Organic Persistent Intelligence, Surveillance, and Reconnaissance

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Organic Persistent Intelligence, Surveillance, and Reconnaissance (OPISR) is a visionary, game-changing approach to intelligence, surveillance, and reconnaissance. OPISR is able to significantly reduce the time required to obtain and distribute relevant intelligence to the frontline warfighter. OPISR is a novel combination of distributed image processing, information management, and control algorithms that enable real-time, autonomous coordination between ad hoc coalitions of autonomous unmanned vehicles, unattended ground sensors, and frontline users. In September 2011, a prototype OPISR system was demonstrated with more than 12 unmanned vehicles and unattended ground sensors supporting three users.

INTRODUCTION

In the spring of 1940, the combined French, British, Dutch, and Belgian forces outnumbered their German counterparts in troops, mechanized equipment, tanks, fighter planes, and bombers. The Me 109E German fighter aircraft was roughly equivalent to the British Spitfire, and the French Char B1 tank was superior to the German Panzer III. In addition, the Allies were fighting on their home soil, which greatly simplified their logistics. Yet in less than 6 weeks, the Belgians, Dutch, and French surrendered to the Germans, and the British retreated across the English Channel. Even though the Allies had superior equipment and larger forces, they were defeated by the Germans, who employed *Auftragstaktik*, a command and control technique that enabled "edge" warfighters to directly coordinate on tactical decisions by using modern communications equipment (during World War II, this was radio). Allied forces were forbidden to use radio because it "wasn't secure," and Allied maneuver decisions were made by generals at headquarters and based on hand-couriered reports. German decisions were made on-the-fly by Panzer III commanders and Ju 87 (Stuka) pilots conversing over the radio. By the time the French commanders met to decide what to do about the German advance, Rommel and Guderian's Panzers had traveled more than 200 miles and reached the English Channel.

As demonstrated repeatedly in military history, including the German advance in 1940, the speed at which battlefield decisions are made can be a deciding factor in the battle. A process model that describes military command and control is the observe, orient, decide, act (OODA) loop described by Boyd (Fig. 1).[1] Boyd shows that, in military engagements, the side that can "get inside the opponent's OODA loop" by more rapidly completing the OODA cycle has a distinct advantage. In their influential study "Power to the Edge: Command . . . Control . . . in the Information Age," Alberts and Hayes[2] use the term *agility* to describe an organization's ability to rapidly respond to changing battlefield conditions. Modern warfare case studies, such as studies of the Chechens against the Russians, and studies of not-so-modern warfare, such as Napoleon at Ulm, indicate that agile organizations enjoy a decisive military advantage. Alberts and Hayes point out that a common feature of agile organizations is an empowerment of frontline forces, referred to as *edge* warfighters. Commanders facilitate organizational agility by exercising "command by intent," through which commanders provide abstract goals and objectives to edge warfighters who then make independent decisions based on these goals and their own battlefield awareness. This empowerment of edge warfighters reduces the OODA loop at the point of attack, providing the desired agility.

A distinguishing characteristic of the conflicts in Afghanistan and Iraq is the explosive growth in the use of unmanned vehicles. Between the first and second Gulf wars, unmanned vehicles transitioned from a novelty item to an indispensable component of the U.S. military. Field-deployable organic unmanned vehicles such as the iRobot Packbot and the AeroVironment Raven are essential equipment for the modern warfighter. The agility provided by field-deployable vehicles comes at a cost—the use of field-deployable units increases logistics and workload demands on frontline forces. When compared with larger unmanned vehicles, field deployable units offer limited sensing and time-on-target capabilities. Medium-sized vehicles, such as the Insitu ScanEagle and AAI Shadow, offer longer time on station and more capable payloads. Medium-sized vehicles also do not make logistics or workload demands on the edge warfighter. Large unmanned vehicles such as the General Atomics Predator and Northrop Grumman Global Hawk offer still more capable payloads and increased time on station and also do not increase edge warfighter logistics or workload. However, providing the edge warfighter timely access to intelligence products produced by medium and large vehicles is a challenge because medium- and large-sized unmanned vehicles produce massive amounts of data that are difficult to process and disseminate from centralized command posts. In fact, Ariel Bleicher reported:

> In 2009 alone, the U.S. Air Force shot 24 years' worth of video over Iraq and Afghanistan using spy drones. The trouble is, there aren't enough human eyes to watch it all. The deluge of video data from these unmanned aerial vehicles, or UAVs, is likely to get worse. By next year, a single new Reaper drone will record 10 video feeds at once, and the Air Force plans to eventually upgrade that number to 65. John Rush, chief of the Intelligence, Surveillance and Reconnaissance Division of the U.S. National Geospatial-Intelligence Agency, projects that it would take an untenable 16,000 analysts to study the video footage from UAVs and other airborne surveillance systems."[3]

If intelligence, surveillance, and reconnaissance (ISR) information from medium- and large-scale unmanned vehicles could be processed and distributed in time, these vehicles could potentially provide significant ISR capability to the edge warfighter. For the edge warfighter to take advantage of the ISR capability represented by these assets, information relevant to that specific warfighter must be gleaned from the mass of information available and then must be presented to the warfighter in a timely manner. This presents a challenge because crews analyzing UAV payload data (far fewer than Rush's 16,000 analysts) are not apprised of the changing tactical needs of all warfighters, nor do the warfighters have the access or the time required to select and access data from UAV sources. Currently, operations centers are used to gather and disseminate information from persistent ISR assets. This centralized information management process introduces a delay between the observation and transmission to the warfighter, which reduces force agility and operational effectiveness. Although U.S. soldiers are empowered to operate on command by intent, their ISR systems are all too frequently centralized systems reminiscent of the French command structure. For U.S.

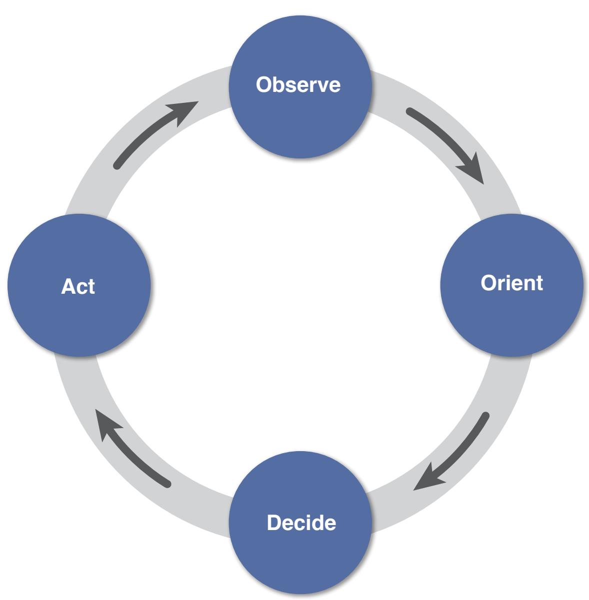

Figure 1. Boyd's OODA cycle models the military decision-making process. Military organizations that perform their OODA cycle more rapidly than opponents gain a substantial competitive advantage.

forces to become fully agile, the ISR systems supporting U.S. soldiers must be as agile as the soldiers they support, and APL has developed a system to do just this. This system is Organic Persistent Intelligence, Surveillance, and Reconnaissance (OPISR), an ISR infrastructure that provides the rapid response of organic ISR systems with the breadth and staying power of persistent ISR systems.

