. Three views of the Prioria Maveric, which has a 2.46-ft (0.75-m) wingspan. (© 2012 Prioria Robotics.)



Figure 4. The AeroVironment RQ-11B Raven, which has a 4.5-ft (1.37-m) wingspan. (U.S. Army photo: Staff Sergeant Don Veitch.)

Prioria Maveric

The Prioria Maveric (shown in Fig. 3) is a human-portable UAS currently deployed with Canadian forces in Afghanistan. It has bendable wings that allow it to be stored fully assembled in a tube with a diameter of 6 in. (0.15 m), and it can be launched and operated by a single soldier. Typical missions include intelligence, surveillance, reconnaissance, and target tracking at the squad level. The Maveric specifications¹⁰ are outlined in Table 1.

AeroVironment RQ-11B Raven

The AeroVironment Raven B (shown in Fig. 4) is a small UAS deployed with the U.S. armed forces. According to the U.S. Army Roadmap for Unmanned Aircraft Systems 2010–2035, “Raven is a rucksack-portable, day/night, limited adverse weather; remotely operated, multi-sensor system used in support of combat-battalion level and below operations and other combat support units. [Military Occupation Specialties (MOS)] non-specific personnel can program, launch, fly, retrieve, and maintain the Raven. . . . The Raven conducts surveillance during routine combat operations, much in the manner of an observation post or a screening element.”¹¹ The Raven specifications¹² are outlined in Table 1.

Propulsion

Both fixed-wing and rotorcraft small UASs use propellers for propulsion. Puller propellers at the front of the vehicle or pusher propellers at the rear of the vehicle are both common configurations for fixed-wing UASs. The propellers are either exposed or in a ducted fan and are driven by either electric or gasoline motors. Electric motors are typically powered by rechargeable batteries (for example, lithium-ion polymer) and tend to be quieter, but they have less endurance than the gasoline motors. Typical electric-powered UASs have an endurance of 90 min or less. The gasoline-powered Mission Technologies, Inc. Buster UAS has an endurance of

the small UAS to avoid (for example, a periodic down-draft behind a certain building when the wind is at a certain speed from a particular direction). The UAS simulation environment and modeling of the environment-vehicle interactions are described in detail in the article by McGrath et al. in this issue.

Communications

UASs use wireless data links to pass C2 data and full-motion video between the air vehicle and the ground control station. UAS communications are limited to the line of sight, and in most cases the range is further limited by the antenna gain and power capability of the UAS. On a small UAS, the maximum range is typically limited to less than 6 mi (10 km). That range has been extended on the upgraded AeroVironment Raven B using the new digital data link.

Three wireless communications architectures are typically used to link UASs. Most UASs implement point-to-point or point-to-multipoint (star topology) communications architectures. With these architectures, single or multiple vehicles connect directly to a ground station over a dedicated link. Communications are centrally managed by the ground node, and communications between vehicles are routed through the ground node. APL pioneered the use of a third architecture, mobile ad hoc network (MANET) communications, on small UASs in 2003.

The exfiltration and sharing of data, autonomous coordination of multiple UASs, tasking and retasking of mission parameters, and ground control of both individual vehicles and networks of vehicles require the transfer of information between the various system nodes. APL wirelessly links its UASs using Wave Relay MANET routers developed by Persistent Systems. These devices communicate using commercial 802.11b/g protocols at the physical layer, but they implement a proprietary routing algorithm that vastly increases the scalability, reliability, and quality of service of the MANET. Wave Relay routers are now used by Special Operations Command and the Naval Postgraduate School to wirelessly link the ranges at their quarterly Tactical Network Topology experiments. Recently, both AeroVironment and Insitu have experimented with integrating Wave Relay routers on their smaller UAS vehicles.

A MANET mesh provides the optimal network topology for the implementation of MLA. Nodes can enter and exit the network without central coordination. In fact, the network is naturally decentralized. MLA does not require spanning trees or global connectivity, but it can rely on a delay-tolerant network with multiple broken links. The APL communications protocols and MANET mesh are designed to operate in this type of dynamic network topology where distance

and quality of service between nodes is constantly changing as UASs autonomously and constantly reposition themselves.

As previously mentioned, at the physical layer, the APL MANET communicates using commercial 802.11b/g protocols. Nodes access the air medium using carrier sense multiple access with collision avoidance. Depending on the data rate, the signal is spread using direct sequence spread spectrum or orthogonal frequency division multiplexing. Special routing algorithms, unique to the Wave Relay router devices, expand the network's capacity, increase its reliability, and, through relaying, extend its range.

As part of the MLA, APL has also developed a reliable and robust message handler architecture to manage the input and output of the MLA "belief" messages.¹⁴ This architecture defines the content, structure, prioritization, broadcast scheduling, and supervision of these messages. This communications architecture supports three primary services: Periodic Packet Multicast service, On Demand Packet Broadcast service, and Operation, Administration, and Management (OAM) service. The former two services are for transport of beliefs. The OAM service allows configuration of internal default parameters and allows access to its internal status and statistical counters. The architecture provides these services by supporting three software interfaces: the Belief Transmit Service Interface, Belief Receive Service Interface, and OAM Interface. This message architecture is independent of the communications method but is best integrated with a MANET topology.

