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Micro-Air Vehicle-Enabled Remote Environmental and Chemical Sensing (MAVERECS)

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U.S. Army Combat Capabilities Development Command Chemical Biological Center (DEVCOM CBC) was previously known as U.S. Army Edgewood Chemical Biological Center (ECBC).

14. ABSTRACT (LESS THAN 200 WORDS)

This final report summarizes the Micro-Air Vehicle-Enabled Remote Environmental and Chemical Sensing (MAVERECS)-enabling technology project. This project demonstrated environmental remote sensing by incorporating a chemical detection module (a miniaturized ion mobility spectrometer) and Gumstix computer (La Jolla, CA) into a compact module that was fully integrated into the T-Hawk unmanned aerial vehicle (UAV; Honeywell; Charlotte, NC) electronics. A software implementation of the chemical, biological, radiological, and nuclear (CBRN) common sensor interface was run on the Gumstix processor to demonstrate this standard interface technology on a working CBRN UAV platform. A real-time chemical contamination mapping capability was coded that output KML files directly into the UAV ground control station to display georeferenced detection “heat maps” that were readily exportable to any common operational environment, including the Joint Warning and Reporting Network. The fully functional MAVERECS system was operated on several sorties during the Sophos/Kydoimos (S/K) Challenge III event at Dugway Proving Ground, UT in August 2016, and it successfully detected several chemical simulant releases. Three T-Hawk platforms with integrated chemical and radiological sensing and real-time display and reporting capabilities were delivered to the Integrated Early Warning Advanced Technology Demonstration Technical Manager and to the Defense Threat Reduction Agency operational test range team.

15. SUBJECT TERMS

Chemical detection
Early warning
Contamination mapping
Real-time contamination visualization
Remote sensing
Unmanned aerial vehicle (UAV)
Chemical, biological, radiological, and nuclear (CBRN)
CBRN common sensor interface (CCSI)

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PREFACE

The work described in this report was authorized under the Enabling Technology project, program element numbers PE-0603648D8Z, BA-3 and PE-0902198D8Z, BA-5. This work was started in May 2015 and completed in October 2016.

At the time this work was performed, the U.S. Army Combat Capabilities Development Command Chemical Biological Center (DEVCOM CBC; Aberdeen Proving Ground, MD) was known as the U.S. Army Edgewood Chemical Biological Center (ECBC).

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of endorsement.

This report has been approved for public release.

Acknowledgments

The authors thank the Assistant Secretary of Defense for Research and Engineering office (Falls Church, VA) for supporting this Enabling Technology project. The authors wish to recognize the Defense Threat Reduction Agency Counterforce Systems Division (J9 CXS; Fort Belvoir, VA) for the investment that led to the compact Chemical Detection Module, which made the integration of this capability onto a compact airmobile platform possible.

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MICRO-AIR VEHICLE-ENABLED REMOTE ENVIRONMENTAL AND CHEMICAL SENSING (MAVERECS)

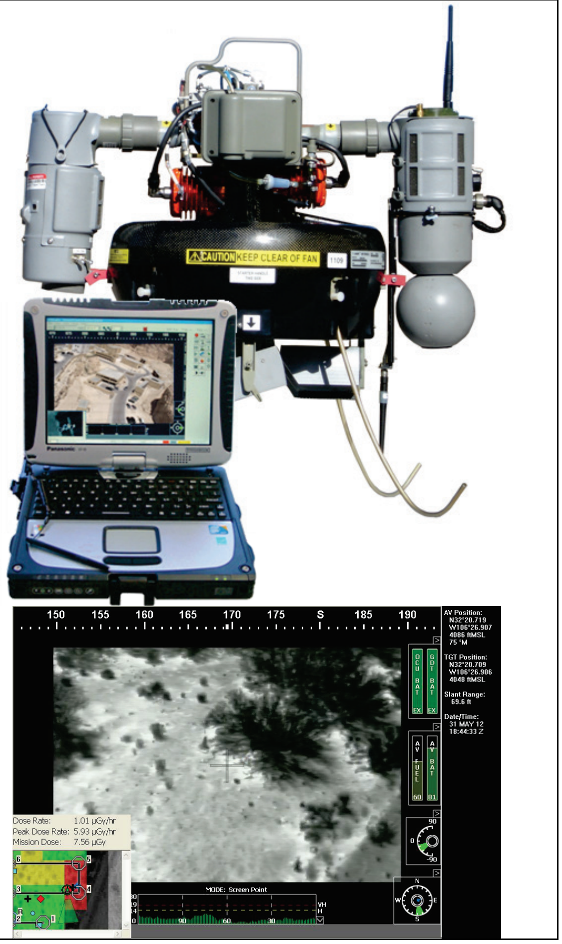
1. INTRODUCTION

The Micro-Air Vehicle-Enabled Remote Environmental and Chemical Sensing (MAVERECS) Enabling Technology (ET) project demonstrated the utility of small, autonomous unmanned aerial vehicles (UAVs) to the chemical contamination avoidance mission. The MAVERECS project revealed the unprecedented capability of UAVs to intercept plumes from suspected chemical agent attacks and to loiter or track a plume while generating real-time heat maps to inform DoD commanders of the nature and extent of contamination from such events. The efficacy of the small unmanned platform to quickly and nimbly generate situational awareness under such circumstances was clearly demonstrated during the Layered Sensing Initiative (LSI) at the Sophos/Kydoimos (S/K) Challenge III event at Dugway Proving Ground, UT in August 2016. Figure 1 depicts the T-Hawk (Honeywell; Charlotte, NC) UAV and its basic configuration specifications.

Physical
- Size: 24 in. diameter (with pods)
- 24 in. height
- Weight: 17.4 lb (dry)
- 19.6 lb (gross take-off weight)
- Fuel: gasoline–oil mix
- Fuel load: 2.2 lb (43 in.^{3})
- Backpackable

Performance
- Endurance: 50 min at sea level
- Climb rate: 25 ft/s
- Turn rate: ±30°/s
- Ceiling: 10,000 ft
- Speed: 40 knots
- Winds: 15 knots (take-off and landing)
- 20 knots (aloft)

Current Payloads
- High-definition Sony electro-optical (EO) (1920 × 1080 pixels) camera with 10× optical zoom, 40° horizonal field of view (HFOV)
- Combined EO/infrared (IR) gimbal
- Forward-looking infrared (FLIR) camera (640 × 480 pixels) with 2× digital zoom, 32° HFOV
- Modular interchangeable sensor packaging changeable in 15 s
- Store 240 min of sensor imagery (9,999 snapshots)



AV Position:
N32°20.719
W106°26.907
4086 ftMSL
75 °M

TGT Position:
N32°20.709
W106°26.906
4048 ftMSL

Slant Range:
69.6 ft

Date/Time:
31 MAY 12
18:44:33 Z

Dose Rate: 1.01 µGy/hr
Peak Dose Rate: 5.93 µGy/hr
Mission Dose: 7.56 µGy

Figure 1. T-Hawk specifications and capabilities (without chemical, biological, radiological, and nuclear [CBRN] sensor options).

The objectives of the MAVERECS ET project were as follows:

- Incorporate an environmental chemical sensor on a Micro-Air Vehicle (MAV) that is already equipped with a radiological sensor.
- Design a suitable air collection and sampling system and housing.
- Add chemical detection visualization to the T-Hawk organic digital data link ground control station in addition to existing radiological contamination visualization.
- Transition technology components and any techniques and procedures learned to emerging technology demonstrations, with the end goal being to inform and enhance remote CBRN and environmental sensing to accelerate this needed capability into a program of record.

These objectives were all met under this ET project. The environmental chemical sensor used is called the Chemical Detection Module (CDM; Figure 2). The CDM is a miniaturized version of the ion mobility spectrometer that is the functional component of the Joint Chemical Agent Detector (JCAD), which is the Chemical and Biological Defense Program's fielded tactical point chemical detection system. The CDM was previously developed with support by the Defense Threat Reduction Agency (DTRA; Fort Belvoir, VA). Of note is that the project team leveraged initial data visualization software from Honeywell (that had been developed in response to the Fukushima nuclear disaster) for the T-Hawk MAV equipped with an embedded A/N PDR-15 γ-ray and neutron detector. The U.S. Pacific Command (PACOM; now known as the U.S. Indo-Pacific Command) and Honeywell team named this radiological detection-enabled T-Hawk version the MAV-R variant. Continuing this naming convention, the team named the MAVERECS MAV equipped with both A/N PDR-15 radiological and CDM chemical detectors the MAV-CR variant.

