Designing Ocean Drones for Maritime Security:

The use of integrated sensing modalities to enhance situational awareness

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***Abstract*— Routine operations at sea such as environmental monitoring and security patrols involve substantial long-term costs in terms of equipment and labor. Moreover, operating in hazardous conditions or during severe weather increases the probability of mission failure and in some cases endangers human lives. Recent advances in unmanned surface vehicle (USV) technologies show considerable promise in alleviating some of the dirty, dull and dangerous work required in maritime industry, ocean research, and law enforcement. In particular, aquatic surface drones like the Wave Adaptive Modular-Vessel (WAM-V) have the potential to serve as robust and highly scalable operational support vessels to rapidly characterize off-shore threats from oil spills, hazardous chemical leaks and radioactive outfall. This manuscript describes the integration of a Chemical, Biological, Radiological, Nuclear and Explosives (CBRNE) sensor system with a remotely operated USV capable of transmitting real-time contamination measurements, video streams, and ancillary data to off-site incident commanders. Results from sea trials, simulations, and tactical operations guide discussion of the navigation, control and telemetry design elements applicable for configuring USV – environmental monitoring platforms capable of enhancing situational awareness for high-risk response and recovery efforts in the marine domain.**

Keywords*— *ocean engineering; drone; robot; unmanned surface vehicle; cooperative autonomy; systems design; sensor fusion; situational awareness; autonomous vehicle; maritime domain; common operating picture; communication network; aerial drone; first responders; natural disaster; environmental monitoring; WAM-V; USV; ASV; UAV; ISR; CBRNE; HAZMAT

I. Rise of the Robots

Popular amazement, disbelief and criticism characterized the first public demonstrations of U.S. Patent number 613,809. Shortly after inventing the radio in 1895, Nikola Tesla had created and built the world's first drone [1]. His radio-controlled and battery-powered vessel used tele-automated switches to control propeller velocity, rudder actuation, and the luminosity of running lights. Although a paucity of public interest in the *pro-bono* potential of '*Telautomation*' plagued Tesla for the rest of his life [2], his prescient demonstration at the 1898 Electrical Exhibition in Madison Square Garden set the stage for the age of modern robotics.

The utility of unmanned vessels have since expanded into highly specialized forms of maritime security, reconnaissance and force projection and are beginning to penetrate further into fields such as ocean research, environmental monitoring, search and rescue, and disaster relief.

Successful application of robotic systems to augment human capabilities requires bridging the knowledge gap from technology potential to operational needs early in the design process. This study employs an anthropocentric system-of-systems design thinking approach to explore salient aspects of automated sensor modalities and human-machine interactions useful for maximizing informational content to enhance situational awareness in the maritime domain.

II. Maritime Security and Defense

A. *Welfare and Warfare*

Traditionally, maritime security was considered a military defense issue concerned primarily with monitoring, evading, and suppressing combatant aerial or naval assets and producing incremental improvements in anti-mine and antisubmarine warfare. Since the October 2000 attack off the coast of Yemen where a small boat laden with explosives managed to detonate the hull of the USS Cole, these initiatives have broadened to include multiple-agency asymmetric warfare strategies which rely on enriched Intelligence, Surveillance, and Reconnaissance (ISR) and small tactical capabilities for interception and interdiction.

Other incidents of maritime terrorism (e.g. the 2004 bombing of SuperFerry14 in the Philippines, and piracy-related attacks in the western Indian Ocean and South China Sea) have been directed almost exclusively at unguarded civilian and merchant marine vessels. Although politically motivated and opportunistic attacks against individual vessels are problematic, a coordinated attack against a major civilian harbor, shipping port, or petrochemical refinery would inflict widespread loss of life and property and result in undeniable economic damage [3].

B. *Catastrophic Errors and Natural Disasters*

Maritime security is not necessarily limited to identification, or disruption of intentional terrorist threats. A disastrous chain of events precipitated by geophysical, or weather-related circumstances and compounded by human error can produce catastrophic results. The devastating 1947 Texas City port explosions were a result of an unfortunate juxtaposition of fertilizer and ammunition cargoes catching fire in the hold of a docked ship with subsequent explosions

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igniting nearby crude oil refineries and grain elevators [4]. Natural disasters such as the 2011 Tōhoku earthquake and ensuing tsunami precipitated the Fukushima Daiichi nuclear reactor meltdowns, creating immediate airborne radiation hazards and releasing long-lasting radioactive debris into the ocean near densely populated areas.