The combination of MLA and the MANET communications topology helps address the challenge of maintaining reliable communications in the urban environment. The high degree of autonomy allows the UAS to continue to operate during periods when communications are lost. The MANET topology allows UASs to drop out of and into the network as communications are obstructed and restored. It also allows for the use of multiple communications paths to pass information. If one path is lost because of line-of-sight issues, a different path can be used to pass that information.

Sensors

Because of their size, small UASs are limited in the sensors that they can carry. Small UASs started with an EO sensor (a video camera). The desire to operate at night motivated the miniaturization of IR sensors. Most fielded small UASs have the ability to swap between modular EO and IR cameras depending on mission needs. These sensors are either fixed or gimballed. If the sensors are fixed, there are typically two: one looking forward, the other looking to the side. Recently, synthetic aperture radars have been miniaturized for small UAS compatibility. The addition of synthetic aperture radar

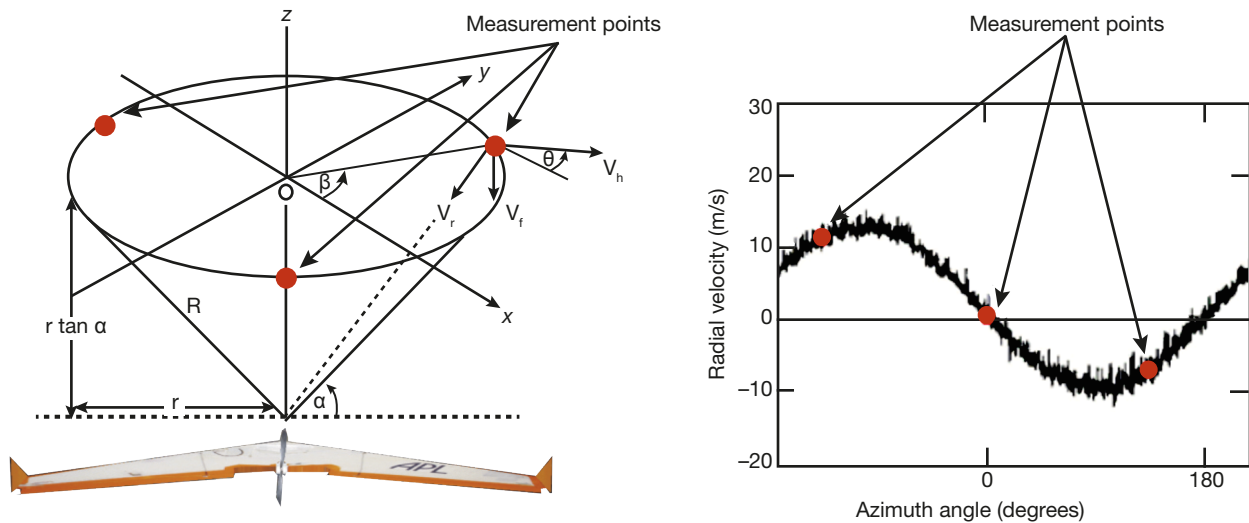


Figure 6. The velocity azimuth display method.

to the small UAS sensor suite provides an all-weather sensor capability.

As part of the IR&D effort, we designed and built a small UAS-compatible optical wind sensor to characterize the surrounding aerodynamic environment during low-altitude, urban UAS missions. The UAS simulation environment was used to model a generic standoff wind sensor to develop a UAS guidance scheme that translated the wind speed in front of the vehicle into preemptive steering commands and to demonstrate that knowing the wind speed and wind direction in front of the vehicle improved the probability of mission success in the chaotic urban aerodynamic environment.⁶ Requirements for the wind sensor including operational range and critical wind velocities were then derived from the simulation's results.

With this information, a UAS-specific design was then considered. The UAS optical wind sensor is based on the same concept that large-scale systems use in commercial aircraft and at airports for vortex monitoring and wind measurement. Deployed sensors produce a 3-D wind field estimate at a set standoff distance by measuring the radial velocity of ambient aerosol particles along a laser beam. Combining multiple measurements along a cone (Fig. 6) allows for the unique specification of the 3-D wind vector through the velocity azimuth display method.¹⁵ Current hardware is designed to operate

at ranges of hundreds of meters and weighs in excess of 50 lb (23 kg), neither of which is compatible with the UAS requirement.

The APL design is novel in that it uses a light-emitting diode (LED) as an optical source. LEDs are power efficient and lightweight, making them a good source candidate for a power- and size-limited platform. From a processing perspective, the sensor operates identically to current technology, where several radial velocity measurements are used to determine the 3-D vector. However, for the UAS sensor, azimuth diversity in the measurement is achieved by using several small apertures (minimum of three) in the nose of the aircraft that are fiber coupled to a common receiver. By using mul-

