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14. ABSTRACT
The scalable emergency system is intended to cover the full scale of possible at-sea incidents from the routine to the rare; from the detection and decontamination of a single piece of equipment before it is loaded on a vessel, to the response, rescue, containment and rehabilitation of a vessel in open waters. The system will be able to safely and quickly decontaminate cargo and personnel, as well as entire vessels at sea and in port. This report details the results of a formal evaluation of seven (7) concepts that were presented as part of the Brainstorming Workshop.

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Program Officer
Attn: Kelly Cooper, Code 331
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April 11, 2007

Subject: Brainstorming Workshop Report, Contract N00014-06-C-0599

Dear Ms. Cooper,

In fulfillment of Contract Line Item No. 0001, Data Item No. A005, *Report on Brainstorming Concept Evaluations*, of Contract N00014-06-C-0599, *Feasibility and Top Level Design of a Scalable Emergency Response System of Oceangoing Assets*, attached please find a copy of the initial report.

If you have any questions or comment, please contact me at 484-557-6590 or edougherty@ablazedevelopment.com.

Very respectfully,

Edmond J. Dougherty
President

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Report on Brainstorming Concept Evaluations

In support of:

Feasibility and Top Level Design of a Scalable Emergency Response System for Oceangoing Assets

Office of Naval Research Contract No. N00014-06-C-0599
Contract Line Item No. 0001, Data Item No. A005

Submitted to
Program Officer
Attn: Kelly Cooper, Code 331
Office of Naval Research
875 N. Randolph Street
Arlington, VA 22203-1995

Submitted by
Ablaze Development Corp.
April 11, 2007

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Overview

This report presents the formal review of the major concepts presented in the Brainstorming Workshop held on December 13th and 14th 2007. During the Brainstorming Workshop a number of ideas were developed and presented. Since the workshop, the major concepts were further refined by the concept originators. A refined description of each of the major concepts is presented in these pages, as well as appendices that further detail equations and related incidents to substantiate the concepts addressed. Based on the refined concepts, the project team reviewed each for feasibility, value, risk, cost and, generally, a "best fit" match for the current project's statement of work. While all of the concepts are considered valuable, those that were considered a best fit for the immediate needs of the current project were selected for further investigation. Hopefully the other concepts will also be further investigated during a later phase.

Concept Evaluations

This section includes the results of a formal evaluation of seven (7) concepts that were presented as part of the Brainstorming Workshop. The concept evaluations include:

1. *Water-borne Autonomous Robot*, Villanova University
2. *Microarray Identification*, Villanova University
3. *Optical Fibers for Detection of Radionuclide Contamination*, Villanova University
4. *Chemical Warfare Agent Sensing and Remediation*, Villanova University
5. *A Cable Driven Monitoring and Decontamination Robotic System*, Villanova University
6. *Terahertz Imaging Technique for Bio-defense*, University of Delaware
7. *Emergency Response Decontamination Ship*, Ship Recycling Research Institute

A detailed description of each concept is provided in the sections that follow.

Water-borne Autonomous Robot

Villanova University------Dr. C. Nataraj

Introduction

The concept of an ocean-going decontamination system has been proposed to effectively diagnose, contain and decontaminate the results of a possible nuclear, biological or chemical incident at sea. Such a decontamination system will need a set of autonomous devices which can be deployed to carry out various operations with least human involvement. In particular, the ability to sample the water or air for radiological, biological or chemical agents and the ability to carry a sample from point to point for a short distance in water is of tremendous utility. It is this need that motivates the current proposal.

Concept

This evaluation aims to carry out a preliminary analysis for the development of a water-borne autonomous robot, nick-named "The Sea Strider," capable of self-navigating short sections of the sea with a morphability to be able to climb aboard a ship.

<u>**Background**</u>

Robots capable of legged, wheeled and tracked motion for land use have been developed over the past three decades; famous examples include the Mars Rover and more recently, the Honda humanoid robot. Many platforms of unmanned air vehicles with some limited autonomy have been developed. Many underwater vehicles have also been developed largely by the Navy. Our focus here is on robotic devices that can traverse the water on or just under the surface; we will also require the functionality of being able to climb aboard a ship. Hence this literature survey is limited to any such existing devices.

In recent years, the interest in mimicking nature's approaches has increased in order to improve the performance of man-made mechanisms in liquid environments. This is mainly due to promising features that biomimetic mechanisms have, and conventional propeller driven (or water-jet) mechanisms lack. The majority of current liquid environment applications are characterized by high Reynolds numbers. As a result, present biomimetic mechanisms focus on fishlike swimming techniques since these outperform other aquatic creatures in these types of environments. Before we present a survey of swimming robots, it may be hence instructive to review fish swimming mode classifications [20] using the body's part used for propulsion. The pictures (widely available) are omitted for reasons of brevity.

- *Anguiliform*: The entire body is used to propel, and a muscle wave is propagated perpendicular to the body. The body is usually elongated, like in snakes or eels.
- *Carangiform*: About a third of the last part of the body is used for propulsion by oscillating the caudal fin and the caudal peduncle (tail). A subclass of carangiform

is *thunniform*; such fish swim very fast. Their caudal fins have a high aspect ratio. An example is the red tuna, the fastest fish in the world, with speeds of up to 100 mph.

- *Subcarangiform*: this is a term used to define fish that are between anguiliform and carangiform. The oscillation is smaller than in anguiliform mode. An example is the salmon.
- *Ostraciiform*: only the fins are oscillated and the rest of the body does not move. The paired fins are mainly used to propel and the caudal fin is less used. The bodies of these fish are often inflexible. They mainly live in reefs and swim slowly, and hence maneuvering is a more important aspect of the motion. Example: boxfish.
- *Labriform*: these are like ostraciiform fish except that the caudal fin is used as a rudder and pectoral fins are used for propulsion. Example: angelfish.

As stated above, many researchers have derived inspiration from the above swimming modes of natural fish. Current and recent work on fish-like robots includes the following.

- The National Marine Research Institute in Japan [93] has been working on multiple projects, including maneuvering, swimming performance and modular robotics for water.
- The University of Essex in England [37] has multiple interesting fish robot projects.
- Massachusetts Institute of Technology [108, 109] has developed a set of thunniform robots called RoboTuna; their objectives were to develop a more efficient and less noisy propulsion system for underwater vehicles; these robots are not autonomous. University of Michigan [11] has developed a robot called B1 which propels itself with two frog's muscles in a glucose solution.
- Mitsubishi Heavy Industries developed a fossil fish robot in 2001. The purpose was to display Coelacanth, an extinct fish, to the visitors in amusements parks.
- Beijing University in China [139, 62, 63] has built a semi autonomous underwater vehicle propelled by a fin for archaeological exploration, which resembles torpedoes.
- University of California has recently built a biomimetic micro underwater vehicle (12 mm long) with oscillating fin propulsion.
- Some robotic clubs have also built fish robots ("hobby" robots) like Dongle [34], a fish robot developed by the Seattle Robotic Society.
- Ecole Polytechnique has developed a Boxybot [29] among many other similar swimming robots.
- Amphibious robots typically rely on walking motion, where the robot is limited to the ocean floor. This greatly simplifies the design requirements, but limits the robot's ability to navigate obstacles. Examples include a mechanical hexapod, called Aqua [8], at McGill University in collaboration with York University and Dalhousie University, and Ecole Polytechnique in Switzerland [29] who have developed *AmphiBot I*, an amphibious snake robot capable of crawling and swimming as well as an elongated body robot resembling the lamprey.