C. Dirty, Dull, and Dangerous

Characterizing the rapid evolution of man-made or natural disaster scenarios in coastal zones is complicated, dangerous and demands timely information. Preventative patrols and persistent harbor monitoring can be tedious and labor intensive endeavors. The dirty aspects of handling or being in close proximity to quantitatively sample hazardous material, radiation, or toxic compounds released in littoral environments [5] may even preclude investigation or monitoring of an unfolding public disaster - especially when concentrations of contaminants are unknown or thought to be beyond acceptable limits for human exposure[1].

Incident commanders and disaster relief coordinators recognize the value of dispatching constantly updated information to direct personnel away from potentially dangerous situations or to concentrate resources in the most efficient manner. Beyond ameliorating risk to human life, the persistence, versatility, and scalability of certain drone systems are intrinsically appealing as tools to aid comprehensive and accurate assessments of emergent situations.

This study presents the conceptual needs and processes necessary to integrate a chemical, biological, nuclear, radiation, and explosive (CBRNE) sensor system with a Wave Adaptive Modular-Vessel (WAM-V) unmanned drone (as shown in Fig.1) to create a mobile, adaptive, and robust sensor network capable of generating persistent maritime situational awareness for applications such as automated port and harbor surveillance (as shown in Fig 2).

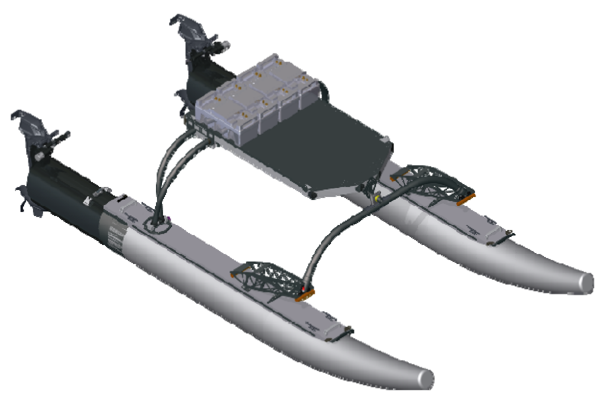

Fig. 1 Wave Adaptive Modular-Vessel (WAM-V)

III. UNMANNED MARINE SYSTEMS

Unmanned vehicle systems spanning sea, air and land domains can be categorized as manual, semi-automated, automated, and autonomous with varying levels of human supervisory control and subroutines. Autonomy (as distinguished from intelligence) can be further conceptualized as independent agents interacting within an operational architecture on a continuum ranging from random to deterministic to adaptive to collaborative. Synthesizing data outputs from bio-chemical and navigational sensors have been used to guide adaptive underwater vehicle operations [6] autonomously trace and map underwater hydrocarbon plumes, and to detect, localize, and characterize subsea munitions and unexploded ordnance [7]. Cutting edge research in maritime robotics is now focusing on coordinating operations (within and among) different vessel classes of unmanned marine systems such as Remotely Operated Vehicles (ROV), Unmanned Underwater Vehicles (UUV), Autonomous Underwater Vehicles (AUV), Unmanned Surface Vehicles (USV), and Autonomous Surface Vehicles (ASV) - each with distinctive capabilities and constraints.