THE OPISR SYSTEM

OPISR is a software and communications subsystem that, when added to an ISR asset such as an unmanned vehicle or unattended sensor, supports the rapid, autonomous movement of information across a tactical force. As shown in Fig. 2, warfighters interact with OPISR as a system. When using OPISR, warfighters connect into the OPISR "cloud," task OPISR with mission-level ISR needs, and are subsequently provided with the intelligence they need. This capability provides intelligence directly to the warfighter without requiring the warfighter to personally direct, or even know about, the OPISR assets gathering the information. OPISR is autonomous. As a system, OPISR seeks out relevant information, pushing key tactical information directly to impacted soldiers in real time. OPISR is capable of rapidly managing large, complex, dynamic situations because it uses a decentralized, ad hoc organizational structure. Systems that use decentralized structures such as OPISR are known to be more effective at the timely coordination of complex systems. An explanation of why decentralized command and control systems can provide more rapid response than centralized systems is found in "On Optimizing Command and Control Structures"[4] by Scheidt and Schultz. OPISR tracks the location and ISR needs of all Blue forces, maintaining a contextual awareness of the warfighter's current tactical needs.

As relevant tactical information becomes available, OPISR presents it directly to the warfighter through an intuitive handheld device. The information requirements that are used to determine information relevance are defined by the warfighter through the same handheld interface. This interface supports abstract queries such as (*i*) patrol these roads; (*ii*) search this area; (*iii*) provide imagery of a specific location; (*iv*) track all targets of a specific class on a specific route or location; or (*v*) alert me whenever a threat is identified within a certain distance of my location. Information that matches these queries is sent by the system to the handheld