- Some recent exotic versions of aquatic robots include the basilisk lizard (*Basiliscus plumifrons)* which has the unique ability [111] to walk across water (the so called Jesus lizard robot); practical issues especially in unruly sea conditions remain unsolved.

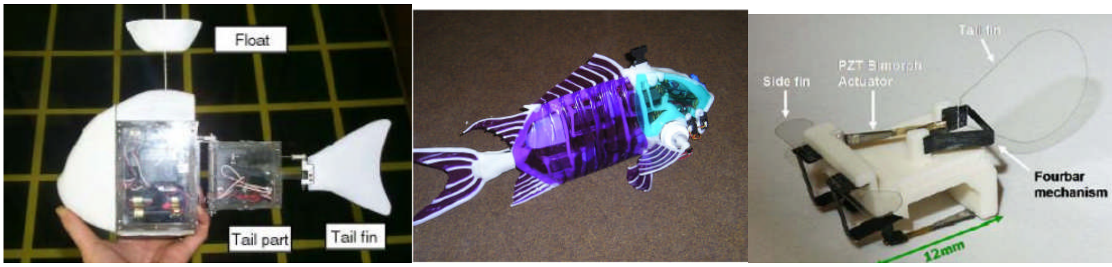

Figure 1: Example robotic fish (PF300, G4, boxfish)

Some examples from the referenced web sites are shown in Figure 1. Others may be found in the references listed at the end of the proposal in Appendix A. This is an evolving field, and with all of these research efforts, terrestrial and/or aquatic mobility, control, navigation, communication, obstacle avoidance, and payload remain critical issues to be resolved for successful operation.

Proposed Concept

Ultimately, our proposed robotic system needs to be able to do the following.

- Traverse short stretches of the sea in multiple sea states in an autonomous manner.
- Employ a variety of sensors to assist its own navigation and localization.
- Communicate with the host ship and the destination ship with the required bandwidth for sensor information, control, video, etc.
- Carry a payload as required.
- When the destination ship is reached, be able to board the ship and climb aboard without shedding any of the payload or destroying itself.
- Work cooperatively in a group of similar or dissimilar robotic devices.
- Be able to come back to the host ship (homing).

The expected project outcomes from the current phase would be clearly more limited in view of the time and resources available; it should hence start with an analytical study of various designs of robots that will benefit from biomimetics but will not necessarily be limited to that. In other words, an improvement on nature's own efficient designs would be the first objective. The concept is that of a fish-like robot with (possibly hidden) legs and standard actuating devices (motors and linkages) that help it climb the sides of a ship.

The different phases of the current project are expected to be the following.

- Development of conceptual designs following the general principles outlined here.
- Technical analysis (explained in the next section).

- Experiments (of parts of the system) to verify and validate specific technical and mathematical models.

Technical Issues

The technical issues associated with being able to achieve locomotion and autonomy for the Sea Strider can be classified as follows.

1. Dynamics and hydrodynamics
2. Control design for locomotion
3. Localization
4. Navigation and Obstacle avoidance
5. Materials
6. Motive force design (motors, links, and other mechanisms)
7. Electronic hardware, sensors, communication devices, and power sources.
8. Mechanical design

Of the above tasks, 1 and 2 present the most difficulty and need fundamental scientific investigations. Although 3 and 4 are not trivial, they can be adapted from existing research in the general robotic field and from the PI's own research background. 5 can be an issue with the peculiar constraints the problem is likely to pose, but is more likely to reduce to an optimal selection from a wide variety of choices. 6, 7 and 8 are expected to be standard engineering design issues – not trivial, but not expected to result in technical breakthroughs. It is hence expected that much of the effort in the initial phase will focus on 1 and 2.

There are other important issues which are worth mentioning. For example, several liquid environments are harsh and robots would be required to withstand high pressures, high temperatures, corrosive chemicals, and impact with debris. Hence, robustness is an important factor in prolonging the life of the device. In addition, stealth and blending well with the surroundings are important in tactical missions that require avoiding detection. Finally, navigation in real environments requires control techniques to achieve tasks autonomously. Although all these are important issues we should not focus on them in the first phase of the project.

Dynamics & Hydromechanics

Clearly, the fish (or, any aquatic robot) moves through water by exerting forces on the water in accordance with a control law applied to a movable control surface. Hence, an accurate design needs an analysis of the hydromechanics, dynamics of the robot and a suitable control law. The three aspects are hence intertwined and cannot be easily separated for analysis. However, it is instructive to discuss the three aspects individually in order to elucidate the challenges clearly.

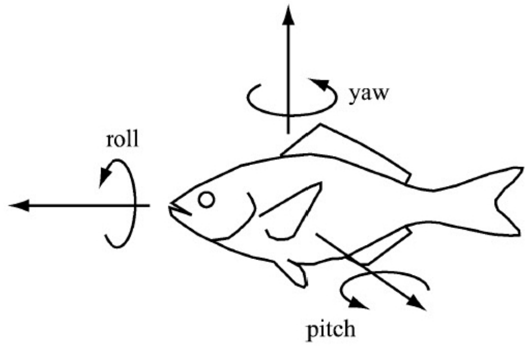

Figure 2: Dynamics of water-borne robot; six degrees of freedom

The dynamics of the robot (if it has only rigid components) is given by that of a rigid body in three dimensions. Such a rigid body has six degrees of freedom – three translational and three rotational. They are illustrated in Figure 2. The equations of motion are complex and are derived in detail as a supplement in Appendix B.

A fish or the robot being ultimately conceived here is not rigid however. In fact, the flexibility of the fins is important and advantageous to effective and optimal control. Hence the dynamics involves infinite degrees of freedom, or in other words, is governed by partial differential equations with large motions. This is a nonlinear dynamic problem in itself (even without the hydrodynamics). Accurate modeling is important in order to be able to predict the dynamic behavior precisely; more importantly, accurate models make the control problem much more tractable.

Recent research in the performance of the fins and tails of live fish has revealed that the rhythmic, oscillatory motion of fish body and fins results from a matching of effective impedance between that of the dynamics of the actively controlled musculature and the fluid loads. This is a fluid-structure interaction problem that requires deep understanding of the control laws employed by fish, the mechanical and material properties of the actuating muscles and the body of the fish, as well as the fluid mechanics of the flow around the body. Published papers that include observations and studies of fish provide information on the body properties, while fluid mechanics studies provide insight on basic flow mechanisms [73-77, 20, 30, 134]. Conceptual advances are, however, still needed in order to simplify the problem of fish locomotion, and to provide engineering information to build robotic vehicles. Our vehicles will in fact employ actuation mechanisms and control laws that could be different from fish; hence, it is expected that the impedance matching (if indeed it is possible) would not be the same since the actuation methods are different.

A few fundamental questions then arise; answers to these questions would help arrive at an optimal robotic swimmer.

- How is the motion of fish affected by the mechanical and material limitations of their own bodies and the control laws they employ?
- Is the final motion non-optimal (or sub-optimal) as far as fluid mechanics and dynamics are concerned, due to structural, material, and control-law limitations?

- How can we extract optimal flow mechanisms that can also apply to different actuation and control mechanisms?

Motion within viscous liquids (such as water) carries a heavy penalty on the energy required for locomotion and maneuvering if the motion is not optimized. It would pay, therefore, at least for the fastest and most agile animals, to explore optimization of the fluid mechanics of their locomotion at the expense of redesigning their structure and control laws subject to the limitations of the available materials. This must be achieved through optimization of body geometry and structure, as well as body actuation and control. This then is the key to designing highly efficient robotic swimmers.