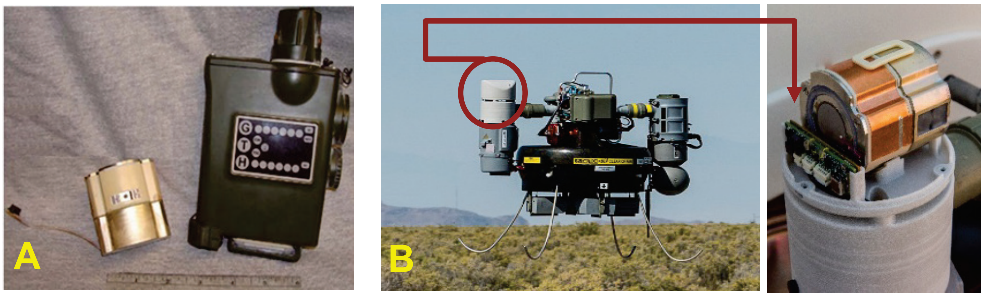
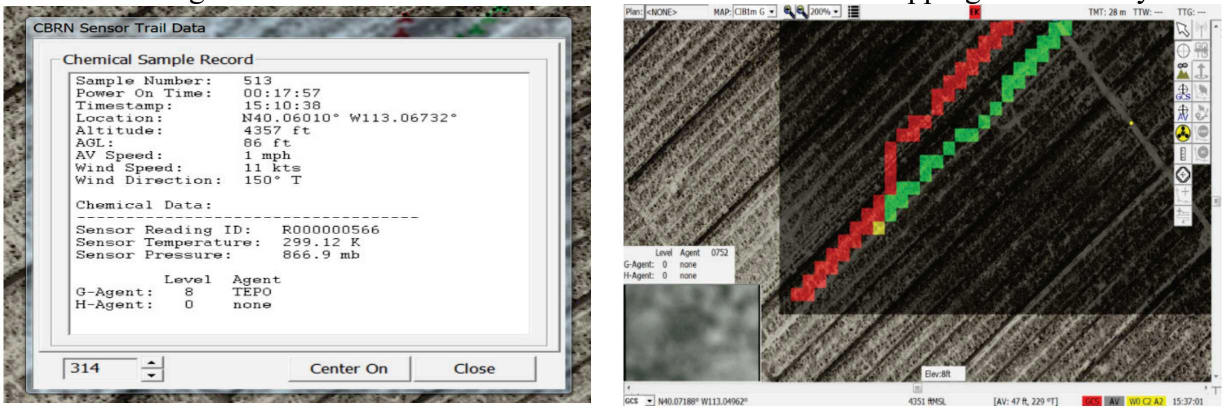


Figure 2. (A) CDM (at left) compared to the JCAD (at right); and (B) CDM integrated onto the T-Hawk avionics pod.

The MAVERECS technology set afforded test personnel the unprecedented capability (demonstrated at the 2016 S/K Challenge) to vector and loiter the mobile chemical sensor into the path of a plume that was presumptively targeted as a potential threat by nonspecific surveillance in the context of a layered sensing architecture. During the August 2016 trials, an event on the test grid was typically first observed by the ground surveillance radar and EO camera force protection system. The event consisted of a truck or trailer movement on the grid and culminated in a dissemination. In combat operations, the observation may include alerts from incoming rocket, artillery, or mortar rounds or even an incursion by a suspicious vehicle or person. Once a kinetic event occurs, be it an explosion or a dissemination, the location but not the makeup of the resulting plume is known. A networked, layered sensing architecture that is interoperable with the command and control system provides the framework for data interchange, so that the coordinates of the kinetic event can be immediately conveyed to the ground station of the airmobile sensing platform. This in turn cues the system to activate the UAV and transport the sensor to intercept the suspect plume. A feature of the architecture (and the UAV technology in particular) is the generation of a flight plan and the navigation of the platform to the coordinates provided with little or no man-in-the-loop operation. When the CDM onboard the MAV-CR records a chemical detection, the onboard Gumstix computer converts the signal into a CBRNE common sensor interface (CCSI) message that is conveyed through the MAV-CR's onboard communications system to the ground station, where it can be represented as a geospatial and temporal icon on the local map (Figure 3). The collection of geospatial detection messages obtained over the flight time of the system are then rendered as an exportable Keyhole Markup Language (KML) layer that can be integrated with the command and control common operational picture.



Chemical agent detection information

```
Sample Number:    513
Power On Time:    00:17:57
Timestamp:        15:10:38
Location:         N40.06010° W113.06732°
Altitude:         4357 ft
AGL:              86 ft
AV Speed:         1 mph
Wind Speed:       11 kts
Wind Direction:   150° T

Chemical Data:
-----------------------------------------
Sensor Reading ID:    R000000566
Sensor Temperature:   299.12 K
Sensor Pressure:      866.9 mb

            Level  Agent
G-Agent:      8    TEPO
H-Agent:      0    none
```

Detection heat-mapping functionality

Figure 3. MAVERECS ground control station CBRN visualization layer depicting geotagged KML file data (left) and real-time heat map features (right). Green indicates no chemical warfare agent (CWA) detected, yellow indicates suspected CWA, and red shows high confidence that higher levels of CWA are present. Each point can be clicked to bring up the georeferenced KML data.

During the August 2016 chemical release trials, the MAVERECS system successfully flew eight sorties in response to cues on the release of the chemical agent simulants triethyl phosphate (TEP) and methyl salicylate (MES) and one biological agent simulant. The MAVERECS team flew seven chemical detection sorties and one bioaerosol collection sortie. After adjusting for the transient nature of the suspect cloud location in the initial sortie, the MAV-CR successfully intercepted and recorded suspect chemical agent in the next five of five sorties. The seventh sortie was intended to detect ground contamination of a persistent chemical agent. Nighttime operational safety considerations and a limited 30 min mission time (due to fuel capacity) prevented thorough ground surveillance and indicated the need for an extended-duration flight capability.

After completion of the S/K Challenge III demonstration, the MAVERECS operational phase of the project was complete. The MAVERECS team delivered three residual MAV-CR systems configured to operate with an onboard CDM or radiological sensor to the Integrated Early Warning Advanced Technology Demonstration Technical Manager at U.S. Army Edgewood Chemical Biological Center (ECBC; Aberdeen Proving Ground, MD; now the U.S. Army Combat Capabilities Development Command Chemical Biological Center [DEVCOM CBC]) and to the DTRA operational test range team at Kirtland Air Force Base (Albuquerque, NM). An additional two MAV-R systems configured with the A/N PDR-15 γ-ray and neutron detector and a MAVERECS ground control station capable of chemical and radiological data collection and visualization were transferred to the Air Force Civil Engineering Center, CX Division (Tyndall Air Force Base, FL) to support their Rapid Airfield Damage Assessment System development efforts.

Lessons learned from the ET project include an emphasis on autonomous operation to minimize the burden of piloting the UAV and to maximize the responsiveness of the platform to intercept a suspect plume on cue when an event is detected by surveillance or force protection assets. The airmobile CDM afforded a responsive and agile relocatable sensor capability that provides three immediate benefits: (1) the ability to characterize the threat present should a chemical release occur, (2) the ability to loiter with and spatially and temporally track a threat plume, and (3) the ability to export plume data in a KML layer that can be rendered on any command and control common operational picture and can also be used to populate detection events in the Joint Warning and Reporting Network (JWARN) through the CCSI interface. Currently, the flight mission duration for tactical UAVs is approximately 30 min or less. This impinges on any system's capability to successfully survey an area of terrain at the ground level to look for potential surface chemical agent. A longer mission duration capability in tactical CBRN remote sensing platforms is clearly needed. The enhanced early warning capability provides a tangible benefit to operational commanders by ensuring a responsive interrogation of suspicious events to provide earlier detection and more accurate mapping of the downwind hazard than would be possible with stationary, prepositioned, unattended ground sensors.

2. CDM INTEGRATION

During the integration of the CDM onto the T-Hawk MAV, several constraints and conditions were considered. The MAV payload capacity was relatively small (approximately 1 lb), which limited the options for interfacing the CDM. The compact Gumstix single-board computer served as a key enabler for the integration and allowed for the necessary sensor readout software to be incorporated into the avionics pod (Figure 4).