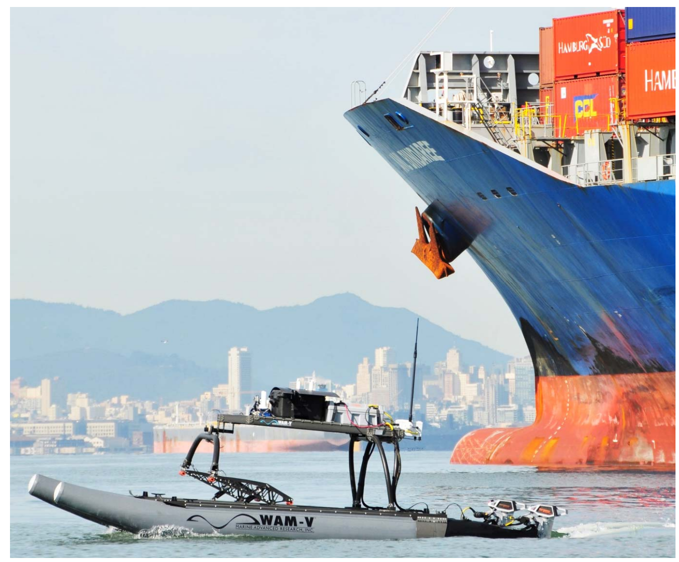

Fig. 2 The 16' Sentinel WAM-V conducting an automated harbor patrol

A. Wave Adaptive Modular-Vessel (WAM-V) Design

Complex, rapidly changing, and highly variable sea states created through interactions of wind, wave, tide, and currents, ultimately constrain the efficiency and dynamic stability of vessels at sea. The inherent tradeoffs between vessel stability, hull speed, draft, payload capacity, maneuverability and seakeeping ability, in turn, can severely limit the scope, range, duration and efficiency of mission critical operations. The twin hulls of a WAM-V continuously conform to the water surface, dissipating wave energy and maintaining forward vessel momentum. The articulations and suspension system of the WAM-V superstructure dampen rotational and translational forces thereby reducing unwanted vessel movements and improving maneuverability. Multiple versions of unmanned, remote-controlled and autonomous WAM-V systems [8] [9] have demonstrated the adaptive utility of these non-traditional vessels for maritime applications.

WAM-V's are now being considered as ideal carrier platforms [10] serving in various capacities of cooperative autonomy as self-healing *ad-hoc* communication networks, recharge nodes, docking stations for underwater vehicles [11]

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[1] Primitive radio controlled boat and aircraft drones were used by the U.S. Navy at Bikini Atoll in the Marshall Islands for in-situ radioactive sampling during the 1946 Operation Crossroads atomic bomb testing.

[12] and (in this study) as a launch and landing vessel for small aerial quadcopters.

B. CBRNE - Incidents and Instruments

Common usage of the acronym CBRNE can refer to the weaponized or accidental release of Chemical, Biological, Radiological, Nuclear or (high-yield) Explosive agents or indicate the various hardware or sensing methods used to detect or quantify these same elements. CBRNE environmental threats can be characterized according to toxicity and hazard levels emanating from volatile gases, alpha, beta, and gamma radiation (fallout), improvised chemical devices, biological aerosols, chemical and biological powders, improvised radiological dispersal devices (dirty bombs), toxic inhalation hazards and many other Hazardous Material (HAZMAT) compounds. [13]

CBRNE disasters are typically resource and time intensive requiring humans to corporeally place or carry sensor equipment for *in-situ* sampling. As such, interoperability, resource unification, and data standardization are required to support the evolution of a fully integrated and modernized CBRN detection system. [14] Simply put, early and accurate detection is the key to effective response and expert mitigation. As of 2012, the Department of Homeland Security (DHS) created a comprehensive standard known as the *Integrated* Chemical, Biological, Radiological, Nuclear and Explosive (ICBRNE) program that creates standards for regional interoperable sensor systems that monitor, report, display and alert appropriate officials during an emergency event. [15]

IV. Understanding Maritime Security

Port and harbor security in the United States can routinely span multiple agencies and overlap city, county, state, and federal agencies, each with particular responsibilities, regulations, workflows, and chains of command. For example, an explosion and fire at a petrochemical refinery and tanker port might involve local firefighters, harbor police, a HAZMAT team, the Coast Guard, and specialized FBI units if criminal misconduct were suspected.

A. The U.S. Maritime Domain

National maritime domain awareness and security fall under the purview of the Department of Homeland Security which is tasked with assessing threat levels, vulnerabilities and consequences. The US Coast Guard serves as the lead Federal agency in security response and threat mitigation and operates under a unified command approach with an Incident Commander responsible for supervising all activity and coordination. A command structure overseen by the Incident Commander(s) may have 9 or more officers in charge of over 33 units depending on the type of incident [16].

Although the Department of Homeland Security is responsible for determining which CBRN agents present ensemble security risks to the United States, hazardous and toxic materials are regulated through the following Federal U.S. agencies:

- Environmental Protection Agency
- Department of Transportation
- Nuclear Regulatory Commission
- Occupational Safety and Health Administration

B. Organizational Interoperability

Designing a vehicle-sensor interface for optimum interoperability is paramount to overcoming disparate agency and jurisdictional information sharing gaps as well as fostering timely and well-coordinated responses to emerging threats.