Although several factors contribute to successful autonomous exploration of liquid environments, the most important performance parameters include the following: locomotion efficiency, maneuverability, mechanism adaptability, mechanical robustness, and autonomy (or level of control). An efficient use of supply energy for locomotion would also permit longer mission ranges and smaller power supplies.

Maneuvering capabilities, enabled by the number of degrees of freedom, are needed for navigation in complex geometries. In addition, environment properties such as density, viscosity, or the surrounding geometry can change over the course of a mission. In such situations, mechanism adaptability is required in order to maintain locomotion performance.

Some recent advances will help in guiding our research. For example, studies [126] have suggested that gains in locomotion efficiencies could be achieved over traditional propelled devices when implementing fish swimming techniques. Studies have proposed that mechanisms implementing fish swimming techniques could also yield superior maneuverability by diminishing turning radii and improving acceleration capabilities. In order to improve performance, biomimetic mechanisms should optimally implement geometric and kinematic attributes from creatures with good performance in environments of interest. By mimicking both the motions and body shapes, we hope to recreate the dynamic interactions with the environment that yield superior locomotion characteristics. However, biomimetic approaches can only go so far with conventional discrete and stiff mechanisms used to implement them.

Most motions displayed by nature’s creatures are kinematically complex. Therefore, there is an inherent disadvantage when trying to imitate these with discrete mechanisms since large numbers of degrees of freedom are required making the resultant structures very complex. The resultant complexity can diminish internal mechanical efficiencies mostly through frictional losses. In addition, the large number of parts reduces mechanical robustness since the flexibility required in biomimetic vehicles increases the challenges of sealing and protecting sensitive parts. Also, an increase in the number of degrees of freedom increases the sophistication of control techniques needed. These limitations influence the performance displayed by current biomimetic mechanisms [101].

In summary, most real fish appear to have much higher efficiency than the best robotic mechanisms. This could principally be because we have clunky (!) rigid mechanisms trying to imitate nature's beautifully evolved designs. Hence, we feel that flexible control surfaces may help us bridge this gap. This should be our final intended design.

Control

Control of nonlinear processes is an evolving research area. There are roughly two categories: accurate model-based controllers and approximate heuristic methods. Model-based control procedures include optimal, adaptive, model predictive, sliding mode, and many other methods. Heuristic methods include fuzzy logic, neural network and combination procedures. Analytically sound model-based methods are accompanied by stability guarantees and are reliable and robust with predictable ranges of performance and accuracy, whereas, in general, heuristic methods do not come with any such assurances. However, it may be possible to get "quick and dirty" solutions using such methods. Given the limited time in the first phase of the project, the initial focus should be on a heuristic method to simulate the effect of control on the dynamic performance.

Other Issues

Size: The study should attempt to develop a range of sizes by carrying out non-dimensional parametric studies of hydrodynamics and dynamics.

Scalability: Scalability is an important consideration in the feasibility stage, as a design that is acceptable may be no longer so if a bigger or smaller design is needed for the application. This issue should hence be carefully considered using nondimensional models. In general, scalability will break down for much larger or for micro situations. In any event, the limits of such scaling should be explored in order to guide future designs.

Evaluation

An ocean-capable decontamination system is a very novel concept that is the overall project objective. Such a system could deal with a variety of situations as documented in the recent Brainstorming session held at Villanova University. Many of the scenarios discussed would involve sensing and/or decontaminating an area that could include the water itself or a ship in water. In such instances it would be necessary to collect samples, or to distribute certain agents in the water, or be able to autonomously reach the contaminated ship and to return to the host ship while carrying a specific payload. All of these tasks would need, and could benefit enormously from an aquatic robotic system which would reduce exposure of dangerous contaminants to personnel. In this context, an autonomous robotic system can be effectively considered to be a *mobile intelligent sensor* thus extending the range of sensing capabilities as well as reducing the number of sensors needed for a large area.

The proposed study here is preliminary research to determine the most optimal designs for the elements of such a system by carrying out fundamental and technological studies. The proposed designs are quite flexible permitting tailoring to a wide variety of applications. The risk involved is that the proposed set of devices may not be as efficient as necessary rendering them impractical for long term use. The potential long-term benefit is the increased insight into a general family of innovative devices that could help spawn a new technology.

Relevance to the Navy & Beyond

Automation is an important priority for the Navy with the long-term objectives of reducing manning and decreasing casualties. In addition, many operations such as decontamination and handling hazardous substances are clearly better done by automated tools than Navy personnel to reduce injury and exposure to dangerous circumstances. As the Navy moves towards Sea Basing it is ever more important to collect a large set of automated tools that work in unison in high sea states to perform critical missions. The proposed project is one of several such automated tools that can considerably enhance the Navy's mission.

In the commercial arena, automated robotic systems have multitudinous applications that defy being jammed into a short list. Applications abound in entertainment and education as well as more serious tasks of search and rescue missions and reconnaissance. In particular, the proposed concept delves into an area that has not seen much progress primarily because most of the robotic technology has advanced by ignoring physics (which cannot be done for aquatic robots leading to severe lack of efficiency and accuracy).

Conclusion

This proposal aims to carry out a preliminary analysis for the development of a water-borne autonomous robot, nick-named "The Sea Strider," capable of navigating short sections of the sea with a morphability to be able to climb aboard a ship. Fundamental scientific investigations on locomotion should be performed on conceptual designs to estimate the limits and accuracy of physical performance. Suitable control systems should be designed, and appropriate off-the-shelf sensors selected and integrated. Analytical and computer studies should be performed to predict the dynamic performance under varying environmental conditions.

To summarize, the following tasks are recommended.

- Conceptual designs for the Sea Strider should be derived. These are likely to start with simple rigid structures not very different from existing robotic fish in any of the functional forms discussed earlier. It should then progress to more complicated designs primarily with compliant control structures; this will be a novel improvement over most existing designs, but are expected to yield considerably higher efficiencies as discussed above. One initial concept could involve a streamlined cylindrical body with a flexible tail that can be activated by servo motors in the yaw plane using a system of pulleys and cables. The flexible tail can be achieved by using a compliant material reinforced by metal (or composite) rings. It should include a wireless module to be able to be controlled from a nearby PC as well as appropriate power sources. Subsequent designs could integrate a controller with localizing sensors (GPS, INS, etc) to increase the level of automation.

- The principles of dynamics and fluid mechanics would need to be employed to arrive at mathematical models. In the process of deriving the mathematical models many approximations will have to be made; otherwise, the models may become too complex to solve, to optimize, or to derive control laws for. It may be recalled that fluid mechanics leads to a set of nonlinear partial differential equations from continuity and momentum (even if the energy equation is ignored). The strongly coupled rigid body equations consist of 12 nonlinear ordinary differential equations. This is without even involving the control problem. It would be foolhardy to try to solve these equations in conjunction with nonlinear time transient fluid dynamic equations or to design a practical functioning device using these horrendously complicated mathematical models. It is therefore very important to use judicious assumptions and approximations to simplify the model equations to make them solvable and usable, while at the same time not losing the essence of the behavioral predictions that we can extract from these equations.
- The solutions of the coupled dynamic and fluid dynamic equations will involve a judicious use of computer tools. For example, using Fluent will give us a very accurate fluid model; however, dynamic studies of motion may be difficult with such a model. It is anticipated that all models will be developed on a simulation environment such as MATLAB/SIMULINK that will speed up program development as well as help carry out parametric studies.
- It is anticipated that the above process will be iterated as the results will lead naturally to suggestions of changes in design. In addition, we intend to carry out the process on progressively complicated designs (including a flexible control surface).
- Control could be designed using standard feedback control techniques in addition to some heuristic methods such as fuzzy logic or neural network techniques. These are standard techniques which can be implemented using supplied tools (such as the MATLAB fuzzy logic toolbox).
- The final phase would focus on a conceptual system design which will attempt to package together the designed form and material structure with selected sensor and actuators.