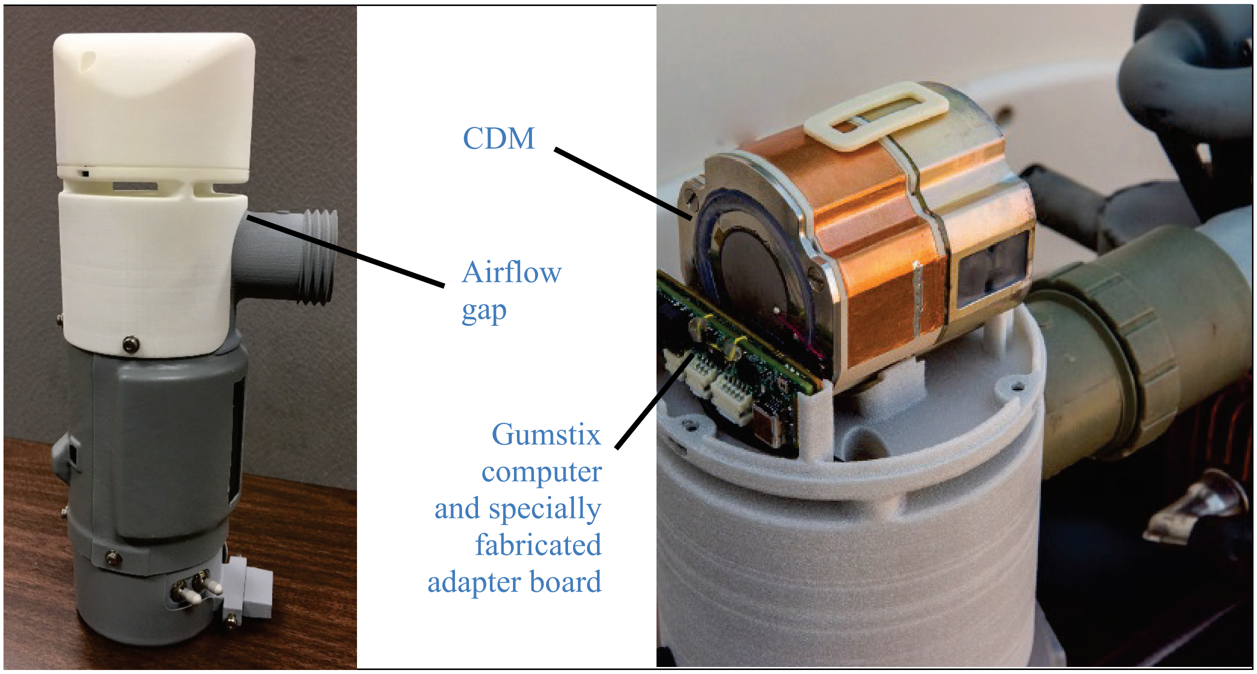


Figure 4. Integration housing for the CDM and Gumstix computer.

To interface the CDM to the avionics pod, a specially fabricated adapter board was designed that enabled the onboard power system to power both the Gumstix and the CDM itself. The adapter board served as a data interface between the Gumstix and the T-Hawk data and communications system and connected the CDM with the ground station (Figure 5). A custom cable assembly that connected the CDM to the MAV's Global Positioning System (GPS) data and power lines was also specially fabricated.

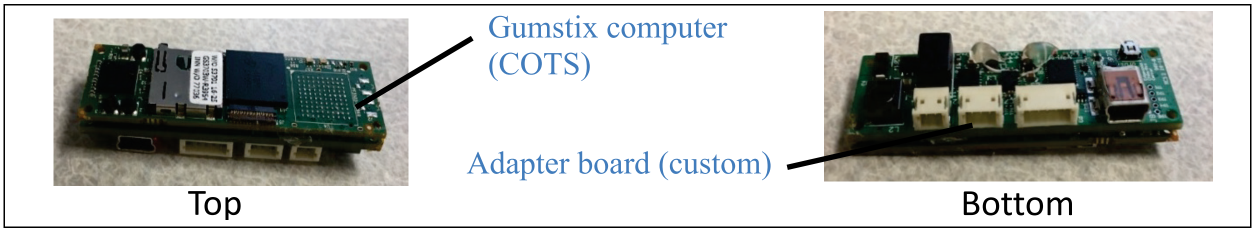


Figure 5. Commercial off-the-shelf (COTS) Gumstix computer interface and custom adapter board.

The airflow inlet of the CDM housing was designed and tested to ensure consistent omnidirectional air sampling by the CDM while it was mounted on the MAV-CR. Computational fluid dynamics (CFD) modeling enabled optimization of the housing design to accommodate the CDM inlet and outlet. Figure 6 shows an example of the CFD results.

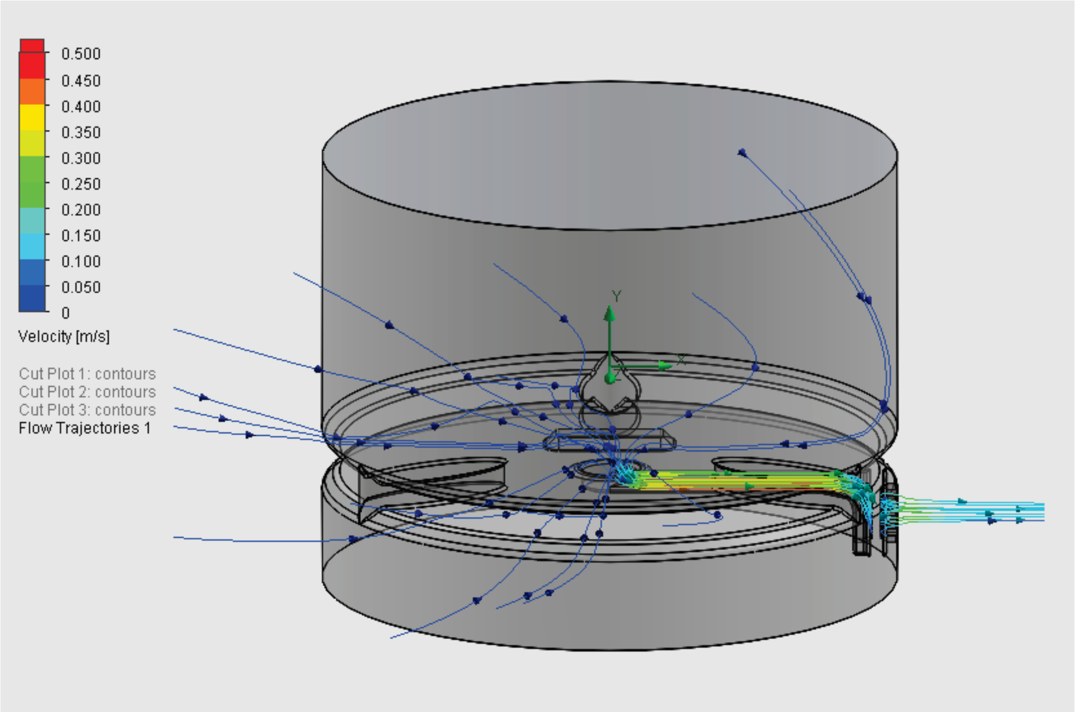


Figure 6. Example CFD run to characterize the inlet and outlet flow rates when the CDM was installed in the housing with the air gap omnidirectional inlet.

Additional CFD runs enabled analysis of the inlet design and CDM interface to the housing under various conditions, such as when the MAV was stationary or mobile. The CFD results are summarized in Figure 7 and Table 1.