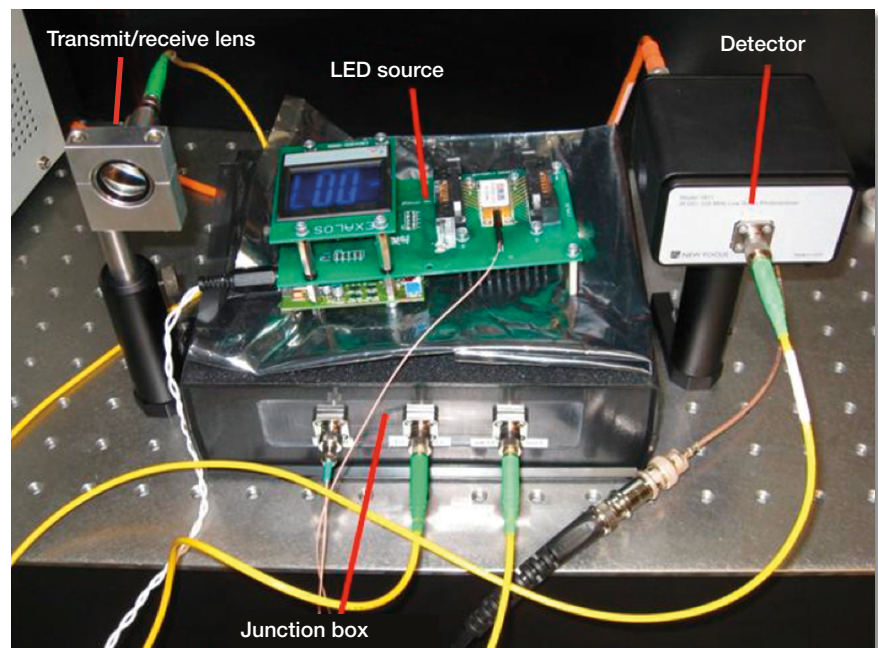


Figure 7. Prototype optical wind sensor.

multiple fixed measurement points (instead of a gimballed mirror) and fiber-optic coupling, the sensor has a target weight of less than 2 lb (0.9 kg).

The prototype optical wind sensor (Fig. 7) was integrated and successfully tested using a Lambertian hard target mounted on a translation stage. Figure 8 illustrates the results of this test, where the Doppler frequency is consistent with the speed of the translation stage. Radial speed measurements were repeatedly demonstrated with the accuracy required to produce a 3-D vector needed for UAS navigation. This accomplishment proves the suitability of an LED source for making the required radial velocity measurements.

For the second phase of testing, APL attempted to measure the radial velocity of environmentally realistic aerosol particles. Optical properties of atmospheric aerosols at relevant altitudes were found in the literature¹⁶ and used as the basis for selecting test particle sizes (1.0- μm -diameter silica beads) and number concentrations (5×10^4 to 2×10^5 particles per liter). Testing was then moved to the Dynamic Concentration Aerosol Generator (DyCAG) test facility, which allows the user to control airspeed and atmospheric particle concentrations. Velocities during the testing were in the range of 1.3–7.2 ft/s (0.4–2.2 m/s), which is consistent with expected speeds of the UAS. Unfortunately, no return signals were found in the collected data, and the sensor was not able to compute the speed of the air flow. The return signal-to-noise ratio was probably not sufficient to extract the velocity estimate. Given this explanation, two approaches form the basis for future

work: (i) improving the hardware signal-to-noise ratio by redesigning the receive aperture to collect more backscattered light or (ii) implementing more sophisticated signal processing to extract the velocity estimate at a lower signal-to-noise ratio.

Guidance, Navigation, and Control

Small UASs are either remotely piloted or follow a mission plan created by their operators. Remote piloting involves using a joystick controller to maneuver and control the throttle of the small UAS. The operator either uses the sensor feed and telemetry or watches the vehicle from the ground to determine the control inputs.

If a mission plan is used, the operator inputs a series of points that specify a 3-D location in space. The small UAS then flies automatically from point to point using its knowledge of its own location and altitude. This is called waypoint guidance. The UAS uses GPS, an inertial measurement unit, and a barometer to determine its altitude and location. Typical points include waypoints that shape the path of the UAS flight and loiter points that cause the UAS to circle around a specified location. Loiter points are typically used to maintain video coverage of a target of interest. The mission plan can be modified in real time by adding, deleting, or moving waypoints. Mission plans also have built-in procedures for loss of communications and returning to base.

Fixed-wing UASs are controlled using combinations or subsets of ailerons, elevators, flaps, and rudders. Rotorcraft use combinations of traditional helicopter controls that depend on the configuration of the vehicle: pitch of the rotor blades, plane of the rotors, and number of revolutions per minute of the rotors. A more detailed explanation of UAS guidance, navigation, and control appears in the article by Barton in this issue.

During the IR&D project, we investigated three different schemes for directing the flight path of the UAS. In the first scheme investigated, MLA was used to enable a single UAS user to simultaneously operate multiple UASs in an unreliable communications environment. Specifically, MLA was used to direct the flight path of multiple UASs to conduct a cooperative area search mission. The second guidance scheme, Procerus's OnPoint software, enables UAS target tracking and engage-