The anticipated outcomes are as follows.

- A set of conceptual designs for the Sea Strider.
- Hydrodynamic analysis results for the conceptual designs under assumed sea conditions.
- Dynamic analysis results for certain standard locomotion modes.
- Control system design results integrating the hydrodynamics and dynamics
- Conceptual electro-mechanical design for integration of sensors, actuators and communication devices.

The above results should be delivered in the form of technical reports (including theoretical equations, graphs, tables, and experimental graphs), and computer codes (in MATLAB, SIMULINK, C). In addition, monthly and quarterly reports and presentations would be delivered as requested by the Project Manager.

Microarray Identification

Villanova University-----Dr. Metin Duran

Introduction

Rapid onsite detection of pathogens in water environments remain as one of the major challenges in eco-toxicology, public health maintenance, and, more recently, bioterrorism prevention. This is partly due to the fact that conventional pathogen identification methods rely on culturing pathogens from water samples. Culture-based methods have two major drawbacks: 1) Some pathogens are not culturable and thus they are not detected by conventional technologies. 2) It may take days to culture and identify the pathogen and therefore timely response is impossible in many cases. Microarray technology or commonly referred to as “gene chips” have recently emerged as a highly innovative and promising technology for pathogen detection. This project evaluated the concept of microarrays as an innovative tool for rapid and accurate onsite detection and identification of biological agents.

National Research Council (in 2001) and subsequent National Drinking Water Advisory Council (in 2004) recommended identifying pathogens in water environments in new ways that involve genomics. Microarray technology is one the most promising genomic technologies for detection of pathogens, in part due to rapid advances in identification of pathogen-related genes and developments in array technology within the last decade. U.S. Environmental Protection Agency (EPA) has made microarray technology one of its top research priorities in public health arena. Moving in that direction, EPA held an expert workshop in Cincinnati, Ohio on March 22-23, 2005 to explore the feasibility of using microarray technology for detecting waterborne pathogens. The overall conclusion of the workshop was that despite some issues in terms of sensitivity and matrix interference, the microarray technology may be ready for detection of a small number of pathogens and that with carefully directed research the technology is likely to become dominant means of pathogen detection within next decade [127].

Concept

The concept evaluated is a fully-functional microarray facility within an oceangoing decontamination system that can be used for rapid detection of microbial pathogens including bioterrorism agents.

First microarrays, more commonly known as DNA, gene, or genome chips, were introduced by a group of scientists from Affymetrix (Santa Clara, CA) led by Dr. Stephen P.A. Fodor [36]. The invention appeared to be a synthesis of biochemistry and the photolithography techniques used in chip design in the local semiconductor industry. The scanner that would read the output was developed at the same time [70]. Another team, from the Stanford University, led by Dr. Brown and Dr. DeRisi should also be mentioned due to their popularization of this technology among scientific researchers, particularly in cancer research [32-33]. Microarrays provide a means to look at tremendous number of genes (sometimes a whole genome of a microorganism) at once, in order to observe and understand interactions within the genome as a response to environmental conditions and treatment. The technology is based on the principle of hybridization (hydrogen bonding) between complementary nucleotides that make up the genomic material, DNA or RNA. The complementary base pairing and other factors such as ionic strength, temperature, and solvents of the environment are the driving force for hybridization. The technology is based on Southern blotting techniques. However, the current procedure is following Northern and dot blotting techniques more commonly. DNA microarrays today are created by robotic machines that arrange minuscule amounts of hundreds or thousands of gene sequences, the probes, on a single microscope slide or some form of a flexible membrane. Most recent microarray contain up to 48,000 genes, probes, on a single 75x25 mm slide.

The principles of microarray manufacturing and hybridization of labeled targets with the probes on a microarray slide are depicted in Figure 3. When a gene is activated, cellular machinery begins to copy certain segments of that gene. The resulting product is known as messenger RNA (mRNA), which is the cell's template for creating proteins. The mRNA produced by the cell is complementary, and therefore will bind to the original portion of the DNA strand from which it was copied. Figure 3 explains the main steps involved in analyzing gene expression via a microarray [36]. a) Probes are generated from an annotated genome sequence and spotted on a microarray slide. For target preparation, RNA is extracted from two experimental conditions and labeled with fluorescent dyes by reverse transcription. The labeled target is then hybridized with the array, and the fluorescence of the features is determined using an array scanner. b) After image analysis, quality filtering, data transformation, and normalization are done. The remaining steps are dependent on the experiment, but in most cases, the data are tested for different gene expression, clustered, and finally stored in a database.

In order to study gene expression, that is to determine which genes are turned on and which are turned off in a given cell, the messenger RNA molecules synthesized by the cell as a response mechanism must first be captured and extracted. Then the extracted mRNA molecules are "labeled" by attaching a fluorescent dye to each mRNA piece. Red cy5 and green cy3 dyes are commonly used for labeling (see Figure 4). Next step is hybridization of the labeled mRNA, the so called labeled *target* gene, with the complementary genes, *probes*, on the microarray slide. Upon hybridization, the microarray is washed in a buffer solution to remove mRNA pieces that do not hybridize with any of the probes, or *spots*, on the microarray. A fluorescent scanner is used to quantify "spots" on the microarray that emits fluorescent due to hybridized target gene. If a particular gene is very active, it produces relatively large quantities of mRNA, which hybridize to the DNA on the microarray and generate a bright fluorescent area. Genes that are somewhat active produce fewer mRNAs, which results in dimmer fluorescent spots. If there is no fluorescence, none of the messenger molecules have hybridized to the DNA, indicating that the gene is inactive. Researchers frequently use this technique to examine the activity of various genes at different times. Figure 4 shows the principles of hybridization of labeled targets to probes.

There are three types of DNA microarrays: cDNA arrays, short oligonucleotide array, and long oligonucleotide array. The basic technology for microarray is a glass slide coated with poly-lysine that provides positively charged surface for better attachment of DNA (silica ions of glass are changed with ammonia ions). Blocking, prevention of intermixing between DNA molecules, is accomplished by filling spaces in-between with succinic anhydride.