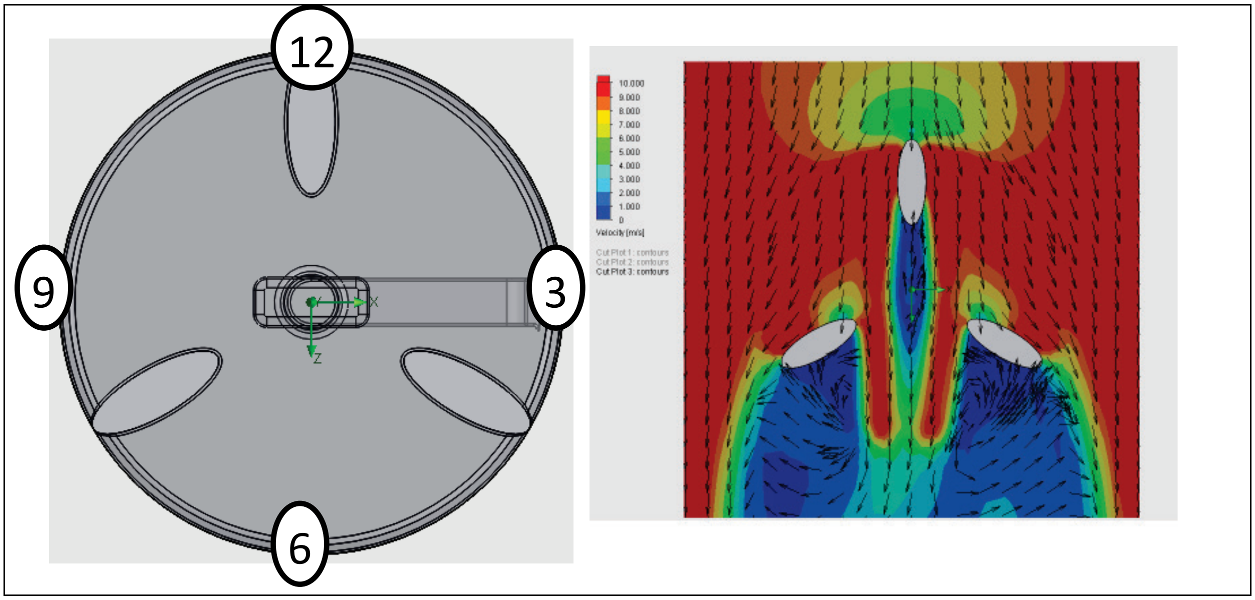


Figure 7. Air gap inlet “clock position” diagram used for CFD modeling (left) and a CFD flow field result (right).

Table 1. Summary of CFD Computational Results for the Air Gap Inlet

Case	**Air Gap Inlet Description**	**Approximate Velocity Below Inlet (m/s)**
1	Stationary	0.05–0.1
2	V_∞ 10 m/s same vector as fan exhaust (from 9 o'clock)	8–9
3	V_∞ 10 m/s opposite vector as fan exhaust (from 3 o'clock)	7–8
4	V_∞ 10 m/s perpendicular to fan exhaust (from 12 o'clock)	1–2
5	V_∞ 10 m/s perpendicular to fan exhaust (from 6 o'clock), body tilted 20°	8–9

V_∞, aircraft velocity.

The mounting location for the CDM and its inlet housing was selected based on center of gravity and density altitude (DA) considerations. The conditions at Dugway Proving Ground were used to compute the DA parameters. Table 2 summarizes these results.

Table 2. DA Computations (Go or No-Go and Time Limits) for the MAV with a 0.65 lb CDM Payload*

Condition	**Fuel Load (%)**	**Go or No-Go**		
		8100 rpm and Maximum DA (Time Limit)	**8300 rpm and Maximum DA (Time Limit)**	**8500 rpm and Maximum DA (Time Limit)**
Day, DA =8000	100	No-go	No-go	No-go
	80	No-go	No-go	Go (32 min)
	60	No-go	No-go	Go (24 min)
	40	No-go	Go (16 min)	Go (16 min)
Night, DA = 6600	100	No-go	No-go	Go (40 min)
	80	No-go	Go (32 min)	Go (32 min)
	60	No-go	Go (24 min)	Go (24 min)
	40	Go (16 min)	Go (16 min)	Go (16 min)

*August 2015 DAs for Dugway, UT:
Week 1: day, 8048 ft at 88 °F; night, 6435 ft at 63 °F.
Week 2: day, 8080 ft at 91 °F; night, 6625 ft at 67 °F.
Week 3: day, 8036 ft at 89 °F; night, 6632 ft at 66 °F.
Week 4: day, 7997 ft at 90 °F; night, 6471 ft at 65 °F.

3. SOFTWARE INTEGRATION

The Gumstix single-board computer runs a compact version of the Linux operating system. A customized Canary implementation written by ECBC personnel for the CDM was adapted for the MAV data management system used on the aircraft and in the ground station. Canary is ECBC's sensor-agnostic implementation of the CCSI. The MAVERECS Canary driver received GPS and time-stamp data from the MAV once every 2 s. The MAVERECS Canary driver sent chemical sensor status reports to the MAV each time a GPS update was received. Sensor updates were in the form of a partial CCSI message; each contained an alert channel report without Extensible Markup Language (XML) header information. Full CCSI data, including complete chemical sensor readings and location reports, were logged to a database onboard the chemical sensor and were downloaded after each mission.

4. COMPONENT AND SYSTEM TESTING

ECBC personnel traveled to Honeywell's Small Unmanned Systems Division in mid-July of 2016 for final integration and testing of the CDM hardware, the Gumstix computer and custom adapter board, and the CCSI software interface to the T-Hawk MAV electronics and ground station systems. The components were tested individually and as an integrated system to verify accurate operation of the CDM with the MAV electronics and power systems and to finalize the Canary software code. The Canary code was run on the Gumstix computational environment to translate the native CDM detection and system status data stream into CCSI-compliant messages that were compatible with the MAV-R ground station software. All remaining bugs in the hardware and software were rectified over a three-day period. At the end of this collaborative engineering work, the MAV-CR variant of the T-Hawk was born.

The next step was for the Honeywell pilots to perform test flights with this new MAV-CR variant to verify the safety of flight and stability operations. The pilots performed regression testing at Tyndall Air Force Base. The pilots then coordinated with an Air Force Government Flight Representative to obtain an experimental airworthiness certification that would permit missions to be flown at Dugway Proving Ground.

5. INTEGRATED SYSTEM DEMONSTRATION AT S/K CHALLENGE III

The MAVERECS integrated system was included in the S/K Challenge III, part of a multi-day test event at Dugway Proving Ground in August 2016. MAVERECS was part of the remote sensing demonstrations funded by DTRA and dubbed the LSI. The objective of the LSI was to demonstrate improved integrated early warning and situational understanding by assembling sensor and contextual data from multiple surveillance systems, dedicated chemical and biological sensing components (including stationary and mobile sensor elements), and aerosol plume mapping and tracking via light detection and ranging (LIDAR) and optical scattering. These sensing modalities converged in an interoperable computational environment that enabled the near-instantaneous data transfer of detection events into the JWARN chemical and biological defense program command and control platform via publish and subscribe protocols. The warning functionality of JWARN was further enabled by the sensor computational environment or sensor CE, as implemented by a software architecture developed for this express purpose, the Integrated Sensor Architecture (ISA).

During the LSI, system performance over the baseline process was demonstrated by alerting the JWARN operator of the occurrence of suspicious triggering events such as hostile activity or incoming mortar, artillery, or rocket rounds. This enabled the JWARN operator to cross-cue surveillance assets and capture contextual information to correlate sensor alerts to improve the rate at which decisions could be affected. This enhanced situational understanding and interoperability facilitates earlier warning of potentially affected units that are downwind of the threat agent. Various command and control environments (including the RaptorX threat detection network) were implemented to demonstrate the flow of alert information among the various sensor modalities and JWARN, and from JWARN to the end user. This process is also well represented by the U.S. Army's Nett Warrior end-user device, which has been functionalized to receive and transmit standard nuclear, biological, and chemical messages.

Other systems exercised during the S/K Challenge III (Figure 8) include the following:

- The ISA makes all sensors (and their feeds) dynamically discoverable and available to a Soldier, platform, or commander, regardless of sensor type or ownership, in a manner that reduces response times, integration complexity, and life-cycle costs.
- Cerberus Scout (FLIR Systems; Wilsonville OR) is a tripod-mounted system with EO video, infrared video, laser range-finding, and ground surveillance radar.
- Real-Time Eyesafe Visualization, Evaluation, and Analysis LIDAR light detection and ranging system (REVEAL; Spectral Sensor Solutions [S3]; Albuquerque NM) could simultaneously detect, map, and track aerosol plumes to ranges of >5 km, and derive wide-area 2D horizontal vector wind-field information by applying advanced algorithms to the motion of the aerosol features in the plumes and the surrounding atmosphere.
- JCAD, CDM, and ECBC's Second Generation Tactical Biological Detector (TacBio Gen II) are point detectors that were used to implement the CCSI standard to obtain consistent connectivity and data exchange.
- The Joint Effects Model application was used to coordinate the JWARN system with a Chemical Hazard Indicating and Ranging Pack interface to aggregate data from the chemical and biological sensors, including the JCAD and TacBio Gen II systems. In addition, JWARN received presumptive threat aerosol alerts and locations from the REVEAL system. The JWARN workstation also enabled access to surveillance system data including alerts (spot reports) and imagery from the Cerberus Scout.
- ECBC's Volatile Organic Compound Kit (VOCkit) is a device that exposes colorimetric sensor array (CSA) "tickets" to the headspace above dilutions

and mixtures containing agents, solvents, simulants, and common environmental contaminants. Color images of the CSAs are captured before, during, and after exposure. Sophisticated algorithms for sample identification (using a comprehensive signature library) have been developed at ECBC and implemented in the platform.