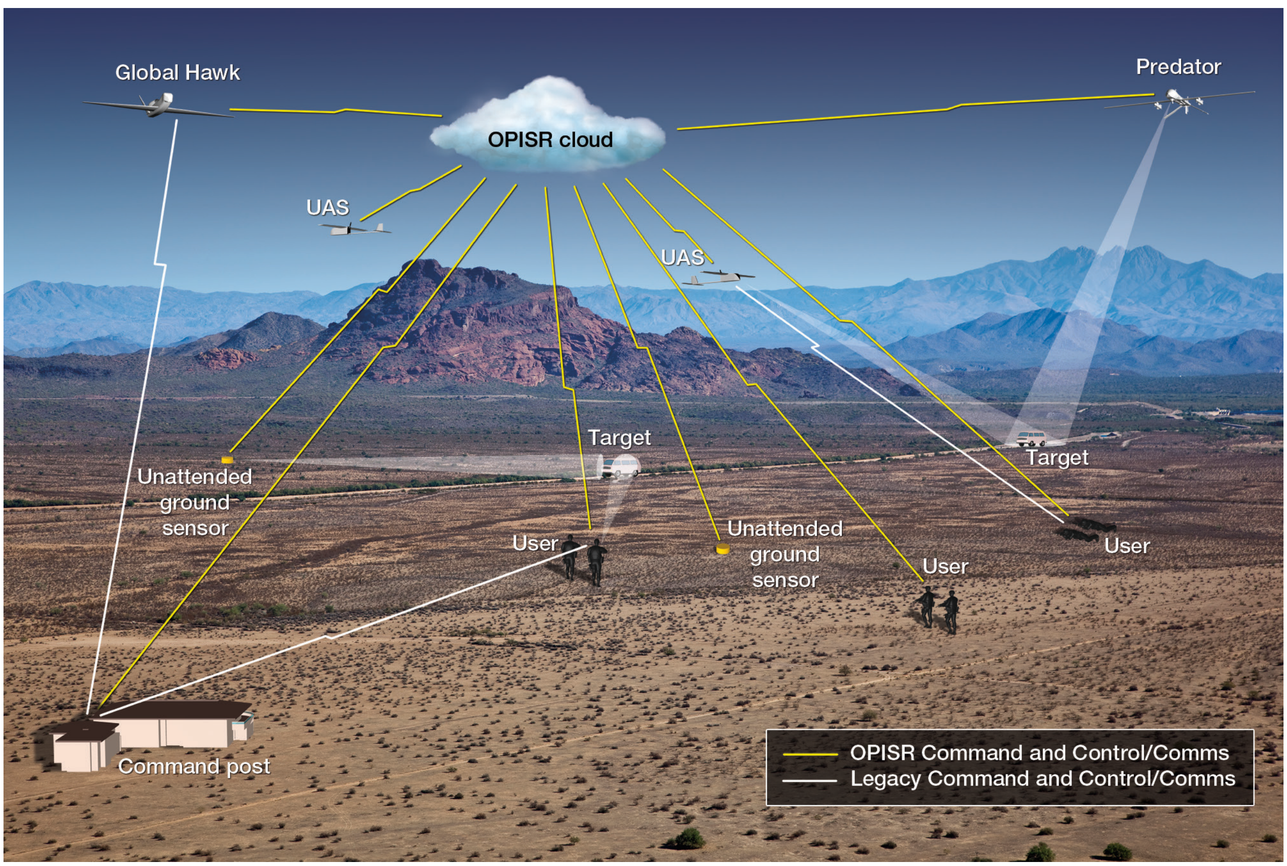

Figure 2. OPISR's concept of operation allows UAVs of various sizes to communicate with each other, with users, and with commanders through an ad hoc, asynchronous cloud. The cloud communicates goals from users to vehicles and sensor observations from users to vehicles. Comms, communications.

device. The handheld interface provides a map of the surrounding area that displays real-time tracks and detections and imagery metadata. The imagery metadata describes, at a glance, the imagery available from the surrounding area. OPISR-enabled vehicles are autonomous—if the information required by the warfighter is not available at the time the query is made, OPISR unmanned vehicles autonomously relocate so that their sensors can obtain the required information. OPISR-enabled unmanned vehicles support multiple warfighters simultaneously, with vehicles self-organizing to define joint courses of action that satisfy the information requirements of all warfighters.

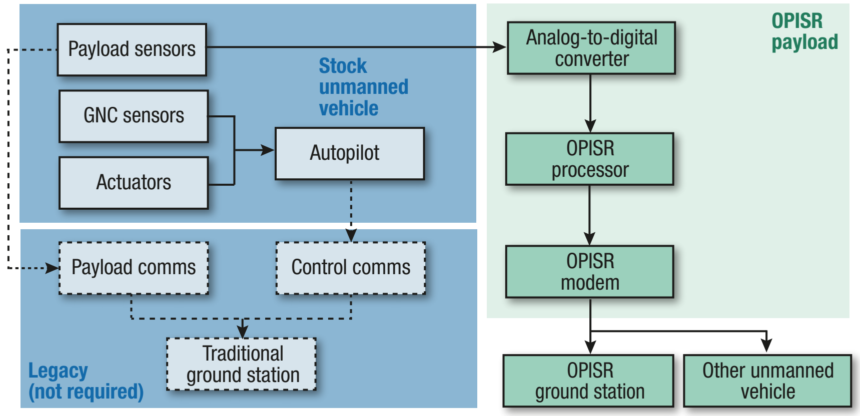

Figure 3. OPISR's hardware architecture is based on a modular payload that can be fitted onto different types of unmanned vehicles.

Because warfighters are required to operate in harsh, failure-prone conditions, OPISR was designed to be extremely robust and fault tolerant. OPISR's designers viewed communications opportunistically, designing the system to take advantage of communications channels when available but making sure to avoid any/all dependencies on continuous high-quality service communications. Accordingly, all OPISR devices are capable of operating independently as standalone systems or as ad hoc coalitions of devices. When an OPISR device is capable of communicating with other devices, it will exchange information through networked communications and thereby improve the effectiveness of the system as a whole. However, if communications are unavailable, each device will continue to perform previously identified tasks. When multiple devices are operating in the same area, they will self-organize to efficiently perform whatever tasks warfighters have requested (devices are capable of coordinating their efforts even when they cannot communicate over a network if they are capable of observing each other through their organic sensors). Task prioritization is based on warfighter authority and warfighter-assigned importance.