Discerning levels of supervised automation, autonomous over-ride interfaces, parameter input methods, and data transmission needs for a human-in-the-loop system design can be guided by understanding command structures, work flows and the primary responsibilities of various agencies involved with incident response.

C. Regulations, Standards, and Protocols

Furthermore, when designing unmanned systems for intelligence, military, or law enforcement agencies it is important to anticipate and keep current of evolving protocols which may influence network and data security engineering decisions. The National Maritime Domain Awareness Architecture Plan (NMDAAP) mandates new standards now being established by U.S. Defense, Transportation and Intelligence communities that defines mission-focused information exchange protocols for standardized vocabulary and secure data integration of maritime information via the Maritime Information Sharing Environment (MISE).

Unfortunately, legacy regulations such as the International Maritime Organization 1972 Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) have not kept pace with USV innovation in defining the manner in which automated surface vessels interact with manned (human-at-the-helm) vessels or which USV sensor(s) are suitable substitutes for human perceptions of seeing, hearing and feeling used in piloting traditional watercraft.

V. Human-Robot Intelligent Interactions

A. Sensing, Perception And Cognition

Humans are able to make adaptive inferences in indeterminate states with fluctuating degrees of uncertainty and incomplete information, however the quality of tactical decisions is largely dependent on contextual sensitivity [17]. Machine learning and hybrid probabilistic modeling techniques [18] are augmenting human pattern recognition and improving natural human abilities to dynamically adapt to emergent changes in ontological domain states existing outside of (or even parallel to) *a-priori* mission objectives or parameter constraints. Improving human perceptual acuity is especially relevant for piloting or comprehending and interpreting multi-parameter input to facilitate dynamic forecasting [19].

In fact, a major benefit of elevated task automation in sensor-based robotic technologies is that by computationally reducing parameter space dimensionalities from multiple data sources, humans are able to focus on higher levels of strategic and inferential decision making [20]. Furthermore, adaptive automation in control and instrument display systems, such as providing operational support to humans only when needed or requested, creates stable system performance and minimizes human error by reducing information overload and fatigue [21].

B. Data and Information Fusion

Combining sensor data or information in a meaningful way to estimate or predict discrete and continuous state variables (e.g. identity, attribute, activity, location, motion or relational interactions) is the essence of data fusion research. A sufficient discussion of data and information fusion models [22] is beyond the scope of this paper, however a practical simplification of these concepts for maritime security applications might consider raw instrument data flow (e.g. from Automatic Identification System (AIS), Radar, GPS, infrared cameras and hydrophones) to create low-level information (e.g. vessel classification, collision avoidance/ tracking, heat signatures, or acoustic profiles). High-level functional processes would then transform these aggregate inputs through statistic, algorithmic, and operational logic so that human cognitive processes are able to synthesize patterns, draw inferences, map contextual associations and to create predictive models which enhance situational awareness and support decision making processes (Fig. 3).

C. Human-Machine Interfaces

The optimal manner to incorporate humans into higher order decision process is a challenging problem because although humans interacting with robotic systems may be domain experts, they are not equally likely to be robotics experts or nimble pilots endowed with acute motor reflexes.

Although the variety of operational capabilities, sensor packages, and levels of automation in unmanned and human hybrid environmental sampling systems [23] is continually improving, the inherent heterogeneity of sensor systems can create overly rigid or isolated approaches to the engineering of human-machine-interfaces [24]. It is therefore important to incorporate process-design methods for control and display interfaces which complement hardware and vessel system-design decisions and reduce unnecessary path dependencies based on hardware architecture and physical component interactions.

Previous work on systems design for Autonomous Underwater Vehicle real-time graphical user interfaces [25] describes effective approaches to integrate vehicle navigation, scientific sensor, and vehicle system status essential for exploring unstructured environments while under human operator supervisory control. What is clear from these studies and related automated aircraft control research [26] is that complex monitoring devices used as pilot or navigational aids for automated vehicles must have an intuitively rendered baseline indication of a 'normal' state without overly complex or cluttered displays.