- Array Configured of Remote Network Sensors (ACORNS) is based on a 5.25 in. diameter BLU-108 munition fit form and uses support and sensor modules of varying heights (up to a maximum of 31 in.). These modules or "pucks" can be stacked to create a multi-use sensor. The base command and control functionality is provided within the modules to enable plug-and-play capabilities between modules.
- The Deep Purple Unmanned Aircraft System (UAS) was designed by ECBC's Advanced Design and Manufacturing team. The quadcopter UAV platform has a payload capacity of 5–7 lb and a range of a few kilometers. The Deep Purple UAS was integrated with the modular ACORNS pucks to afford a configurable payload.
- The motorized Mobile Detection Assessment Response System (MDARS; Land Sea Air Autonomy; Finksburg, MD) unmanned ground vehicle is a robotic autonomous platform that provided autonomous mobility for a cluster of sensors including JCAD, TacBio Gen II, VOCkit, and ACORNS systems.

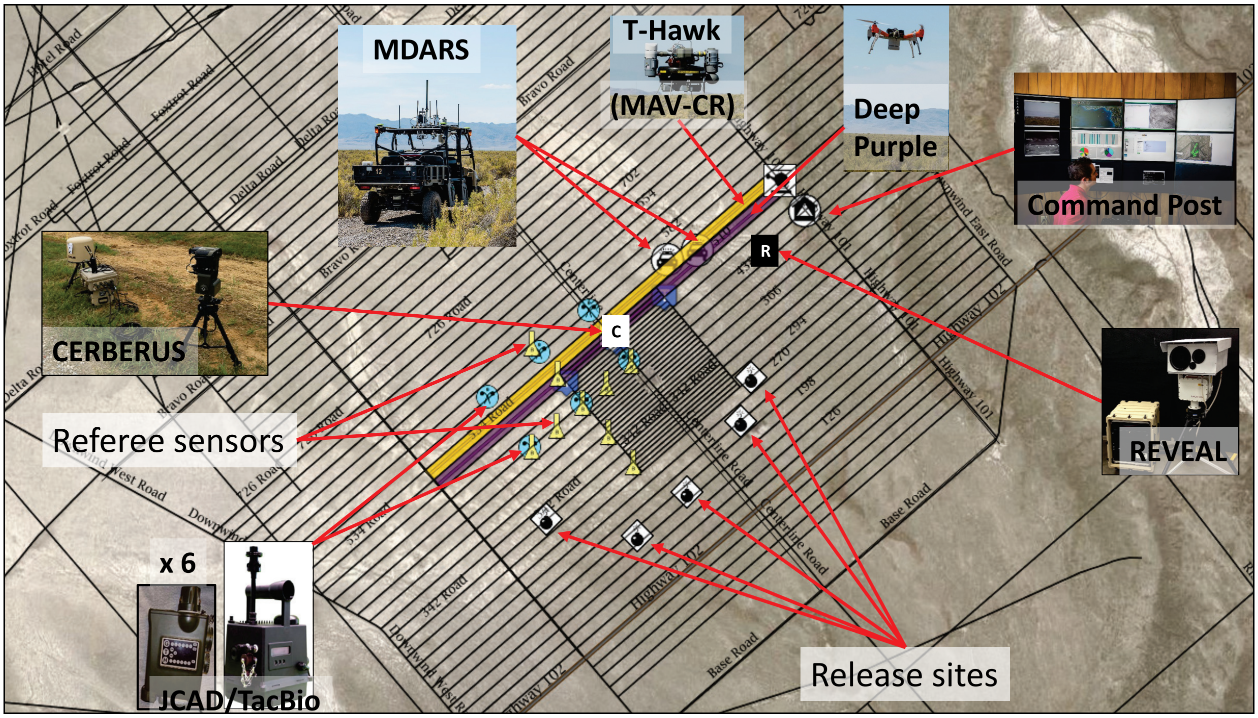


Figure 8. Layout of systems exercised under the LSI. The MAV-CR equipped with a CDM travelled principally along the purple track shown for this event.

The MAVERECS system played a pivotal role within the LSI, demonstrating the agile capability of an air-relocatable sensor cued by the detection of a suspicious activity, incident, or kinetic event that was immediately observable by either the Cerberus Scout continuous surveillance system or direct visualization. Most importantly, the MAVERECS system (composed of the MAV-CR, Gumstix computer with CCSI, and real-time ground control station data transmission and visualization software) added remote chemical identification that occurred within minutes of receiving a cue to launch a sortie to investigate a suspect cloud or chemical dispersion event. This rapid remote surveillance and detection capability provides a commander with the ability to investigate an incident early in the life cycle of an aerosol or vapor plume event. Accordingly, this capability supports earlier detection of a threat agent and better, higher-fidelity situational understanding of the affected area. Compared with current state-of-the-art methods, this higher-fidelity situational understanding allows a commander to apply higher levels of confidence to make faster decisions with respect to protective posture level, contamination avoidance, and response.

Table 3 summarizes the specifics of the various sorties that the MAVERECS system engaged in during the S/K Challenge III event. In each case, the MAVERECS operator received a cue with coordinates of the suspected incident and a prediction of the downwind track of any resulting plume. The operator readied the vehicle and entered coordinates for the flight path, and the system autonomously executed the sortie.

Table 3. Summary of MAVERECS Missions During S/K Challenge III, August 2016

Date* and Flight	**Time/Estimated Duration**	**Simulant**	**Results and Notes**
22 Aug Flight 1	0020/30 min	TEP	Launched MAV-CR to range centerline after cue from REVEAL LIDAR post detonation of 20 kg of TEP. Did not detect TEP. Small release amount and high winds (gusts >20 knots) likely dispersed plume before MAV-CR could get to cloud.
22 Aug Flight 2	0300/22 min	TEP	Spray dissemination at 2 L/min for 10 min (64.7 kg) of TEP. MAV-CR cued and launched at 0301 toward range centerline. Began detecting TEP at 0307. Altitude at detection time was 84 ft above ground surface. Pilot kept MAV-CR in cloud for several minutes before returning to launch site.
23 Aug No flights	2200–0400	None	Pilots remained on standby over the 6 h simulant release window. No releases took place because metrological conditions were poor.
24 Aug Flight 1	0221/21 min	TMP	Explosion was a 20 kg fill of TMP. The CDM detected 1 bar (lowest level) of an unknown chemical. Nonconclusive, but did recognize this G agent simulant that is not included in the basic CDM library. Likely that the plume dispersed before MAV-CR could get to the predicted intersect point.
25 Aug Flight 1	2245/30 min	MES	Cued and launched against an explosion of 20 kg of MES. Pilot was given coordinates in UTM units rather than Army standard MGRS units. As a result, could not fly to intersection point. Area search did not detect MES. Winds were >15 knots.
25 Aug Flight 2	2335/25 min	TEP	Cued and launched against a 10 min spray release of TEP (43.8 kg total released). Detected and mapped TEP starting at 10 min 30 s into flight.
25 Aug Flight 3	0027 and 0042/ 30 min	MS2 bacteriophage and *Bacillus globigii* (both biosimulants)	Cued and launched in response to bio dissemination. Flew to centerline to intercept point and hovered around that point. MAV-CR had paper spray sampling collector. CDM detected 1 bar of L and HN (likely interferent from bioaerosol chemical solvent). Returned to launch point and gave biocollector to ECBC for laboratory analysis.
25 Aug Flight 4	0158/23 min	TEP	Launched in response to cue off REVEAL LIDAR-detecting plume from 20 kg of TEP explosive release. MAV-CR detected 1 bar TEP readings in two locations. Confirmed CDM can detect relatively small and fleeting plume from an explosive release (20 kg) vs a line-spray dissemination.
25 Aug Flight 5	0350/30 min	MES	MAV-CR flew to centerline of range lane after receiving cue of a plume detected by REVEAL LIDAR. After reaching centerline and not detecting MES from the 20 kg explosive release, MAV-CR pilot flew to explosion release coordinates and surveyed the release area at altitudes of 80 ft down to 20 ft above ground level. Purpose was to look for residual MES gas emanating from ground location of the release. Because of night operation combined with brushy terrain and relatively high winds (>15 knots sustained), MAV-CR pilot did not fly lower than 20 ft above ground surface for safety reasons. He was able to fly around the release target for approximately 4 min (0407 to 0411) before having to return to launch pad at 0415 due to low fuel and wind conditions. Note: MAV-CR sat on launch pad awaiting cue while running for 10 min, which affected time allowed on MES release point.