OPISR Hardware

Off-the-shelf unmanned vehicles and unattended sensors can be incorporated into the OPISR system by adding the OPISR payload. As shown in Fig. 3, the OPISR payload consists of three hardware components: an OPISR processor that executes the OPISR software, an OPISR radio that provides communications to other OPISR nodes including OPISR's handheld interface devices, and an analog-to-digital converter that is used to convert payload sensor signals into digital form. Unmanned vehicles that have an onboard autopilot capable of providing stable flight can be modified to become autonomous vehicles by connecting the autopilot to the OPISR processor. When the vehicle is operating autonomously, the autopilot sends guidance and control (GNC) telemetry to the OPISR processor. The processor uses the GNC data to devise a continual stream of waypoints that are sent to the autopilot to follow. The OPISR processor also uses the GNC telemetry to produce metadata that are associated with the sensor data. The combined sensor data and metadata are then used by the OPISR system as a whole.

In service, unmanned vehicles frequently use separate communications channels for control and imagery. Because OPISR devices perform both image processing and control on board the device, these communications channels, and the traditional pilot ground station, are no longer required. In effect, OPISR devices are capable of operating fully independently of direct human supervision. Note that OPISR devices are still responding to warfighter requests; however, these devices accomplish this without requiring continuous communications with the warfighter being serviced. Although OPISR does not require traditional control and payload communications, OPISR devices do support these legacy capabilities. Because the OPISR nodes communicate over a separate channel, OPISR functionality may be provided in tandem with traditional control. This is in keeping with the OPISR dictum that OPISR be an entirely additive capability; unmanned vehicle owners lose no functionality by adding OPISR. However, OPISR vehicles are responsive to commands from human operators and will, at any time, allow an authorized human operator to override OPISR processor decisions. Likewise, legacy consumers of information will still receive their analog data streams. Note that even when the OPISR processor is denied control by the UAV pilot, the OPISR system will continue to share information directly with edge warfighters as appropriate.

OPISR Software

OPISR is based on a distributed multiagent software architecture. Each software agent serves as a proxy for the device on which it is located, and all devices within OPISR have their own agents including unmanned vehicles, unattended sensors, and user interfaces. As shown in Fig. 4, each agent is composed of four major software components: a payload manager, which manages the sensor information from the device's organic sensors; a distributed blackboard, which serves as a repository for the shared situational awareness within the agent system; an agent communications manager, which manages the flow of information between agents; and a cSwarm controller, which determines a course of action for those devices that are capable of autonomous movement. All devices within the system, including the warfighter's handheld device, are peers within OPISR.

Distributed Blackboard

In the 1980s, Nii[5,6] described a method for multiagent systems to communicate with each other in an asynchronous manner called a blackboard system. Like their namesake in the physical world, blackboard systems allow agents to post messages for peer agent consumption at an indeterminate time. Each OPISR agent contains a personal blackboard system that maintains a model of the agent's environment. Three types of information are stored on each agent's blackboard: beliefs, metadata, and raw data. Raw data are unprocessed sensor data from a sensor within the OPISR system. Metadata is information that provides context to a set of raw data including sensor position, pose, and time of collection. Beliefs are abstract "facts" about the current situation. Beliefs include geospatial artifacts such as targets, Blue force locations, or search areas. Beliefs can be developed autonomously from onboard pattern recognition software or data fusion algorithms or asserted by humans. Mission-level objectives, the goals that drive OPISR, are a special class of belief that must be produced by a human. The storing and retrieval of information to and from agent blackboards is performed by the blackboard manager. The blackboard manager accepts, stores, and retrieves information from sensors on board the agent's device, from other agents, or from pattern recognition/data fusion software contained within the agent. The integrity of the data stored on the blackboard is maintained by a truth maintenance system (TMS). The TMS performs two functions. First, the TMS resolves conflicts between beliefs. The simplest form of conflict resolution is accomplished by storing the belief with the more recent time stamp. For example, one belief might posit that there is a target at grid [*x*, *y*] at time t_0, and a second belief might posit that there is no target at grid [*x*, *y*] at time t_1. More sophisticated conflict-resolution algorithms are scheduled to be integrated into OPISR in 2012. The second TMS function is the efficient storage of information within the blackboard. When performing this task, the TMS caches the most relevant, timely information for rapid access and, when long-lived systems generate more data than can be managed within the system, the TMS removes less important information from the blackboard. For caching and removal, the importance of information is defined by the age, proximity, uniqueness, and operational relevance.