VI. VEHICLE - SENSOR INTEGRATION

A. ICBRNE Sensor Fusion

The Lifeline Interoperable Network Communicator (LINC) is a self-powered, Wi-Fi compliant field environmental monitoring tool with an integrated GPS, network

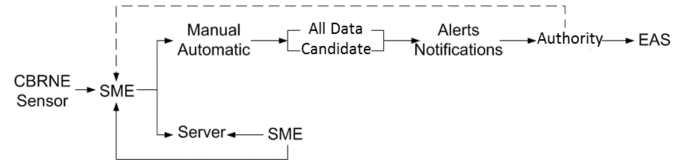

Fig. 3 Conceptual Diagram of ICBRNE Information Flow

communicators, and cellular uplink that enables remote live viewing of the information gathered from interfaces with CBRNE sensors capable of transmitting sensor readings and location data once per second for 14 hours (Fig. 4).

The Multi-Meter Viewer consolidates live data from various CBRNE sensor displays as virtual instrument faceplates integrated into a map view showing the instrument's location, alarm status and other meta data. The Multi–Meter Viewer functions as a remote central command center, displaying data and providing both audible and visual alarms. A Geographical Information System (GIS) interface provides instrument tracking and survey information as map layers allowing Subject Matter Experts (SME), incident commanders and safety professionals the ability to instantly view and share field instrument data. Table 1 provides a summary of common network and public safety terms relevant to this field.

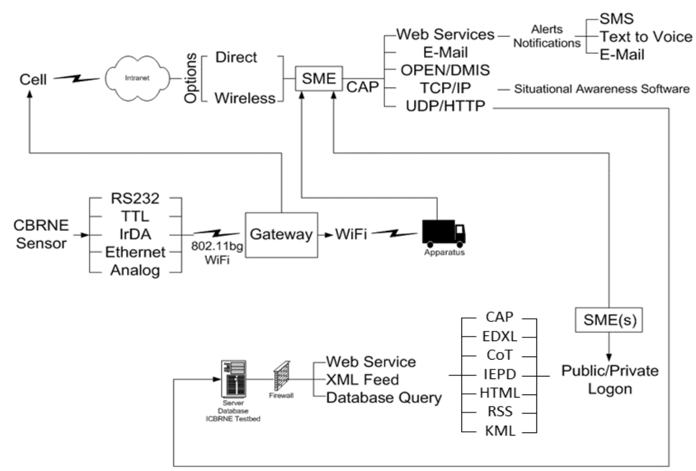

Fig. 4 Data Flow and Network Design of an ICBRNE

Table 1 Information System and Public Safety Acronyms

SME	Subject Matter Expert
CAP	Common Alerting Protocol
EAS	Emergency Alert System
EDXL DE	Emergency Data Exchange Language Distribution Element
UDP/HTTP	User Datagram Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
CoT	Cursor on Target
UCore	Universal Core
IEPD	Interagency Exchange Protocol Document
Rss	Real Time Simple Syndication
HTML	Hypertext Markup Language
XML	Extensible Markup Language
KML	Keyhole Markup Language
TTL	Transistor Transistor Logic
IrDA	Infrared Data Transmission

B. Navigation, Control, and Telemetry

The Sentinel WAM-V is equipped with independent control units with onboard processors. A high-level controller based on a Linux operating system handles waypoint navigation and communicates with a low-level controller, GPS, and Inertial Navigation System (INS). The low-level controller interfaces with twin electric outboard motors and a parallel Lithium Ion battery bank communicating through RS-485 protocols. The low-level controller controls vessel velocity and direction through differential steering actuators mounted on the outboard motors. Control input and feedback information between the low-level controller and high-level controller are transmitted via RS-232. A pilot can operate the Sentinel WAM-V in a Line-of-Sight mode using a UHF handheld radio controller which interfaces directly with the low level controller and provides an independent analog video Point-of-View from the vessel. A second pilot can take over control of the Sentinel drone at increased distance via the mobile Command Station which concurrently transmits sensor readings, video imagery, vessel status, and position. Figure 5 shows a graphical user interface for controlling the Sentinel.