*Date of flight testing reflects start time for that night's trials.

HN, nitrogen mustard; L, lewisite; MGRS, Military Grid Reference System; TMS, trimethyl phosphate; UTM, Universal Transverse Mercator.

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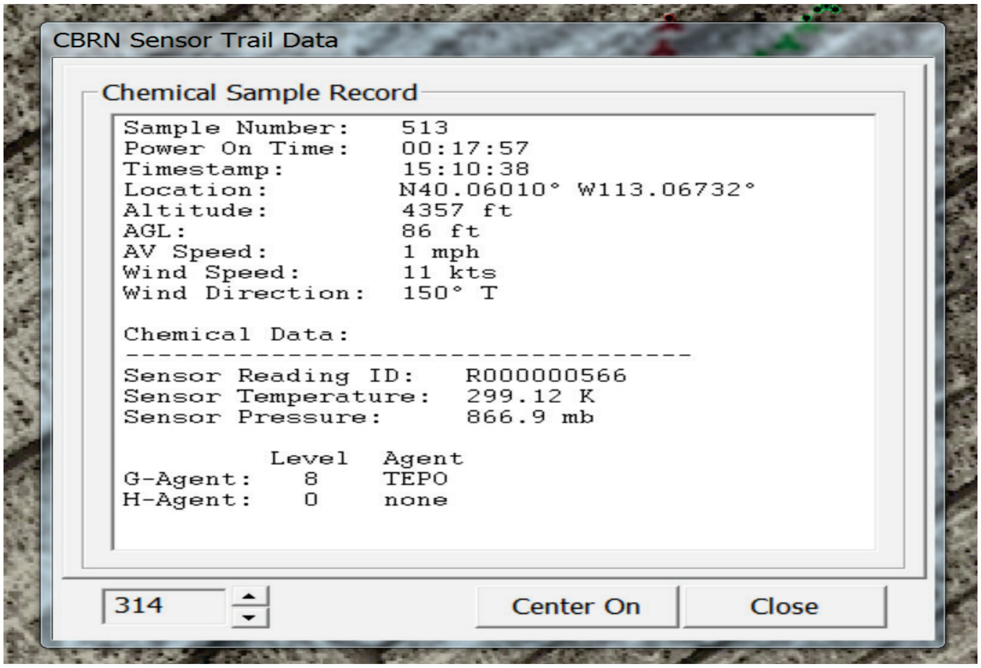
The MAVERECS team learned from the initial sortie result that the suspect cloud predictive coordinates had to reach the MAV-CR ground control station within a few minutes or else the cloud could move beyond the area of interest, depending on metrological conditions. After the first sortie, the MAV-CR successfully intercepted the suspect cloud in five of five sorties and reported the presence of likely chemical warfare agent. For the seventh chemical release (an explosion of MES, which is a mustard [H-series] simulant), the team attempted to detect ground contamination after the MES cloud passed from the area of interest. To detect ground contamination, the pilot needed to get the MAV-CR within approximately 10 ft of the ground surface to stir up air currents that would bring surface vapor, droplets, and dust with MES into the air intake of the CDM. Nighttime operation and a limited mission flight time of approximately 30 min precluded a methodical survey of the ground area, and no MES was detected. The eighth and last sortie was designed to collect a biological aerosol from the suspect cloud. The collection method was a paper-spray cartridge placed in line of the MAV-CR electronics module cooling airstream. After the sortie was completed, the paper-spray cartridge was labeled and transferred to the ECBC test team for subsequent analysis. No result on the paper-spray bioaerosol collection sample was reported back to the MAVERECS team at the time of this report. However, this last MAVERECS sortie successfully demonstrated the proof of concept for in-flight bioaerosol collection from a suspected biological cloud.

The MAVERECS system successfully intercepted five of seven of the chemical plumes released during the event and generated detection results on its onboard CDM. Additionally, the MAVERECS system flew one sortie to collect a biological aerosol sample on a paper-spray collection cartridge. The 1 × 5 × 0.3 cm cartridge was installed in line with the exhaust cooling airstream of the MAV-CR electronic pod. The CDM detection results were relayed to the MAVERECS ground station, where an intuitive situation display revealed the flight track of the MAV-CR and the color-coded, geospatially referenced detection state of the CDM (green for clear, yellow for possible, and red for detection). Examples of these data products are provided in Figures 9–12.

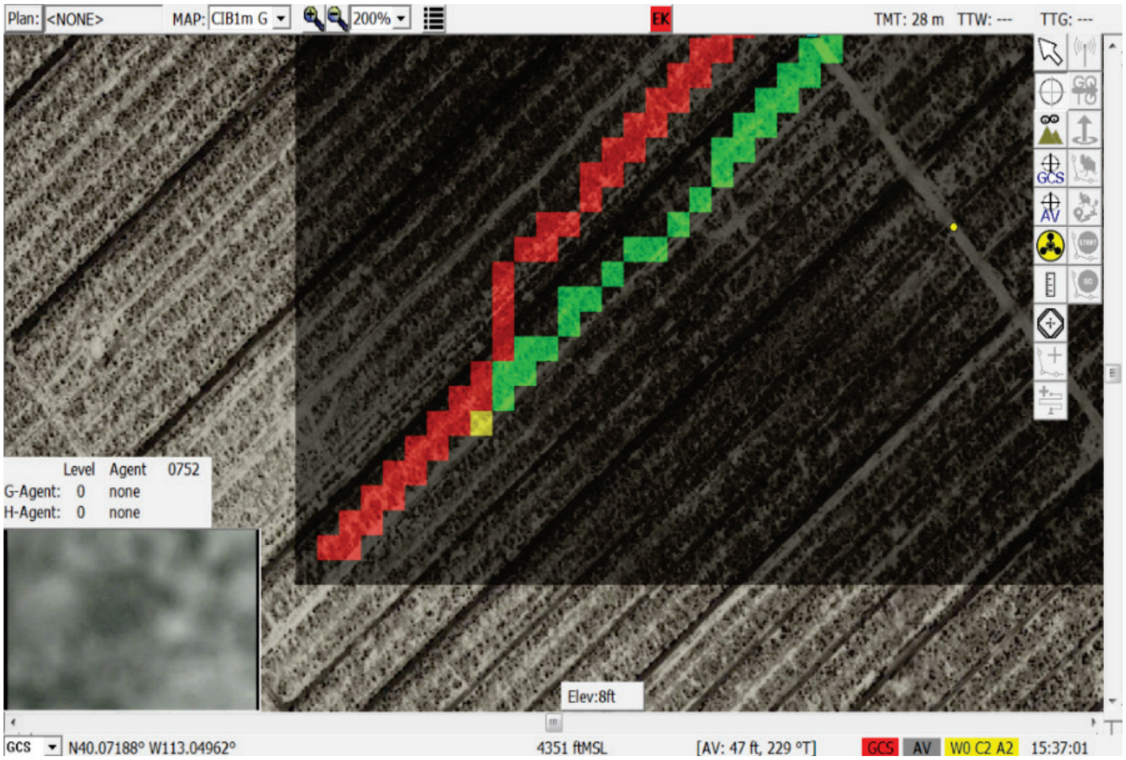


```
Sample Number:    513
Power On Time:    00:17:57
Timestamp:        15:10:38
Location:         N40.06010° W113.06732°
Altitude:         4357 ft
AGL:              86 ft
AV Speed:         1 mph
Wind Speed:       11 kts
Wind Direction:   150° T

Chemical Data:
-----------------------------------
Sensor Reading ID:    R000000566
Sensor Temperature:   299.12 K
Sensor Pressure:      866.9 mb

          Level   Agent
G-Agent:    8     TEPO
H-Agent:    0     none
```

Figure 9. A MAVERECS chemical detection event data point logged as a KML file on the MAV-CR control station during a TEP release event during S/K Challenge III.