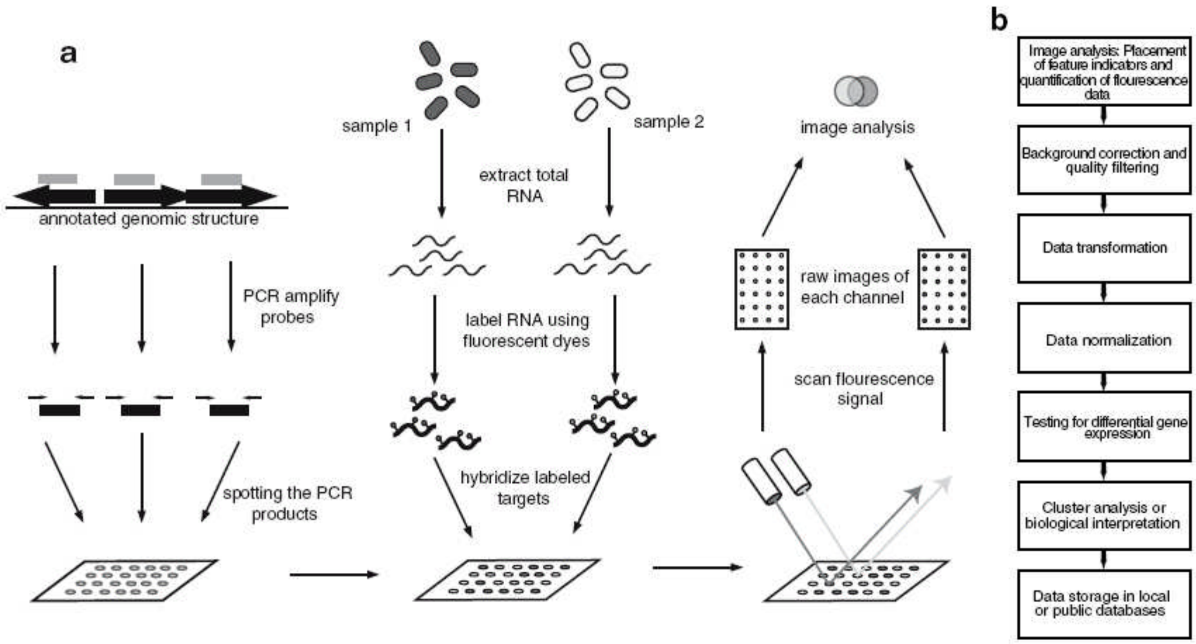

Figure 3: Steps in analyzing gene expression via a microarray

Microarray technology has already become a standard tool in medical field, especially in cancer research. In recent years there have been several exploratory research projects that evaluated the feasibility of using microarrays for pathogen detection. Most of these projects attempted to detect pathogenic bacteria and viruses in medical field (Ehrenreich, 2006; Wang et al., 2002) and there has been limited work in application of microarrays for pathogen identification in water and/or air.

Figure 5 shows a scanned microarray (a virus chip) after hybridization with expressed genes in red and green fluorescent whereas Figure 6 shows a close up view of a small section of another virus chip.

Evaluation

Current approaches for the detection of pathogens, or other biological agents, rely on cultivating the pathogens, or some indicator organisms, on selective solid media and enumerating the number of cells that can form colonies. An alternative approach is to inoculate pathogens or indicators in broth and indirectly measure growth by turbidity or similar parameters. Such approaches are commonly used for monitoring and regulating biological safety in many different fields including public health, food safety, and medicine.

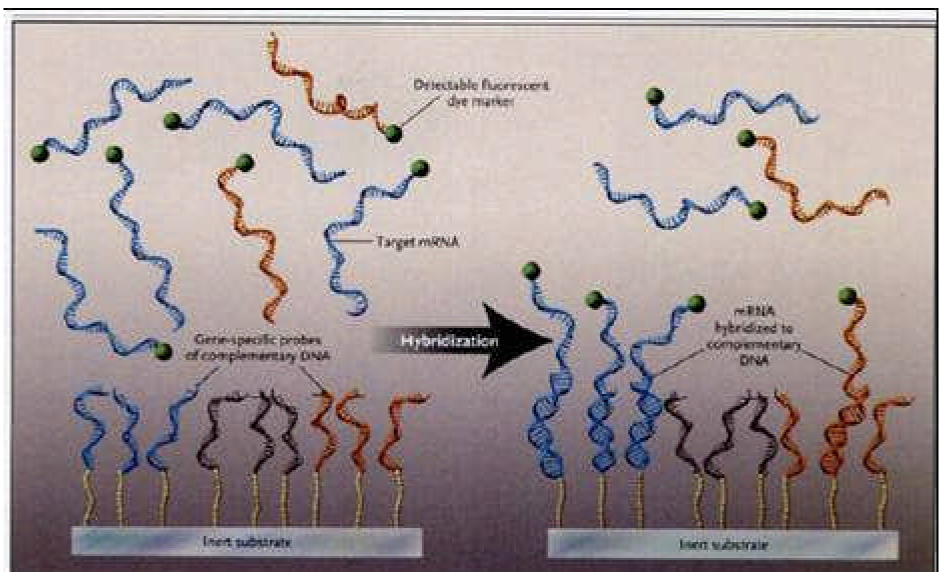

Figure 4: Principles of hybridization of labeled targets to gene probes on a microarray [42]

Although culturing-based methods are sensitive, allowing detection of even low number of cells, they depend on pathogens' or indicator organisms' ability to grow on solid or liquid media. Considering that many emerging and re-emerging pathogens, as well as bioterrorism agents, are non-culturable, these conventional methods have limited use. In addition, conventional methods are extremely slow for emergency response situations, taking days to obtain accurate results. Therefore, development of alternative technologies that are accurate and rapid for on-site detection of biological agents is of great importance to Navy. For example, isolating and testing *Bacillus anthracis* at the United States Capitol complex in October 2001 took approximately five weeks during which the facility had to be shut down and the affected locations remained sealed off and guarded to prevent entry. It is not a farfetched scenario to imagine a Navy vessel experiencing a norovirus outbreak and having to remain off-duty for weeks until accurate pathogen detection is carried out. Another hypothetical case may involve a cargo ship carrying bioterrorism agents or infectious waste leaking its cargo on the US shores. Immediate and effective response to such cases would require rapid and accurate identification of the biological agent. For these reasons, accurate and rapid detection and identification of biological agents is of utmost importance to Navy.

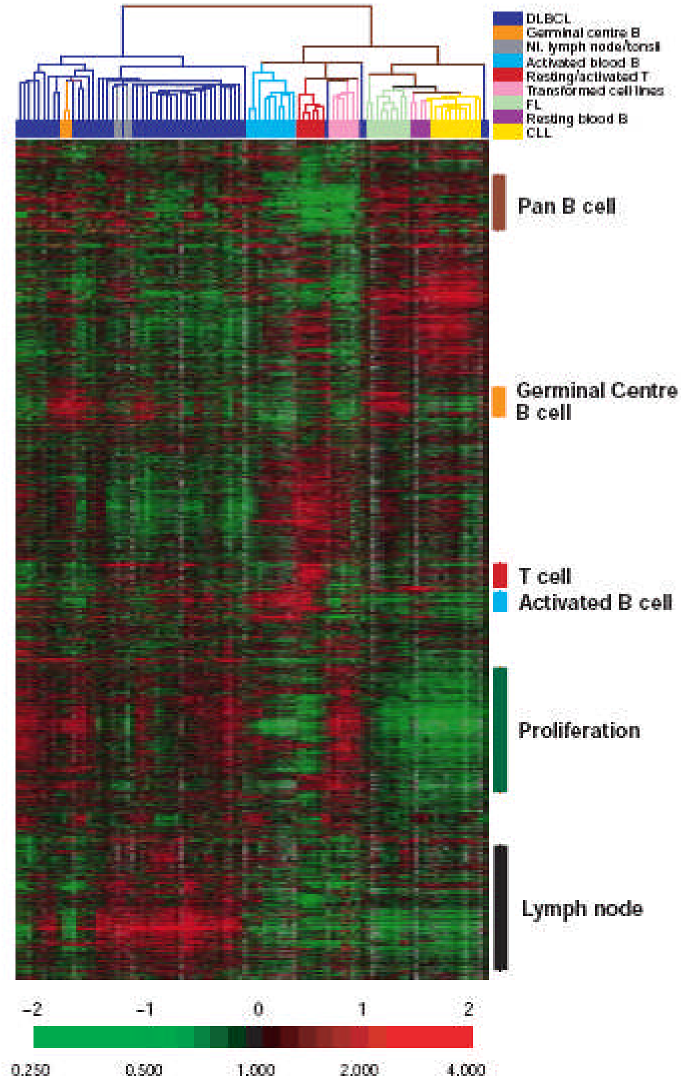

Figure 5: A typical microarray scanned after hybridization, used in cancer-related research.