Agent Communications Manager

Coordination between agents is asynchronous, unscheduled, and completely decentralized, as it has to be, because any centralized arbiter or scheduled communications would introduce dependencies that reduce the robustness and fault tolerance that is paramount in the OPISR design. Because agent communication is asynchronous and unscheduled, there is no guarantee that any two agents will have matching beliefs at an instance of time. Fortunately,

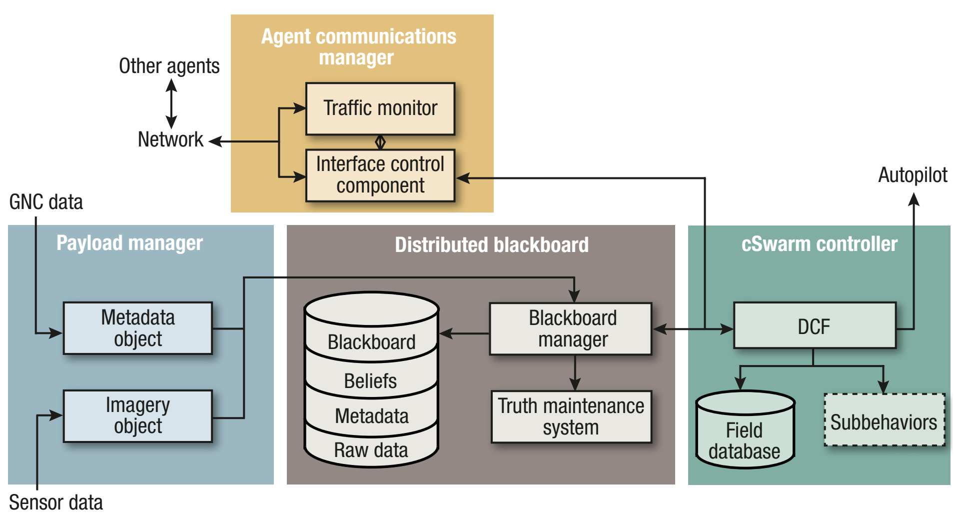

Figure 4. OPISR software architecture contains four major elements: the payload manager generates new "beliefs" from sensor observations, the distributed blackboard maintains situational awareness by aggregating beliefs from the on- and offboard observations, the agent communications manager exchanges beliefs between other vehicles and users, and the cSwarm controller devises a course of action based on beliefs. DCF, Dynamic co-fields.

the control algorithms used by OPISR are robust to belief inconsistencies. Cross-agent truth maintenance is designed to the same criteria as agent-to-agent communications: Information exchanges between agents seek to maximize the consistency of the most important information but do not require absolute consistency between agent belief systems. Information exchange between agents is performed by the agent communications manager. When communications are established between agents, the respective agent communications managers facilitate an exchange of information between their respective blackboards. When limited bandwidth and/or brief exchanges limit the amount of information exchanged between agents, each agent communications manager uses an interface control component to prioritize the information to be transmitted. Information is transmitted in priority order, with priority being determined by information class (beliefs being the most important, followed by metadata), goal association (e.g., if a warfighter has requested specific information, then that information is given priority), timeliness, and uniqueness.