Plan: <NONE>
MAP: CIB1m G
200%
TMT: 28 m TTW: --- TTG: ---

```
          Level  Agent   0752
G-Agent:   0     none
H-Agent:   0     none
```

Elev:8ft

GCS N40.07188° W113.04962° 4351 ftMSL [AV: 47 ft, 229 °T]

Figure 10. A MAVERECS chemical detection heat map generated during a MAV-CR sortie at S/K Challenge III. Each mapped data block is geotagged to an associated KML file like the one shown in Figure 9.

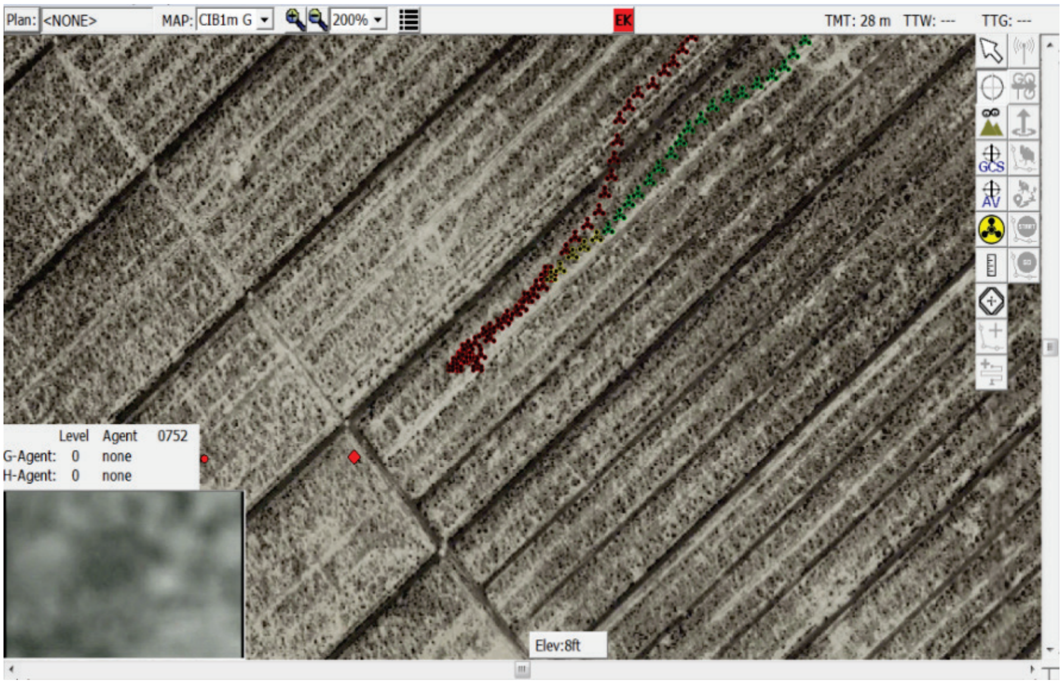


Figure 11. MAVERECS control station can toggle between the heat map and an alternate trail-mapping display to show detection results during a MAV-CR flight.

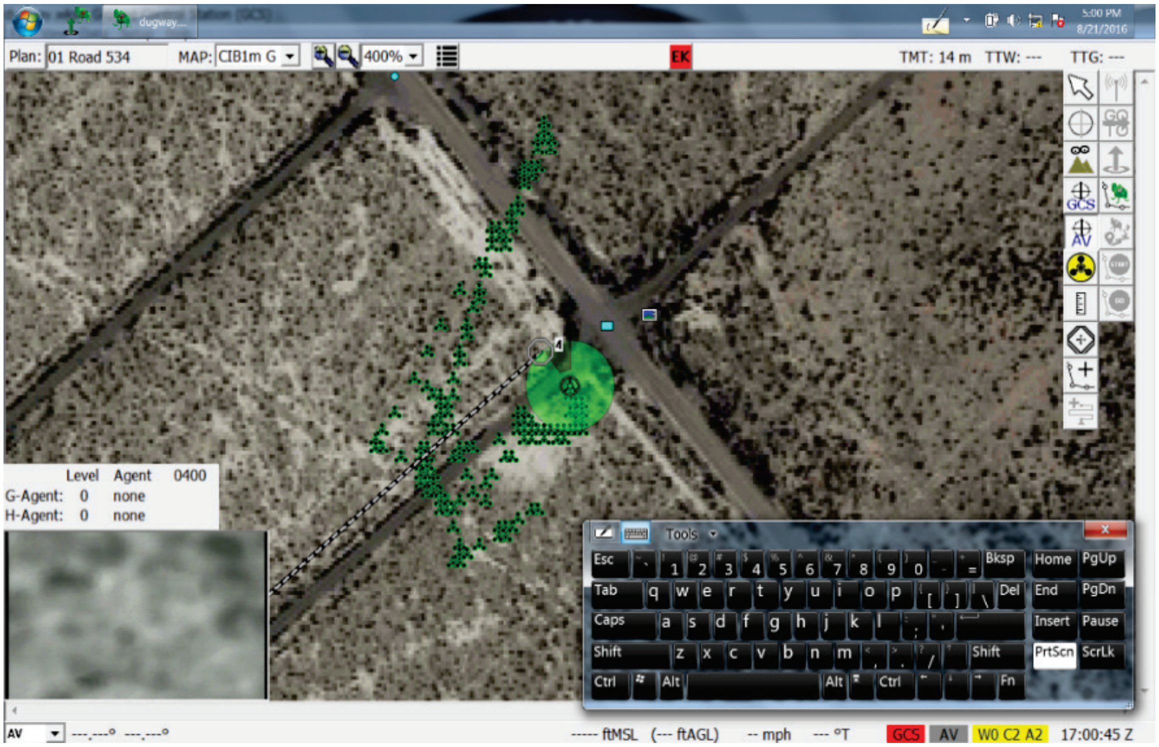
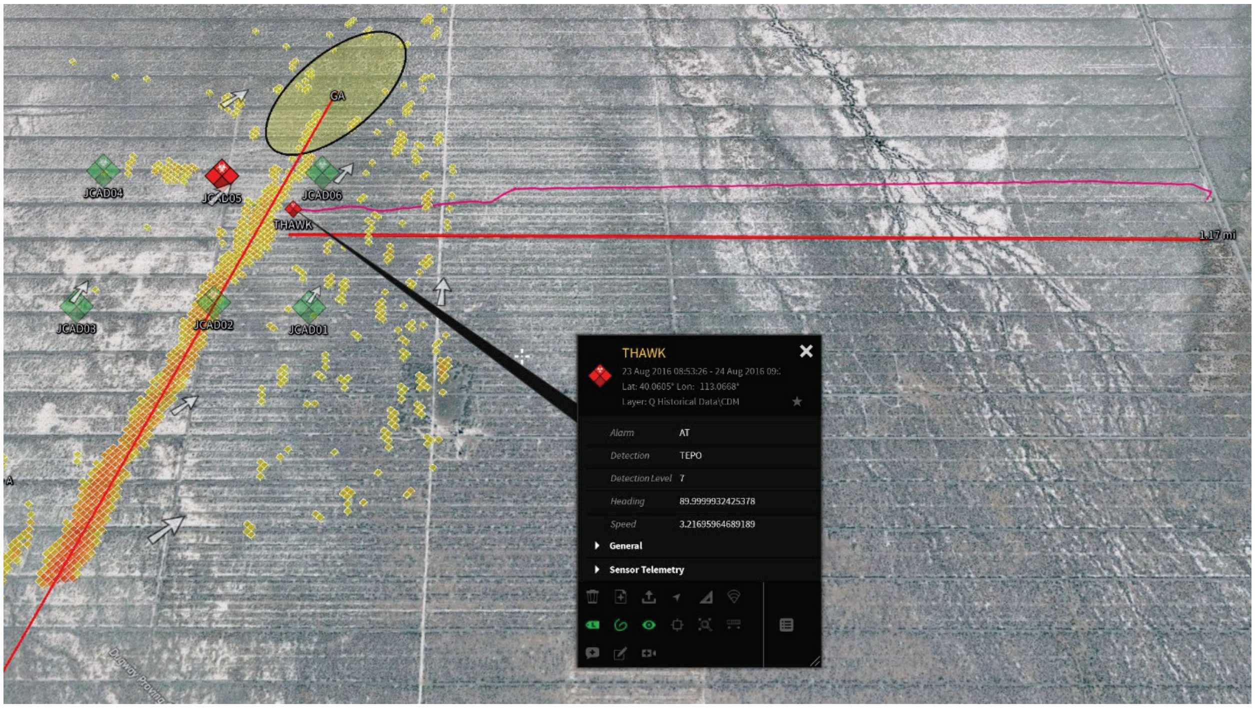


Figure 12. Trail-mapping display showing negative detection results during the MAV reconnaissance flight on 25 August 2016. The reconnaissance mission surveyed the release site of an MES explosive dissemination at altitudes ranging from 20 to 80 ft above ground level.