The Sentinel WAM-V communicates with the Command Station via network-redundant 2.4 GHz ISM band radios. Commands and feedback information (as represented in Fig.6) are sent on this wireless link between a computer and high-

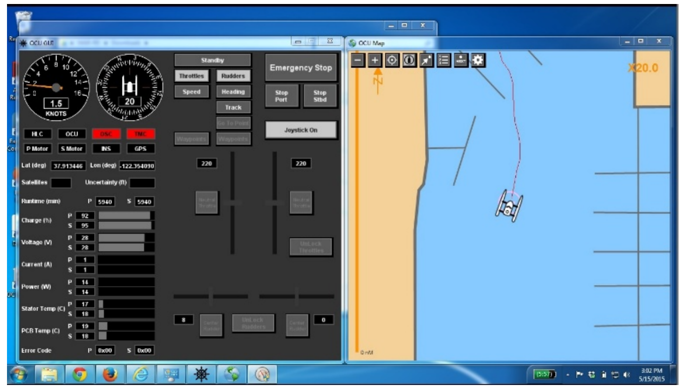

Fig. 5 The Sentinel WAM-V Command Station GUI. The tele-operated vessel waypoint navigation and differential steering and velocity control system allow offsite vessel piloting. The Graphical User Interface indicates system status, motor amps, temperature, battery charge, velocity, range, direction, and vessel position in a dynamic GIS environment with embedded nautical chart layers.

level controller. A Windows based computer runs the control software GUI and provides a moving chart of the Sentinel's location. Network carrier switches allow continuous vehicle teleoperation via multiple cellular providers to insure minimal