Autonomous Control: cSwarm

OPISR's autonomous unmanned vehicles use an approach called dynamic co-fields (DCF), also known as stigmergic potential fields, to generate movement and control actions. DCF is a form of potential field control. Potential field control techniques generate movement or trigger actions by associating an artificial field function with geospatial objects. In OPISR, the objects that are used to derive fields are beliefs. Fields represent some combination of attraction and/or repulsion. By evaluating the fields for all known beliefs at a vehicle's current location, a gradient vector is produced. This gradient vector is then used to dictate a movement decision. Developed at APL in 2003,[7] DCF extends an earlier potential field approach called co-fields[8] by making the potential fields dynamic with respect to time and also making vehicle fields self-referential. Self-referential fields are fields that induce vehicle decisions that are generated by the vehicle's own presence. Adding these dynamic qualities is key to managing two well-known problems with potential field approaches: namely, the tendency of vehicles to become stuck in local minima and the propensity to exhibit undesired oscillatory behavior. As implemented in OPISR, DCF is used to cause specific behaviors such as search, transit, or track, as well as behavioral selection. The DCF algorithm is encoded in the cSwarm software module. All unmanned vehicles in OPISR execute cSwarm. DCF behaviors specific to unique classes of vehicle are produced by tailoring the field formula, which is stored in a database within cSwarm. OPISR autonomous unmanned vehicles are capable of a variety of behaviors including:

- Searching contiguous areas defined by warfighters
- Searching linear networks such as roads
- Transiting to a waypoint
- Blue force over-watch
- Target tracking
- Perimeter patrol
- Information exchange infrastructure, in which unmanned vehicles maneuver to form a network connection between an information source, such as an unattended sensor, and warfighters that require information on the source. Note that the warfighter is not required to specify this behavior; the warfighter needs only to specify the information need, and the vehicle(s) utilize(s) this behavior as a means to satisfy the need.
- Active diagnosis, in which vehicles reduce uncertain or incomplete observations through their organic sensing capabilities. For example, a UAV with a sensing capability that is able to classify targets will automatically move to and classify unclassified targets being tracked by a cooperating radar.

In addition to the mission-level behaviors described above, OPISR vehicles exhibit certain attributes within all behaviors. These universal attributes are:

- Avoiding obstacles or user-defined out-of-bounds areas
- Responding to direct human commands. OPISR unmanned vehicles are designed to function autonomously in response to mission-level objectives; however, when operators provide explicit flight instructions, OPISR vehicles always respond to the human commands instead of to the autonomous commands.

OPISR EXPERIMENTATION

The current OPISR system is the culmination of a decade-long APL exploration of autonomous unmanned vehicles. Key technical elements of the OPISR system were demonstrated in hardware-in-the-loop experiments as early as 2003. More than 20 hardware demonstrations have included the following: DCF,[9] the distributed blackboard,[10] delay-tolerant communications,[11] and simultaneous support for multiple end users.[12] As successful as these experiments have been, APL, prior to 2011, had not integrated the full suite of OPISR capabilities described in this article on a large, disparate set of vehicles. In September 2011, APL demon-