The application of microarray technology to detection of biological agents in complex matrixes faces several challenges that must be overcome before it can be used for a myriad number of different applications.

1. Environmental samples typically have extremely low concentrations of cells and therefore extraction of sufficient genomic material from environmental samples will require an efficient extraction and concentration approach.

2. Complex matrices such as salt water have various inorganic and organic constituents at different concentrations. Such compounds interfere with protocols involved in microarray analysis, such as amplification of nucleic acids by PCR.

Successful application of microarray technology for detection of waterborne pathogens hinges upon overcoming these challenges. Both EPA and National Research Council expect significant breakthroughs within next decade on both fronts. The technical proposal outlines an approach to address these challenges and presents an experimental methodology to investigate the feasibility of using microarrays on an oceangoing unit to detect and identify biological agents.

It should be noted that the use of microarrays is not limited to an oceangoing unit. Once the feasibility of the technology is established, a wide spectrum of applications is possible including;

- Monitoring air quality for biological threats.
- Determining effectiveness of treatment for biological agents.
- Detection of pathogens (accidental and deliberate) in drinking water and water supplies.
- Tracing sources of biological treats based on DNA.

Conclusion

The concept evaluation and feasibility work indicates the importance of accurate and rapid detection and identification of biological agents. Such ability is crucial for the Navy for timely and effective actions for containment, determination of source, and providing effective treatment when faced with biological threats. The current approaches for detection of biological threats are time consuming and they do not work for emerging contaminants such as bioterrorism agents.

Microarray technology, developed within the last decade and heavily used in the medical field, is seen as the ultimate technology that will be used for detection and identification of pathogens. National Research Council (in 2001) and U.S. Environmental Technology have recently indicated the current challenges that hamper wider applications of microarray technology must be studied and they expect that the technology will replace conventional approaches within next ten years.

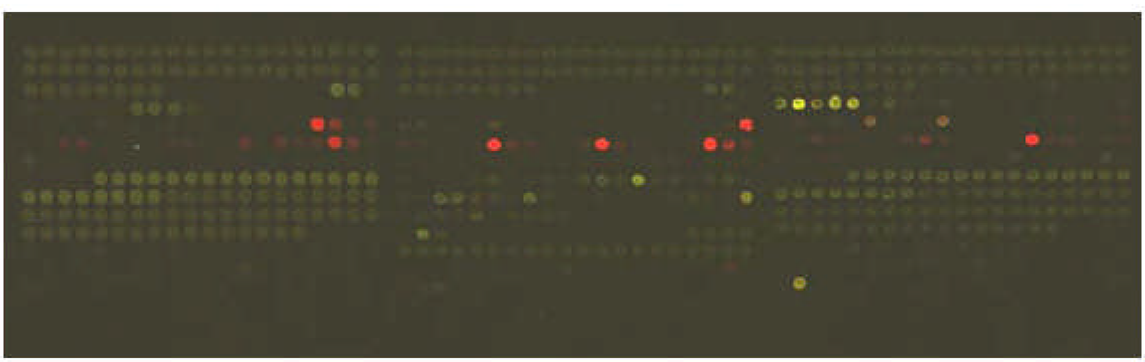

Figure 6: Microarray (virus chip) after hybridization

Figure 6 illustrates a section of a microarray (virus chip) after hybridization showing genes expressed (green and red fluorescent). The intensity of fluorescence is used for semi-quantitative estimation of degree of gene expression.

A technical proposal is developed to investigate the feasibility of using microarray technology on an oceangoing decontamination unit for accurate, sensitive, and rapid detection of biological agents including bacteria and viruses. It will address some of the challenges such as sensitivity and matrix interference that currently hamper wider application of microarray technology for pathogen detection.

Optical Fibers for Detection of Radionuclide Contamination

Villanova University----Dr. Rosalynn Wynne

Introduction

Nuclear particle detection and identification are of growing importance to the military and to society as a whole. Threats of nuclear attacks or accidents exist that have the potential to affect deployed vessels and to affect civilian populations at nearby ports [31]. A compact, light weight, reliable optical fiber based nuclear radiation contamination detector would be beneficial to a seagoing decontamination system. Glass optical fiber scintillation detectors for sensing neutrons and gamma particles are proposed. The proposed detectors will incorporate a microstructured optical fiber to transmit and amplify the light signal from a scintillation material due to radiation exposure. Microstructured optical fibers (MOFs) are specialty optical fibers in which a series of carefully spaced periodic micron-sized cavities within an air-silica lattice in the cladding of the fiber provide extraordinary waveguide characteristics not demonstrated by standard optical fibers. (see Figure 7) One advantage of this approach is to possibly minimize the radiation absorption losses that can attenuate and distort the scintillation light by using air-core MOFs. Air-core MOFs demonstrate a modified photonic band gap confinement such that the fiber can be designed to support the propagation of light of a desired spectral range along the air-core [67,110]. This unique air guidance property may permit scintillation light to propagate through the air-core thereby avoiding the absorption that occurs at scintillation wavelengths in the solid-core region of a conventional optical fiber. This system may also offer the possibility of longer transmission fiber lengths such that the electronic signal processing equipment location can be removed from the radiation site avoiding both radiation and EM interference.

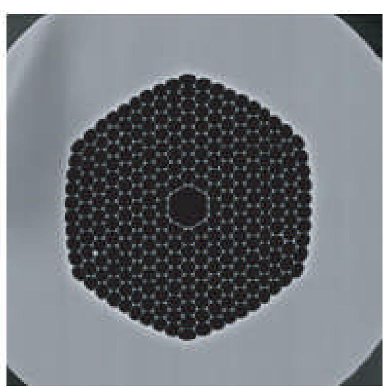

Figure 7: Cross-section of a Corning Photonic Band Gap™ specialty fiber. Typical core diameters range from 8µm to 12µm. The fibers are standardized to have a 125-150um cladding diameter.

Common weapons grade material used in warfare technology and possible cargo for Navy vessels can be composed of either plutonium or uranium radioactive material. Neutron detection is necessary for the identification of weapons grade plutonium [112]. Gamma-ray detection is also important in the detection of uranium. The goal of this proposed work is to develop a miniaturized neutron and gamma-ray nuclear detector that is immune environmental interference. The detector will use a glass scintillator in an all glass optical fiber system that may provide radiation resistance to the detection system. The optical fiber amplifier will compensate for the short attenuation lengths normally associated with glass. A number of patents exist on optical amplification of nuclear radiation detection [52, 45]. However, the scenario of a MOF based optical fiber amplification system has not been presented.

Current Technology

Optical fiber nuclear radiation detectors have been developed over the years [1]. Current real-time detection techniques rely on ionization processes that: induce currents (e.g. gas and semiconductor detectors) or emit light (e.g. scintillation detectors). These systems involve a scintillating probe either glass or plastic that is joined to a length of optical fiber for transmission of the scintillation signal. The advantages of these systems include miniaturized sensing apparatus for high spatial resolution or distributed sensing for applications such as monitoring nuclear reactors [16, 89], detecting underground radon levels [136] and radiation health applications [57]. Although glass scintillators have high radiation resistance and are suitable for detecting high energy particles efficiently, plastic scintillators are often employed. Plastic scintillators demonstrate less attenuation over lengths longer than glass materials [1]. The sensing end of the scintillation materials are often polished [57] or coated [1] with a material the strongly reflects the scintillation light to promote signal confinement and propagation along the fiber to the detector.