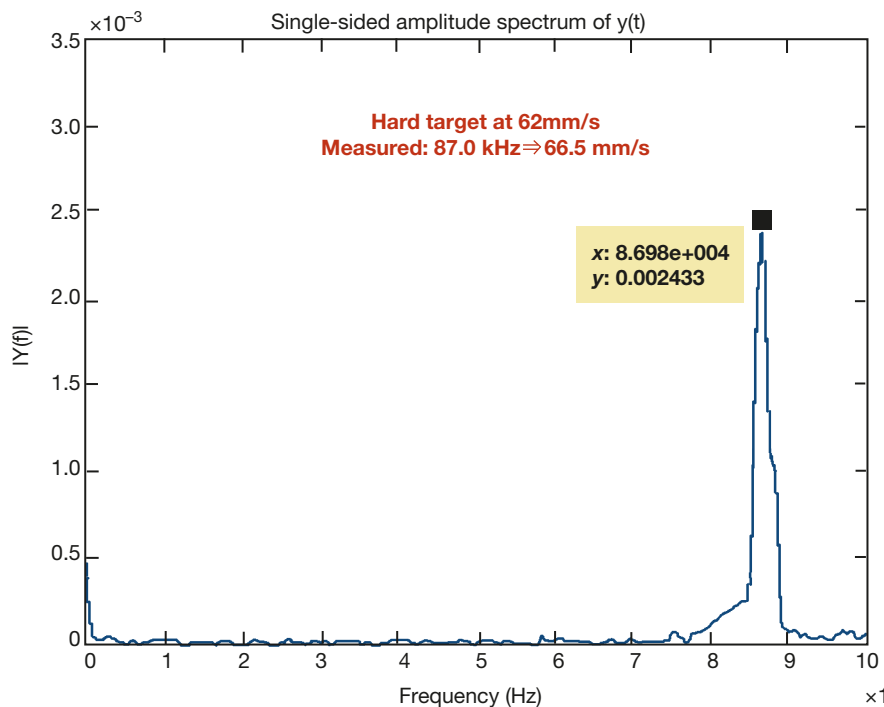


Figure 8. Laboratory test results of the prototype optical wind sensor.

ment. The software's video processing and guidance logic tracks the feature points of an operator-designated target, points the sensor to keep the target in the field of view, directs the flight path of the UAS to maintain the target in the sensor's field of regard, and provides inputs to the guidance commands if the operator chooses to engage the target. The primary OnPoint sensor is an optical sensor. The third scheme investigated was simultaneous localization and mapping (SLAM), which is an optical guidance scheme for navigation. It is particularly well suited for navigation in an urban environment where GPS accuracy is an issue.

Mission-Level Autonomy

MLA is a decentralized approach in which the operator specifies the mission objectives and prioritization, and the UASs self-configure to achieve the mission objectives. The UASs use stigmergic potential fields to coordinate movement, tasks, and flight mode transition. "Stigmergy is defined as cooperative problem solving by heterarchically organized vehicles that coordinate indirectly by altering the environment and reacting to the environment as they pass through it."³ Each UAS computes its own dynamic potential field by modeling actions that help it achieve mission objectives as an attractive force and modeling actions that are detrimental to mission success as a repulsive force. The sum of all the attractive and repulsive forces at each instant in time forms the current potential field for each individual UAS. The magnitude of the attractive and repulsive forces is typically a function of distance and time. Given this information, the net force on the UAS determines its path and where it points its sensors.

Figure 9 is an example of a stigmergic potential field for a UAS. In this example, repulsive forces are generated by no-fly zones and other UASs (airspace deconfliction and mitigation for unnecessary duplication of

effort). Attractive forces are generated by the mission objectives (i.e., the location of an area that has not been searched, the location of a potential target, the direction of a radio signal of interest, etc.). As Fig. 9 shows, the stigmergic potential field of the UAS takes into account the other UASs that are on its ad hoc mobile mesh communications network. In addition to sharing its location, each UAS shares its beliefs about its environment (e.g., areas that have been searched recently, target locations, mission objectives, etc.) with the other UASs on the network. This sharing of beliefs enables cooperation among the UASs.

For example, assume that a group of UASs have the mission objective of searching a specified area. The area search mission objective is uploaded to the group of UASs with a georeferenced grid encompassing the area that needs to be searched. The UASs are attracted to the grid areas that have not been searched and repulsed from the other UASs and from grid areas that have already been searched. Thus, each UAS makes a decision on its own about where to search next on the basis of the location of the other UASs, the grid areas the other UASs have searched, the grid areas it has searched, its current location, and the grid areas that still need to be searched.

Through the use of the mesh network, UASs can share their location and beliefs about the environment with UASs that they do not have direct line-of-sight communication with. As a result, mission objectives from the operator and beliefs from the UASs are hopped from vehicle to vehicle, enabling non-line-of-sight UAS operation. This decentralized approach to autonomy will not yield an optimal search pattern for the area in question, but it is a robust approach to achieving the mission objective. If there are issues with communications, each UAS will still execute the area search mission on the basis of the limited information it is able to receive. If additional UASs are added to the group or if some are unable to continue, no replanning or reoptimization is required. Each individual UAS continues to search the areas that have not been searched, regardless of the total number of UASs that are cooperating to search the given area.

MLA significantly reduces the operator workload for conducting a mission. In this example, a single operator can conduct the area search mission by prioritizing the mission objectives, specifying the area that needs to be searched, launching as many vehicles as desired, and monitoring the sensor feeds. Executing this area search mission today with multiple UASs would require multiple teams of operators, line-of-sight communication between each UAS and its controlling ground station, and significant coordination across all operators for the initial planning, sharing of sensor data, and contingency replanning.