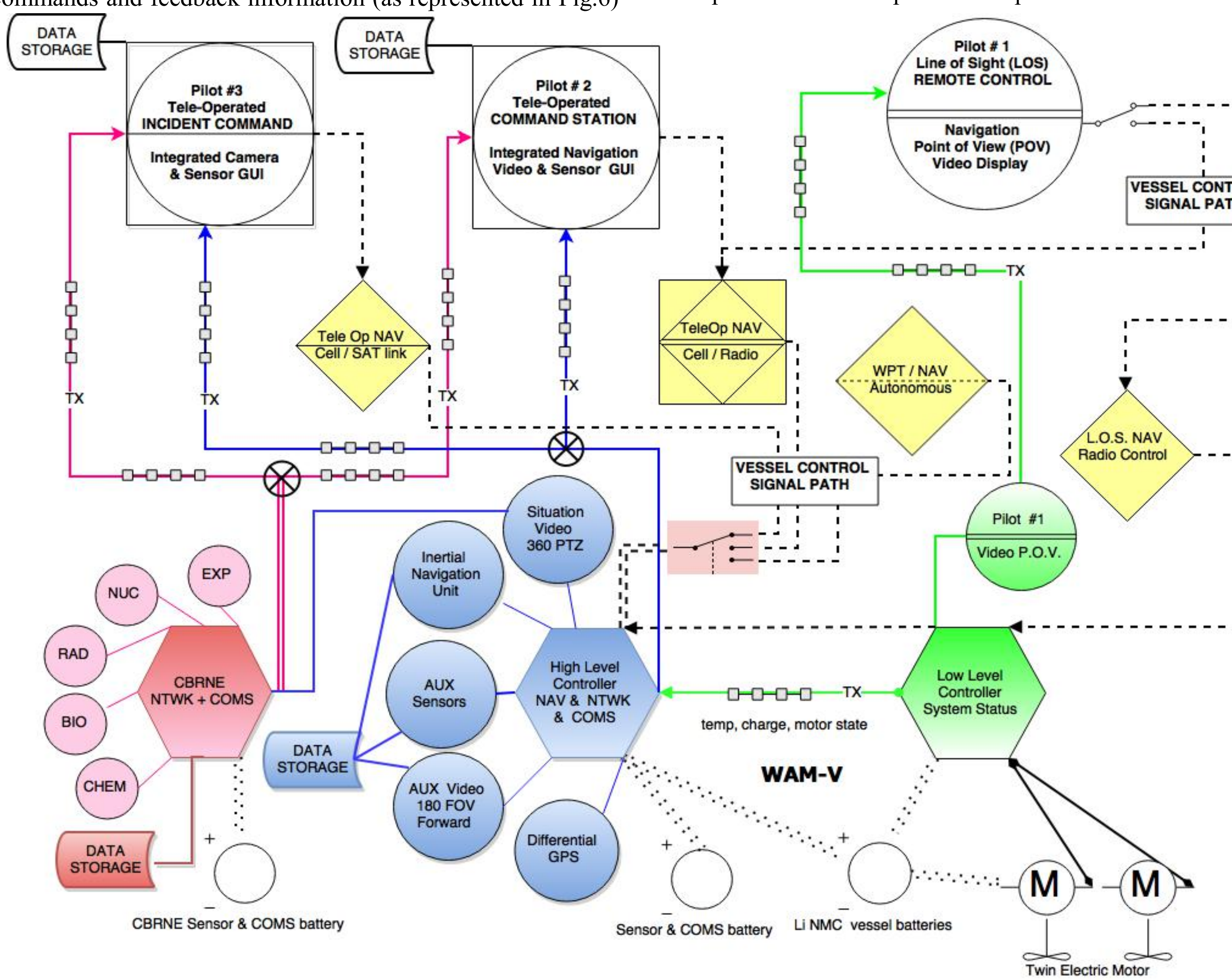

Fig. 6 Sentinel WAM-V instrument, network and control process diagram

signal drop out. An autonomous station keeping mode allows the vessel to return to launch coordinates or continue via waypoint navigation to predetermine coordinates and transmit a location signal when a network is re-discovered. All sensor, imagery, and navigation outputs are replicated to create a Common Operating Picture (COP) for an offsite Incident Command center which can also assume control of the vehicle through a cellular GSM mobile-web interface.

VII. CONCEPT OF OPERATIONS (CONOPS)

A series of Regional Maritime Security and Response exercises conducted in 2014 and 2015 by the Naval Postgraduate School Center for Asymmetric Warfare (CAW) focused on improving the capability of port personnel and regional public safety organizations to mitigate, respond to, and recover from effects of a major disaster along the southern coast of California. Coast Guard, harbor police, EMS, HazMat, firefighters, FBI, Navy, DHS, and private security firms were involved with multiple training and mass casualty exercises to test response plans, processes, and systems. Scenarios included a hijacked passenger ferry, search and rescue exercises near burning vessels, and remote investigations of small Target of Interest (ToI) vessels suspected to contain explosives or radioactive material.

A. Multi-domain Unmanned System in support of Port and Maritime Security

Coastal Trident 2015 tactical demonstrations were conducted to evaluate the capabilities of an integrated multi-domain vehicle system and remote sensor suite to provide a Common Operational Picture for standoff detection of CBRN materials with the following objectives:

- Demonstrate the capability to deploy and navigate an unmanned surface vessel to monitor routine marine traffic using cameras and CBRN sensors.
- Demonstrate the capability to launch and recover an unmanned aerial system (UAS) from an unmanned surface vessel (USV) to provide for enhanced identification and characterization of Targets of Interest (as shown in Fig 7 and Fig 8).
- Evaluate the capabilities of an integrated system of unmanned technologies to support control, data collection, and multi-domain situational awareness.
- Explore Concept of Employment (CONEMP) for collaborative UAS/USV systems to provide persistent ISR capabilities and remote monitoring for hazardous conditions in the port and maritime domains.

Fig. 8 Remote video capture of Target of Interest vessel with suspected CBRNE materials during Coastal Trident tactical exercises.

In order to satisfy the operational mandate for the Coastal Trident tactical demonstrations, a 5 meter Sentinel WAM-V was equipped with a (CBRN) detection system and outfitted to

Fig. 7: Aerial drone video point of view during landing approach to the Sentinel WAM-V marine drone

carry a remote controlled quad-copter drone to create a common operational picture for offsite incident commanders. These tactical sea trial scenarios required the Sentinel WAM-V to deploy to strategic locations to monitor incident conditions and environmental data. A remotely operated quadcopter was launched from the Sentinel WAM-V to provide a synoptic perspective of the target vessels and to give live video feeds of contextual information regarding vessel size, location coordinates, human presence and proximity of the target vessels to other vessels.