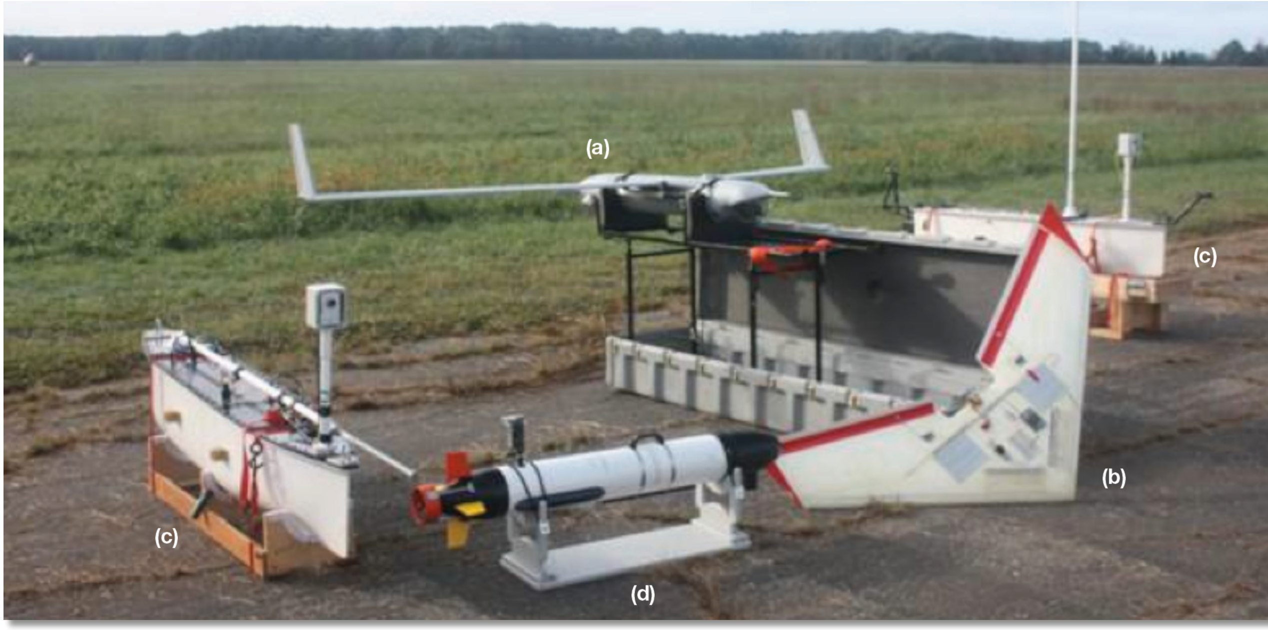

Figure 5. OPISR vehicles featuring (a) ScanEagle, (b) Unicorn, (c) surface vehicles, and (d) Iver2 undersea vehicle.

strated 10 OPISR-enabled vehicles working with three unattended ground sensors in support of three users. The demonstration employed air, ground, surface, and undersea ISR needs with surveillance being conducted under the water, on the water, and on and over land. The autonomous unmanned vehicles included three Boeing ScanEagles (Fig. 5a), three Procerus Unicorns (Fig. 5b), a Segway ground vehicle (Fig. 6), custom APL-developed surface vehicles (Fig. 5c), and an OceanServer Iver2 undersea vehicle (Fig. 5d). These vehicles used a wide range of payload sensors—including electro-optical, passive acoustic, side-scan sonar, and lidar sensors—to detect, classify, and track waterborne vehicles, land vehicles, dismounts, and mine-like objects. ISR tasking was generated by three proxy warfighters, two of which were on land and one of which was on the water. The requested ISR tasks required the use of all of the vehicle behaviors previously described.

Figure 6. OPISR's ground vehicles were Segway RMP 200s that were fitted with lidar, electro-optic, and passive acoustic sensors.

FUTURE WORK

In FY2012, APL is planning additional improvements to the OPISR system. Specific OPISR improvements include (*i*) the integration of more sophisticated data fusion techniques into the distributed blackboard, specifically upstream data fusion and closed-loop ISR, (*ii*) flight testing of autonomous behaviors that allow UAVs to form network bridges between remote sensors and users, (*iii*) introduction of advanced simulation-based test and evaluation techniques, and (*iv*) the integration of Exec-Spec into the OPISR framework and Exec-Spec flight testing. Exec-Spec is an autonomy system developed by APL for spacecraft control. In the OPISR–Exec-Spec integration, Exec-Spec will manage vehicle fault management and safety override functions.

CONCLUSION

The OPISR system is a framework that provides a capability through which numerous unmanned platforms simultaneously provide real-time actionable intelligence to tactical units; abstract, manageable situational awareness to theater commanders; and high-quality forensic data to analysts. APL has demonstrated an OPISR system that includes a distributed, self-localizing camera payload that provides imagery and positional metadata necessary to stitch information from multiple sources; a distributed collaboration system that is based on robust ad hoc wireless communications and agent-based data management; and a user interface that allows users to receive real-time stitched imagery from unmanned vehicles and that does not require users to directly control (or even expressly be aware of) the unmanned vehicles producing the imagery. OPISR is a bold vision that presents an innovative approach to ISR, an important enabler emphasized in the *Quadrennial Defense Review*[13] and other key policy documents, and gives the Laboratory an enhanced ability to help sponsors address future capability gaps in this critical area.

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