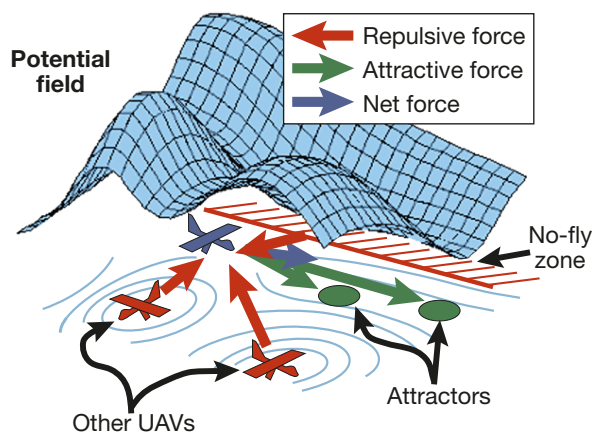


Figure 9. Example of a stigmergic potential field used by APL's MLA.

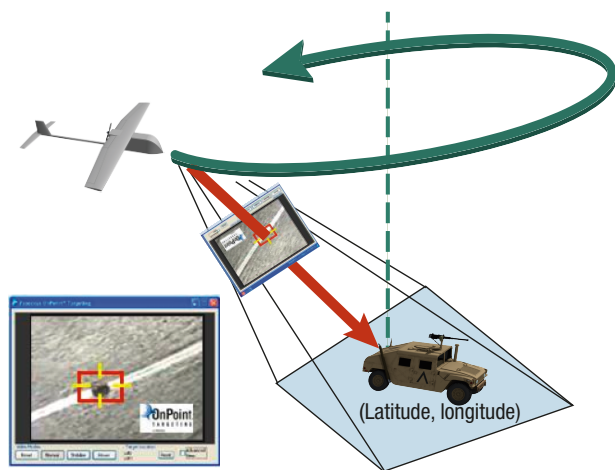


Figure 10. Using OnPoint, a UAS uses feature tracking and telemetry to geolocate a ground vehicle and maintain a loiter around that vehicle.

Target Tracking and Engagement

In all three demonstrations, the IR&D team leveraged the Procerus Technologies-developed video-based tracking and engagement abilities embodied in the OnPoint Targeting product.^{17,18} Once a target appears in the UAS video stream, a single click from the ground station operator activates the target tracking capability. It is a feature tracking-based controller that paints a box around the target, maintains that box between subsequent video frames, geolocates the target using UAS telemetry, and automatically directs the UAS to follow the selected target (see Fig. 10). Position information for the target and UAS heading and speed are continuously estimated. Instead of having to control the UAS and the camera, the operator simply monitors the tracker to

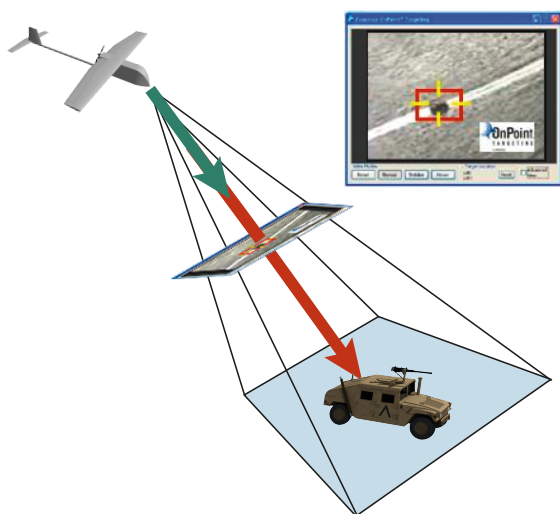


Figure 11. Using OnPoint, a UAS uses feature tracking to generate flight commands to engage (that is, fly into) a target.

make sure it maintains feature lock. OnPoint also provides real-time video stabilization, which improves the operator interface.

In addition to target tracking, OnPoint has a video-based engagement capability. Engagement is achieved by a computer vision-based controller within OnPoint, which directs the Procerus Kestrel autopilot, via high-rate pitch and roll commands, to impact the target designated within the ground station operator interface (see Fig. 11). During the engagement, the operator has the ability to adjust the aimpoint using the cursor or to abort the engagement. These features are important for a weaponized UAS. The military requires a man in the loop for this type of operation. They want a human to make the positive identification of the target, the target engagement decision, and, if necessary, the decision to abort.

Simultaneous Localization and Mapping

In addition to utilizing MLA and OnPoint to direct the flight paths of the UAS, we investigated a guidance and navigation scheme for operating in GPS-denied environments. The scheme uses a state estimation approach called SLAM.¹⁹⁻²¹ In general, SLAM uses sequential observations of stationary environmental landmarks to construct a relative map of a vehicle’s local environment while concurrently localizing the vehicle within the generated map. Therefore, by coupling the landmark states with the vehicle states in a state estimation filter, the vehicle’s inertial navigation system drift errors can be estimated.

Historically, SLAM has been used for robotic navigation in GPS-denied environments. The SLAM approach investigated by APL, however, is tailored to meet the specific challenges imposed by a small aircraft navigating an urban environment—namely, the use of an optical sensor and limited computational resources. Imagery from the optical sensor is processed to track 2-D

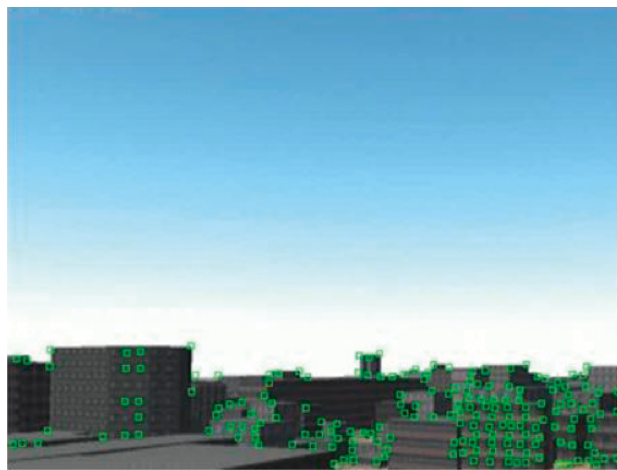


Figure 12. Tracked feature points.