Remotely located pilots directed the Sentinel WAM-V based on coordinates provided by the quadcopter GUI and when arriving close to the aerial drone hover point, switched to Sentinel video feeds and navigational aids of the vessel. The Sentinel WAM-V was then piloted based on observational

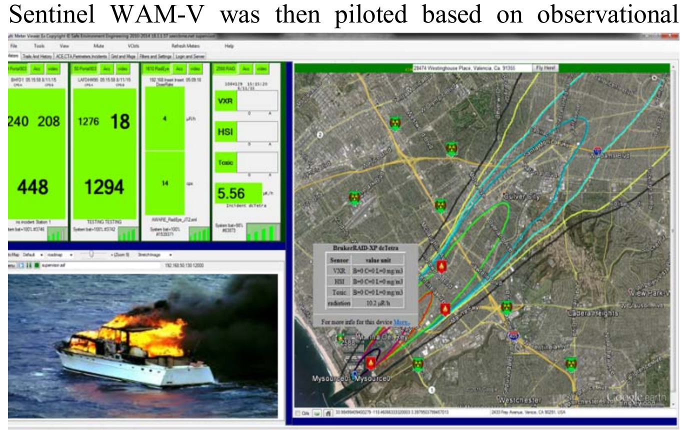

Fig. 9 LINC Multi-Meter ICBRNE graphical user interface showing sensor instrument readouts, contextual video, vessel location and real time dispersal models in an integrated GIS environment

hazards and sensor readings as in Fig. 9 supplied through a tele-operated GUI dashboard showing CBRNE instrument readings, real time video and geo-referenced vessel and quadcopter position in a GIS environment. Offsite Incident Command directed additional maneuvres based on the situational awareness afforded by the integrated informational input of the quadcopter, Sentinel WAM-V, and ICBRNE sensor telemetry updates.

VIII. Discussion and Future Work

Shortly after creating the Telautomatic Boat, Nikola Tesla went on to document his ideas of embodied and cooperative machine autonomy and correctly predicted, *"Telautomata will be ultimately produced, capable of acting as if possessed of their own intelligence and their advent will create a revolution* [27]." Indeed, transformative advances in telecommunications and micro-processing, are making Tesla's predictions over a century ago a common reality and accelerating the potential of beneficial uses of robotic marine systems.

A. Improving Decision Support for Maritime Security

The severity and consequences of emergency events unfolding in the maritime domain are ameliorated by having a common operational picture which benefits from the improved sensing, communication, and distribution of information that robotic vessel - sensor systems can provide. Continual focus should be directed towards developing efficient, adaptable and intuitive human-machine interfaces that augment decision support through robust and reliable networks.

B. Data and Telemetry Considerations

With the ubiquity of small vessel - sensor platforms collecting high resolution imagery and dense data products, bandwidth constriction, storage limitations, and power consumption constraints become apparent, especially for real-time decision support requiring persistent and uninterrupted telemetry.

Data is not information. By understanding and expirementing to discover optimal sampling rates, compression levels, and instrument gain settings necessary to detect phenomena of interest, substantial bandwidth and power savings can be achieved. Onboard automated storage and data processing can help synthesize data into actionable information for telemetry provided the information product and end use is well defined. Automated change detection algorithms can also be designed to trigger higher resolution sampling at periodic intervals when anomolies are detected rather than continuously transmitting dense data packets.

C. Cooperative Automation and Compassionate Autonomy

Future work should focus on advancing cooperative automation between aerial, surface and submarine drones to reduce systematic human error and improve response times and resource allocation for evolving marine security threats. As multi-vehicle systems intelligence approach contemporary understanding of sentience, robotic systems designers should be continually cognizant of when and how humans interact in supervisory roles with increasingly autonomous systems. Human-machine interface design should always ensure ethical and transparent command and mission decision responsibility while ensuring data security, encryption, and chain-of-custody for sensitive information. As the mythological stories of Prometheus and Pandora portend, emergent technologies may have unexpected consequences.

Acknowledgments

I would like to thank David Lamensdorf of Safe Environment Engineering for ICBRNE sensor integration and Dr. Ugo Conti, Mark Gundersen, Toni Lei, and Matt Steiger of Marine Advanced Research for engineering and systems integration for the Sentinel WAM-V sea trials. I appreciate the input from Assistant Chief of Police Michael Hillmann, and Lieutenant Ken Hawkes of the Los Angeles Port Police for their input on interoperational design considerations for law enforcement. Thanks to InstantEye for supplying quadcopters for multiple tactical demonstrations and to Christina Birdsey, Director of Operations and Security at the Port of Hueneme and to colleagues at the Naval Postgraduate School and Center for Asymmetric Warfare for assistance in coordinating multi-agency demonstrations.

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