The field test of the MAVERECS system was demonstrably successful. Although the total number of chemical agent simulant releases during S/K Challenge III was disappointingly limited, the success rate of the system intercepting the airborne plume in flight was appreciable, and the system demonstrated the utility and advantages of an airmobile sensor. The MAVERECS platform and its onboard CDM operated reliably in a field environment throughout the event. Ground-truth metrics were obtained by post-processing of the data generated by several referee systems (including six pre-placed JCADs) operated by the test team on the grid. A principal data source was the West Desert LIDAR (developed at Dugway Proving Ground), which uses pulsed laser, light-backscatter detection, and ranging to track particle fields moving across the grid. Additionally, several Fourier transform infrared spectrometers and ion mobility spectrometers dotted the grid in a regular pattern (see Figure 8). A data reduction effort enables the comparison of actual plume location as garnered from the referee data to the detection results generated by the airmobile CDM on the MAVERECS platform.

An example of such a comparison is shown in Figure 13. The result reveals that the MAV intercepted the plume, and the onboard CDM immediately alerted to the presence of TEP. Figure 13 shows that one of the pre-placed JCADs registered an agent detection, as indicated by the red-colored icon. However, the CDM did not immediately clear down when the MAV flight emerged from the plume. The likely reason for the slow clear-down of the CDM is that TEP presents as a combination of airborne aerosol and vapor. When the CDM is vectored to the highest-concentration centroid of the suspect plume, as it was for this trial, the inlet is likely to pull in a high concentration of liquid aerosol droplets. Liquid aerosol droplets impinge on the CDM inlet and create a reservoir from which TEP vapor can slowly but continuously emerge. The result reveals that a system architecture can "overperform", causing unnecessarily high exposures such as this one that can cause clear-down issues. Figures 10 and 11 (heat map and tracer views of the same run) show this clear-down issue, and the return-flight heat map is red along the parallel path of the incoming-flight green mapping points. However, the clear-down time was an issue with the CDM's ion mobility detector and did not detract from the MAVERECS remote sensing and reporting system.

Future chemical detector payloads may address clear-down time. In the meantime, when using the CDM as the chemical sensor payload, several mitigating procedures and controls are possible. The CDM could be fitted with an aerosol impactor to reduce the chance of droplets impinging on its inlet. The aircraft can dynamically adjust its flight pattern in response to a CDM alert to attempt to avoid the plume center and higher concentrations and readings. Such a feedback mechanism would also enable the development of plume-boundary mapping algorithms.



THAWK
23 Aug 2016 08:53:26 - 24 Aug 2016 09:
Lat: 40.0605° Lon: 113.0668°
Layer: Q Historical Data\CDM

Alarm	AT
Detection	TEPO
Detection Level	7
Heading	89.9999932425378
Speed	3.21695964689189

Figure 13. Reduced referee data for S/K Challenge III release FC08, 22 August 2016, showing the projected plume location in accordance with the referee data relative to the MAVERECS heat map.

6. CONCLUSIONS AND RECOMMENDATIONS

The MAVERECS ET was a successful endeavor. The integration of a CDM onto the airframe and into the avionics system of the T-Hawk to create the MAV-CR variant enabled the systematic design, fabrication, and testing of an omnidirectional inlet suitable for representative sampling while the aircraft is in flight. The project demonstrated real-time tactical remote chemical detection and mapping with the ability to capture information in KML format and to transmit sensor data to a command and control center and further into the JWARN, which manages CBRN incident reporting and command guidance on the battlefield. The performers developed effective and adaptable contamination mapping and visualization software for tactical remote CBRN sensing. The ECBC team demonstrated an interoperable remote sensing CCSI architecture that is platform-agnostic and usable in future remote sensing efforts.

The results of this initiative serve to inform the chemical and biological defense community in particular and the environmental surveillance community in general of the bona fides of a vertical take-off and landing airmobile environmental sensing platform integrated into a larger architecture of interoperable sensing and analytics systems. Resulting information will help shape tactical remote CBRN sensing requirements and will inform the Integrated Early Warning Advanced Technology Demonstration Technical Manager as well as similar initiatives across the DoD community. Additionally, the Joint Project Manager for Nuclear, Biological and Chemical Contamination Avoidance has used results from the MAVERECS ET to accelerate the start of their upcoming CBRN Sensors on Robotic Platforms program of record.

Several principal lessons were learned from the MAVERECS ET. The cross-cueing functionality and waypoint autonomous navigation features of the air platform are conducive to the successful interception and interrogation of a suspicious plume consequent to a kinetic or surreptitious event; however, the agile and rapid insertion of the CDM into the highest-concentration region of a suspect plume can result in ambiguity in the spatial extent of the plume. This is due to clear-down issues that are known to surface when the detector pulls in a significant number of aerosol droplets while sensing the vapor. This issue can be readily mitigated by a combination of engineering controls on the inlet design and operational techniques and parameters that can limit the system's exposure to high aerosol concentrations while conducting the important function of mapping the plume boundaries. A loiter and hover capability is of critical importance to this mission space, as the flight pattern of these agile aircraft is much more precise and customizable than the corresponding flight pattern of fixed-wing UASs.

Enhanced flight duration is a key need for an effective tactical remote sensing capability on the battlefield for sensitive site exploitation and ground contamination mapping missions. These two types of missions generally will not have the benefit of a significant aerosol cloud, and systematic close-to-the-ground sampling patterns will necessitate longer than 10 to 20 min of chemical sensing around the area of interest.

Warfighters briefed on MAVERECS capabilities and results consistently asked how soon they could have this capability. MAVERECS demonstrated significant operational improvement over currently available technology and methods available to the CBRN Warfighter, including (1) being able to autonomously send a remote CBRN detector into a contaminated area rather than having to send a CBRN detection team; (2) getting fidelity of whether a distant cloud contained chemical agent from a remote tactical chemical sensing system; (3) having the remotely transmitted data mapped in real time on the ground control station; and (4) having standardized data files in a format that allows the system to forward visualized and georeferenced information to a local command center and into JWARN.

As was demonstrated by MAVERECS integrated flight controls, autonomy is of paramount importance to this mission space for the platform. The dynamic cueing and vectoring by waypoints passed that is noted in real time by surveillance and other sensor systems would burden a human operator with an exhaustive workload. The MAVERECS ground station interface enabled fully autonomous flight control in a responsive manner that led to successful outcomes, as demonstrated during S/K Challenge III. There is room for improvement in the system's autonomy, particularly in the area of dynamic feedback on in-flight control using the live data stream from the onboard sensor module.

ACRONYMS AND ABBREVIATIONS

ACORNS	Array Configured of Remote Networked Sensors
CCSI	CBRN common sensor interface
CBRN	chemical, biological, radiological, and nuclear
CDM	Chemical Detection Module
CFD	computational fluid dynamics
COTS	commercial off-the-shelf
CSA	colorimetric sensor array
CWA	chemical warfare agent
DA	density altitude
DTRA	Defense Threat Reduction Agency
ECBC	U.S. Army Edgewood Chemical Biological Center
EO	electro-optical
ET	Enabling Technology
FLIR	forward-looking infrared
GPS	Global Positioning System
HFOV	horizonal field of view
IR	infrared
ISA	Integrated Sensor Architecture
JCAD	Joint Chemical Agent Detector
JWARN	Joint Warning and Reporting Network
KML	Keyhole Markup Language
LIDAR	light detection and ranging
LSI	Layered Sensing Initiative
MAV	Micro-Air Vehicle
MAV-CR	Micro-Air Vehicle, Chemical and Radiological variant
MAV-R	Micro-Air Vehicle, Radiological variant
MAVERECS	Micro-Air Vehicle-Enabled Remote Environmental and Chemical Sensing
MES	methyl salicylate
PACOM	U.S. Pacific Command
REVEAL	Real-Time Eyesafe Visualization, Evaluation, and Analysis LIDAR
S3	Spectral Sensor Solutions
S/K	Sophos/Kydoimos
TEP	triethyl phosphate
TMP	trimethyl phosphate
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
VOCkit	Volatile Organic Compound Kit
XML	Extensible Markup Language

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