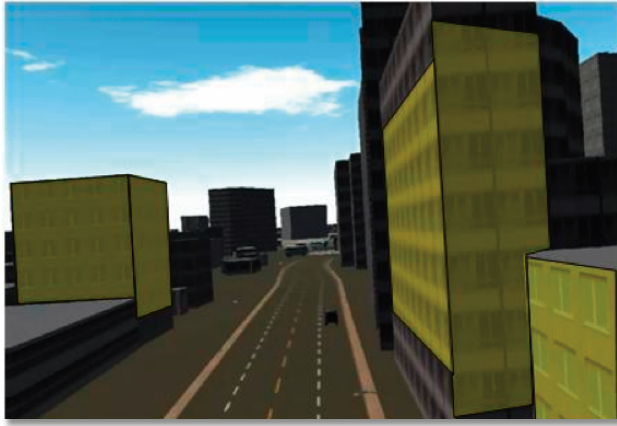


Figure 13. Geometric primitives.

feature points (Fig. 12) by using standard image processing approaches.²² These tracked feature points are poor landmarks in terms of the SLAM estimation problem because they are not necessarily observable from disparate vantage points (because of lighting conditions and occlusions), making data association problematic. Additionally, the resulting map would be a point-cloud representation of the environment, which would increase the computational complexity because of the large number of potential landmarks in the environment.

The SLAM approach addresses these issues by first computing the 3-D location of tracked feature points using a structure-from-motion approach.²¹ Structure-from-motion exploits the camera's epipolar geometry as it moves through the scene and can incorporate the vehicle's motion information provided by the inertial measurement unit. Lastly, the computed 3-D feature points are clustered into geometric primitives typically found in structured, urban environments, such as planes, edges, and corners (Fig. 13). This dimensionality-reduction step produces a map that is less computationally burdensome and is composed of landmarks that are easily reobservable with an optical sensor.

Other Payloads

Payload size, weight, and power are very limited on the small UASs. Typical spare payload weight is less than 2 lb (0.9 kg), and the available space depends on the UAS configuration. Because of these vehicles' small size, there is a significant trade-off between additional payload weight and vehicle endurance. Most if not all of the small UASs were designed to carry a sensor (EO, IR, and/or synthetic aperture radar) and communicate the sensor data to the ground station; thus, the only payload is the sensor and radio. The remaining available weight is usually allocated to batteries or fuel to maximize endurance. Because of the importance of imagery to the UAS operators, other payloads are sometimes added

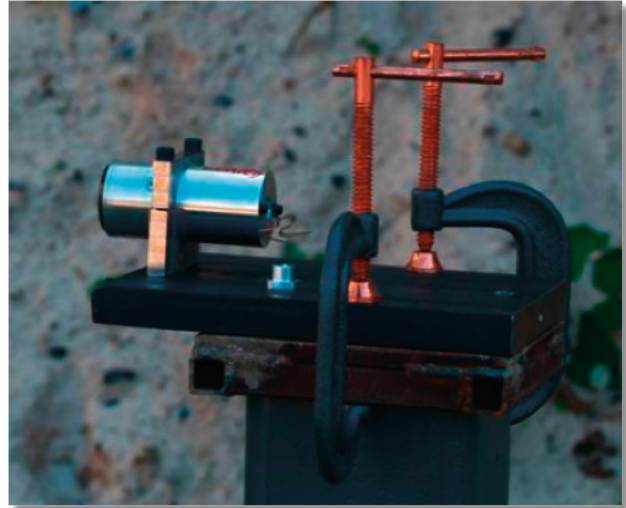


Figure 14. Small UAS-compatible warhead.

at the expense of batteries or fuel, hence the trade-off between payload and endurance.

Some additional payloads being integrated on small UASs include warheads,²³ laser designators, chemical/biological sensors,^{24,25} and various nonlethal payloads (e.g., smoke or flash bang devices).

To address the IR&D challenge of developing a warhead small enough to be carried by a small UAS but lethal enough to eliminate personnel and disable lightly armored vehicles, APL partnered with Custom Analytical Engineering Solutions (CAES) to design a 0.64-lb (290-g), 2-in.-diameter \times 2.64-in.-long (5.08-cm-diameter \times 6.7-cm-long) blast fragmentation warhead (Fig. 14). APL and CAES chose a directional warhead design that achieved the desired fragment density and velocity while minimizing the weight. The directional warhead also minimizes the area of lethal effects, reducing the probability of collateral damage. The fragment pattern density and area of lethal effect are controlled by the shape of the warhead faceplate. This warhead design is flexible and can be optimized for given fragment density and area requirement (as driven by the target type). The warhead is seeded with approximately 84 12-grain (0.778-g) tungsten cubes that are sized for defeat of soft and lightly armored targets. Tungsten is used because of its density, which contributes to more lethal shrapnel.