Polystyrene-polymethylmetacrylate (PMMA) is a commonly used plastic scintillation material [1]. PMMA can be fabricated in fiber form and connected to conventional optical fiber. Plastic (e.g. PMMA and polysterene) fibers suffer from radiation degradation transmission losses mainly at short wavelengths [1]. The scintillation light of PMMA fiber can be coupled to a wavelength shifter which absorbs short- wavelength light and emits a longer-wavelength of light that will propagate with less attenuation along the fiber length to the PMT [1]. Wavelength shifting flours are useful for converting typically UV wavelength light to visible light to reduce transmission attenuation between a scintillator and PMT. For example, liquid helium scintillates at extreme ultra-violet (EUV) wavelengths and a wavelength shifting material tetraphenyl butadiene (TPB) can be used convert the EUV light to blue visible light [16]. Glass experiences less of the radiation degradation such that it can be annealed [1] to reverse signal attenuation or loaded with molecular hydrogen to reduce attenuation effects [16]. Conventional silica glass optical fibers are susceptible to optical absorption and radioluminescence when exposed to nuclear radiation. The scintillation signal can experience a 10dB/m attenuation (for visible wavelengths) and distortion for an incident radiation dose near 1 MGy [16].

Existing glass scintillation technologies include PUMA [112] detection systems. PUMA based detection systems are based on a glass fiber technology (developed at Pacific Northwest National Laboratories, PNNL) that is cerium activated, lithium silicate scintillating material [112, 1]. The material scintillates in the presence of gamma rays and neutrons. Radiation particles incident on the glass fibers prompt energy transitions of the atoms in the glass lattice such that photons at a wavelength of 400nm are emitted. (see Figure 8) Neutron triggered scintillation dominates the scintillation process such that scintillators (NaI(Tl) or BGO) are used to detect gamma- ray emissions from materials like enriched uranium. The scintillated light is then coupled to standard photomultiplier tubes (PMT) for amplification and measurement.

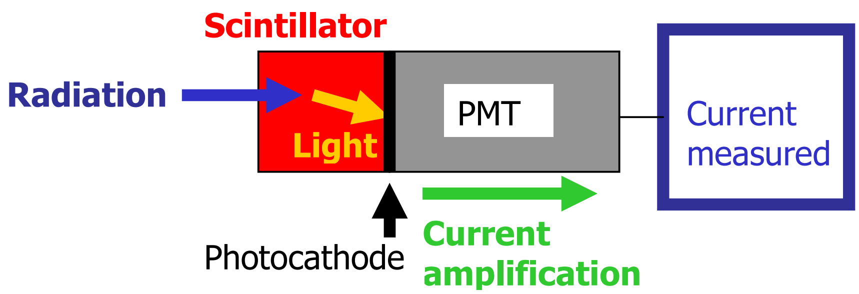

Figure 8: Conventional scintillation measurement scheme.

Concept

Radiation and nuclear material detection projects are currently being conducted at a number of facilities (e.g. Pacific Northwest National Laboratory and Sandia National Laboratory). The novelty of this proposed approach will be to process signals in the optical domain to reduce detection system size and increase separation distance between the electronic signal processing equipment and radiation source location. The probability [89], P(x), that a photon travels some distance x along the optical fiber away from its position of origin in the scintillator is;

$$P(x)=A\exp(-\mu x)$$

where A is a constant that is a function of the geometry of the scintillator, μ is the effective attenuation the photon experiences as it propagates along the fiber system the attenuation is dependent on the scintillation wavelength which is due to the fiber material properties. If the effective attenuation can be reduced by transmitting of the photon via a low index or air transmission region the likelihood of photons surviving the fiber transmission process may increase exponentially.

The proposed system consists of a scintillation material (e.g. lithium glass or bismuth germinate), an air-core MOF fiber filled with wavelength shifting (WLS) fluid and an optical fiber amplifier. (see Figure 9) The WLS fluoresces when stimulated by the scintillator output such that it fluoresces at a longer wavelength. The fluorescent signal will be amplified as it is transmitted along an optical fiber amplifier. Optical amplification can be achieved by installing highly non-linear fiber to induce nonlinear effects and Raman amplification may amplify a transmitted signal allowing longer lengths of fiber to be used for signal transmission. Raman amplification is based on stimulated Raman scattering (SRS) a photon scatters in an atomic system such that it can be inelastically scattered by phonons and give energy to the medium. This can possibly reduce the number of the signal processing equipment occurrences such that many fiber optic extensions from detectors can be plugged into one hub.

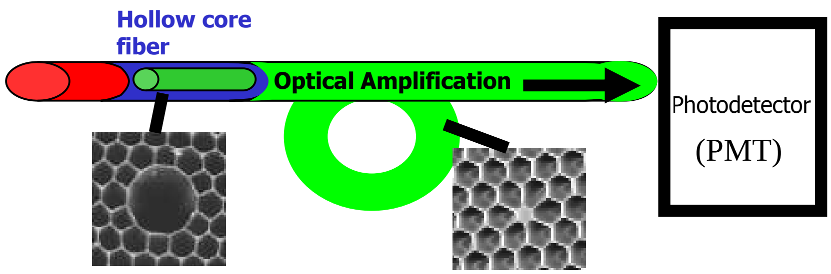

Figure 9: Proposed nuclear radiation detector concept.

Proposed System

Possible radiation source materials [112] for detector calibration include: cesium and cobalt (to support gamma ray emission) and Californium (to supply neutrons). Scintillation materials that will be employed include lithium glass for neutron detection (Saint- Gobain Crystal GS1™) and the inorganic material bismuth germenate for gamma-ray detection (Saint- Gobain Crystal BGO™). A length of scintillating material will be cut and polished on the end face of the fiber to promote light confinement to the fiber. The scintillating fiber will be coupled to a length of a wavelength shifting fluid (Saint-Gobain Crystal BC-517P) filled hollow core microstructured optical fiber to shift the scintillation light to wavelengths that will not be absorbed by the optical fiber amplifier. (see Figure 10). The MOF will be joined by another unfilled length of hollow core fiber (Corning Photonic Bandgap Fiber™) for low loss transmission of the scintillation light. A length of an optical fiber amplifier will magnify the signal from the MOF and transmit the signal to the photodetector. All fiber components will be fusion spliced to reduce coupling losses between separate fiber sections. The PMT (Hamamatsu-Photonics R1635) will produce an amplified electrical current in response to the scintillation signal. The electrical signal is preamplified (Ortec digiBASE) and sent to be analyzed with a multi-channel analyzer (MCA). The Ortec digiBASE is a 14-pin photomultiplier tube base for nuclear radiation spectroscopy applications with scintillation detectors. DigiBASE combines a miniaturized preamplifier and detector high voltage (0 to +1200 V bias) with powerful digital signal processing, multi-channel analyzer, and special features for fine time resolution measurements that are all contained in a low-power (<500 mA), lightweight (10 oz, 280 g), small-size (63 mm diameter x 80 mm length) tube base with a USB connection.

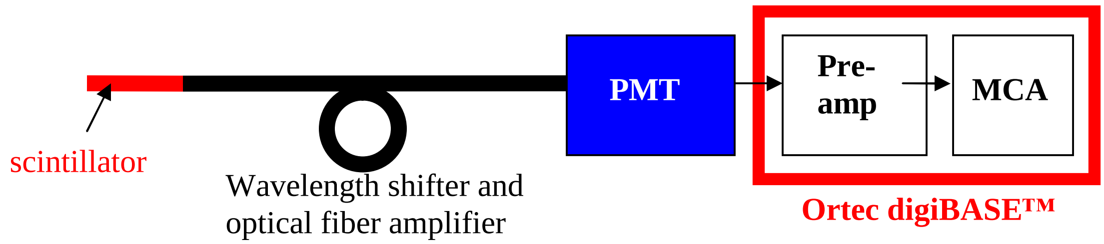

Figure 10: Conventional scintillation measurement scheme.