DEMONSTRATIONS

Tactical Network Topology 2007

In 2007, APL and Procerus Technologies conducted a flight demonstration of CHK UASs performing all elements of the kill chain.²⁶ In this experiment, multiple hunter UASs, operated by APL, autonomously self-configured to search a road network for a suspicious ground



Figure 15. Killer UAS engagement of a moving target.

vehicle using APL's onboard MLA algorithms. The hunter UASs shared their locations and the grids that had been searched over the Persistent Systems Wave Relay radios. When the tracked ground vehicle was found, the hunter UASs tracked it using the OnPoint video-based engagement capability. After the hunter UAS operator designated the vehicle hostile, a dedicated killer UAS, operated by Procerus, attacked the hostile vehicle using the Procerus video-based engagement application.

For this experiment, the video-based feature tracking used for both vehicle tracking and engagement was manually initiated by an operator who also monitored the automatic feature tracking and reinitialized it or intervened with manual feature tracking when necessary, depending on the quality of the transmitted video. With CHK, the hunter UASs can maintain track of the target through the engagement by the killer and can provide immediate battle damage indication to the UAS operator. The MLA algorithms enable cooperation between the multiple hunter and killer UASs and control by two operators.

Three low-cost UASs were used in the CHK UAS flight demonstration. The two hunters were Procerus Unicorn UASs with gimballed EO cameras. The hunter UASs autonomously self-configured to search for the hostile vehicle using MLA algorithms on an onboard processor and a mesh-network radio modem for plane-to-plane communications. The killer was the Procerus Miracle UAS with a fixed forward-mounted EO camera. Although the killer did not utilize an onboard MLA processor, it did receive flight commands from

the MLA algorithms via its ground station.

The UASs used in this demonstration were research platforms; the autonomy, tracking, and engagement technologies demonstrated were used subsequently with other UASs. The experiment was a success. The hunter UASs were able to consistently find, fix, track, and target a high-mobility multipurpose wheeled vehicle (Humvee) driving 10–20 mph (4.5–9 m/s). A typical issue experienced in the field is an unacceptably high probability of sensor-to-track misassociation. APL mitigated this issue by collocating the hunter and killer operators, allowing them to compare videos from the

respective UASs and verify that they were tracking and engaging the same target. On multiple runs, the killer UAS passed within a lethal distance—20 ft (6.1 m)—of the moving Humvee target (Fig. 15) while the hunter UAS streamed real-time video of the engagement for battle damage assessment by the operator.

Ft. Benning McKenna MOUT Facility 2009

We also demonstrated the ability of a group of cooperating small UASs to execute the entire kill chain at the McKenna MOUT urban warfare training facility at Ft. Benning, Georgia. APL's MLA algorithms directed the flight path and sensor pointing of the Prioria Maveric



Figure 16. Hunter UAS location of personnel targets.



Figure 17. Hunter UAS location of a moving vehicle target.

hunter UAS. During testing at the McKenna facility, the Maveric found both personnel (Fig. 16) and moving vehicle targets (Fig. 17).

APL used the feature tracker software to geolocate and track the targets. The geolocated position of the target was used as an attraction in APL's MLA logic to cue the killer UAS to the target's position. The APL and Prioria engineers also observed the MLA software deconflicting the flight paths of the Maveric and the killer UAS while they were cooperating to execute the kill chain. Once the target was in the killer UAS's video, the killer UAS operator used the video-based engagement logic to engage the target. Although the killer UAS suffered a mishap during the first end-to-end execution of the entire kill chain, the Procerus OnPoint software running for the first time on a video processing unit on board the killer UAS did successfully engage a dummy human target accurately enough for the small UAS-compatible warhead to be effective during the demonstration (Fig. 18).



Figure 18. Killer UAS engagement of a human-sized target.

Joint Expeditionary Forces Experiment 2010

In FY2010, the Air Force GCIC selected APL to participate in JEFX 10. Specifically, GCIC and the Navy Second Fleet sponsored APL to demonstrate convoy protection with a group of CHK UASs. In this experiment, APL teamed with the Army Aviation and Missile Research Development and Engineering Center Small UAS Laboratory (which works directly for the Army Small UAS Program Office) and performed the demonstration with three Raven UASs as hunters. To protect the convoy, APL created a road network search behavior for the hunter Raven's fixed, side-looking camera. The hunter search area automatically moved along the road network ahead of the convoy position. During the scenario, the convoy received an intelligence report of a potential threat location. In response, the hunter Ravens conducted an "auction" to determine which Raven investigated the threat and which Ravens continued performing the road network search, which is a modification of the area search behavior demonstrated during the IR&D effort. During the auction, each Raven "bid" on the task associated with investigating the threat. The Raven with the optimal sensor/target pairing had more points to bid and "won" the auction. This scheme allows some degree of task optimization within the MLA framework. Once the threat was detected by one of the hunter Ravens, the same video tracking and geolocation logic provided target coordinates to attract the other hunter Ravens and, ultimately, the killer UAS. After the threat was identified as hostile, the convoy stopped and launched the killer UAS, which attacked the target with the same video-based engagement logic. The find, fix, track, and target portion of the kill chain was demonstrated several times during the weeklong experiment (Fig. 19). As a result of ground control station problems, the engagement portion was demonstrated only on the final day, when the APL and Army Aviation and Missile Research Development and

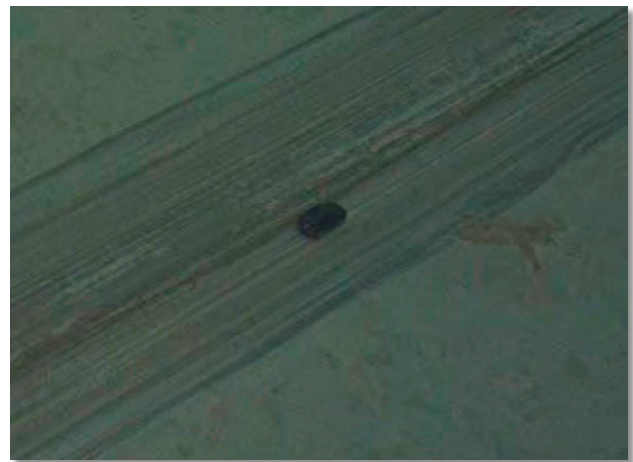


Figure 19. A Raven UAS tracking a target sport utility vehicle.



Figure 20. Killer UAS engaging a target sport utility vehicle.

Engineering Center team successfully engaged a fixed threat vehicle (Fig. 20).

The team was not successful in engaging an approaching threat vehicle. The surrogate killer UAS took too long to launch and was too slow to engage the threat before it reached the convoy. In addition to executing the kill chain, APL reformatted all the hunter Raven video into the predator format (MPEG2/Key Length Value) and sent it along with cursor-on-target messages of convoy, threat, and hunter UAS positions to the local C2 node. The video and cursor-on-target messages were then converted to Link 16 track format in the C2 node and broadcast to the local tactical aircraft via the Link 16 military tactical data exchange network. In the postexperimental data analysis, the GCIC

assessors determined that the target location errors of the reported threat positions were typically 50–150 m (164–492 ft), which is sufficient for tactical aircraft target cueing. According to the GCIC final assessment report,²⁷ “As an experiment, technical assessment, and proof of concept demonstration at JEFX 10-3 it was very successful in validating the CHK software and convoy protection concept in an irregular warfare environment and provided very valuable experience and data for John Hopkins University [Applied Physics Laboratory] developers. Further development and experimentation is highly desirable.”

Warhead Testing at CAES 2009

APL successfully demonstrated the lethality of a small UAS-compatible warhead. Two sets of tests were conducted at the CAES warhead test arena. The first test set involved witness panels to assess the warhead fragment patterns. The second test set assessed the lethality of the warhead against a realistic target. All tests were conducted with the warhead 15–20 ft (4.6–6.1 m) from the target. As part of the warhead evaluation, two different warhead faceplates were tested to determine the relationship between concavity of the faceplate and dispersion of the tungsten cubes. Witness panel tests confirmed that the concave faceplate yielded a more focused pattern than did the flat faceplate. Warhead lethality was demonstrated against a cargo van, shown in Fig. 21. In both the flat and the concave warhead faceplate tests, fragments passed completely through the vehicle and impacted the concrete of the test arena behind the van. As expected, the flat warhead yielded a more dispersed pattern [32 fragments or cubes in a 24-in. (0.6-m) circle] than did the concave warhead [60 fragments or cubes in an 11-in. (0.28-m) circle]. Fragment speeds were computed to be approximately 3200 ft/s (975 m/s).



Figure 21. Warhead lethality test results.

CONCLUSION

On multiple occasions, we successfully demonstrated the concept of CHK UASs executing the entire kill chain against a variety of targets. The successful IR&D demonstrations in 2007 and 2009 led the GCIC and Navy Second Fleet to fund participation in JEFX 10, which allowed assessors from the Joint Fires Integration

and Interoperability Team to evaluate the CHK concept using fielded UASs in an operationally relevant scenario. The positive feedback from the independent assessors indicated that the approach of developing and demonstrating CHK on research UASs in a benign environment, followed by demonstration of additional capabilities on fielded UASs in a realistic environment, was successful.

In addition, APL developed or obtained and then integrated technologies that enable successful engagement of a moving target in an urban environment by a small weaponized UAS. We addressed the challenge of a complicated, urban aerodynamic environment by developing a high-fidelity simulation to characterize this environment and by developing a small UAS-compatible wind sensor to measure the environment and give advance warning to the UAS. We leveraged MLA and the MANET communications topology to mitigate the difficulty of maintaining reliable communications. To address the challenges associated with GPS navigation in the urban canyon, we envisioned the use of optical guidance schemes: SLAM to supplement GPS for navigation and OnPoint for target tracking and engagement. During the IR&D effort, SLAM was only partially developed, but OnPoint was successfully used during all three CHK demonstrations. Finally, APL and CAES developed a small UAS-compatible, directional warhead and demonstrated its lethality and the ability to control the fragment pattern.

This technology has important applications for urban warfare, which is often the most costly in terms of troops, equipment, and collateral damage. As mentioned in the introduction to this article, there is a need to engage moving targets in an urban setting. CHK UASs mitigate some of the issues associated with current air-launched weapons. It is possible to maintain track custody of the target from ID to engagement. The assets are organic to the local commander and can be used quickly, their use of feature tracking attempts to minimize the problem of track misassociation, and the small warhead and video guidance with an operator in the loop minimize the probability of collateral damage.

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