Evaluation

We propose a miniature nuclear radiation detector based on micro-structured optical fiber technology. The detectors will sense neutrons and gamma-rays that are common radiation artifacts of weapons grade nuclear materials. The techniques discussed earlier allow for the composition of an all glass detection system that is nuclear radiation resistance and addresses the issue of signal degradation in glass by using an air-core light guide to transmit the scintillation signal to electronic processing equipment. The transmission length in the optical fiber is also increased by the introduction of an optical fiber amplifier to reduce the number of electronic processing stations. The detectors presented offer advantages such as ruggedness since they are not susceptible to nuclear radiation degradation, humidity, and drastic temperature variations which in addition to portability make the all glass fiber nuclear detection system a good candidate for oceangoing vessels. Oceangoing vessels can be subjected to weather conditions of severely cold or hot climates with precipitation and it is important to have instrumentation especially for ships with radioactive cargo that have reliable nuclear detection without sacrificing cargo space. The detector components are also immune to electromagnetic interference from EMPs which may accompany nuclear attacks or accidental explosions. The detector offers added benefits such as being chemically non-corrosive and having the potential to be “connecterized” to allow for technically low-skilled personnel to install and operate the system.

Conclusion

Packaged detectors can be located aboard military to monitor nuclear reactors that power ships and submarines, nuclear cargo, and nuclear warfare technology. Commercial vessels may also adopt this detection system. Fiber based detection systems may be integrated into common items such as faux plants or ventilation systems for commercial use on oceangoing vessels such as luxury cruise ships. To promote portability, the detection system may be designed to be battery operated. Use signal processing techniques that sample continuously and redundantly to minimize false alarms.

Chemical Warfare Agent Sensing and Remediation

Villanova University------Dr. Randy Weinstein

Sensors Introduction

The Navy is interested in chemical warfare agent detection in both the gas and the liquid phases. Vapor phase sensing is much more advanced than liquid phase analysis and is significantly easier to accomplish. There are several major categories of contaminants which require identification and include microbiological, radioactive, inorganic (such as metals), synthetic organic, and volatile organic compounds [50]. This report will address both vapor and liquid phase chemical detection for chemical weapons which can be considered synthetic organic or volatile organic compounds. Radioactive and biological contaminants are not specifically addressed in this report. However, sensors discussed and developed will have applications beyond chemical warfare agents and will have cross-over uses outside the military for environmental monitoring, industrial quality checks, and homeland security.

There are two general approaches for identifying and quantifying chemicals in the environment, both of which require portability and continuous on-site monitoring of a wide range of possible chemicals. First, the miniaturization and automation of established analytical techniques can be used [107]. These techniques do both separation and identification of chemicals from a mixture. Often this miniaturized process is labeled with the general term “lab-on-chip.” The second approach for identifying chemicals in the environment is to use chemical sensors which are designed to interact with a specific analyte and produce a signal when that compound is present [56]. The signal can often be proportional to the concentration. For the purposes of this report all methods of detection and/or quantification of chemicals in vapor or gas phases will be lumped together as chemical sensing.

Sensors Concept

The basic concept presented here is the development of onsite sensors which can be used for quick notification when chemical warfare agents have been detected. Once agents have been detected, a mobile laboratory will be brought to site for confirmation of the agent followed by detailed analysis and quantification of the contaminant with containment and decontamination. This two phase approach of quick remote sensing followed by detailed analysis has gained growing support as the preferred method for chemical warfare agent monitoring [47]. Since laboratory analytical techniques in a controlled environment with trained personnel are well established, they will not be discussed in this report. It is understood that the selection of analytical equipment, tools, and personnel for this mobile laboratory would need to be part of the final project; however, the selection and uses of sensors is the more difficult process. Hence the state of sensor technology for chemical warfare agents in both the vapor and liquid phases will be discussed.

Sensors Evaluation

Vapor Phase Sensing Evaluation

- There are several vapor spaces that would be of interest for the Navy including
- The vapor head space in cargo containers in port or on board
- The vapor head space within the hold of a cargo ship
- The air handling systems (air conditioning, heating, and dehumidifying) of large passenger ships, military surface vehicles with crew, military subsurface vehicles with crew, and large commercial vessels whose primary purpose is not pleasure
- Vapor space above suspected spills in rivers, open water, or ports
- Vapor space above suspected contaminants in the drinking water supply

These vapor spaces will not contain non volatile inorganic material; therefore, only synthetic organic and volatile organic compounds will be expected in these spaces. Although this report focuses on chemical weapons, other likely sources of interest including explosives, fuels/greases/hydrocarbons, other volatile organic compounds and pesticides could also be sensed with the technologies proposed, although the exact sensor would probably have to be modified for other chemicals.

There have been many publications addressing the area of sensor technology for environmental analysis and monitoring of pollutants, contaminants and chemical hazards [56, 49, 87, 133, 50] and many different types of sensors have been developed, but this report will only cover the ones that have been found to be able to do continuous real-time monitoring in addition to chemical detection with minimal operator requirements as these are planned to be used as remote (autonomous) sensors or aboard ships. Surface acoustic wave sensors, ion mobility spectroscopy, and gas chromatography sensors will be discussed. Several sensors developed for specific applications, including color spot tests and immunochemical sensors will not be discussed due to their difficulty in implementation [47]; however a good summary of them can be found in the literature [87, 56].

Surface acoustic wave sensors (SAWS) [83, 87, 50] allow the mass of a material to be measured when it sticks to the surface of the device. The device surface is coated with an organic or inorganic material that is selected to absorb specific types of compounds. The selection and development of these materials are critical for the process. Often the process is reversible allowing for the desorption of the analyte and continued uses of the sensor with only a small applied thermal load. The SAWS consists of a piezoelectric substrate (usually quartz), with two transducers on the surface. They use a high frequency oscillation that only penetrates about one wavelength in depth. Often the sensors come in pairs with one exposed to the environment and the other used as a clean control [12]. There are no required consumables except for low electrical power which is a distinct advantage of these sensors. They are able to detect low level concentrations of many species. However, the difficulty with these sensors is that often many chemically similar compounds will bind to the surface and moisture and hydrocarbons can also adsorb and produce signals [87]. It is difficult to make a surface that is truly sensitive to only one specific chemical, but usually humidity can be measured separately and used as a corrector factor to prevent water vapor from producing a false positive. Arrays of many SAWS with different chemical surfaces can be operated and combinations of positive responses can be used to help narrow down the possible contaminates [49]. There are already many manufacturers of SAWS and SAWS arrays [49] and they have extensive testing for sensing chemical warfare agents [47]. Similar sensors based upon selective absorption have been made using polymeric coatings which change resistivity (which is measured) once absorption occurs [49].

Another popular technique for chemical sensing is ion mobility spectroscopy (IMS). In this process the sample's molecules are ionized, driven by an electric field down a drift tube, and arrive at an ion detector at different times due to differences in the ions' velocities and not just due to the species molecular weight [87]. The ion mobility spectrometer can achieve very high sensitivity for species that can be vaporized such as explosives, many organic compounds, and chemical warfare agents because the measurements are made at ambient pressure with no rarification of the sample [78, 21]. The process actually uses water vapor present in air to help produce the positive ions so humidity does interfere. Dopants can be added to the air stream to help prevent weak proton accepting compounds from ionizing and being detected, so many chemicals not of interest in air can be eliminated from the analysis [87]. Recently, methods of taking aqueous samples have been established and chemical weapons were even identified in liquid water [123] though alternative ionization techniques, but these required low pressures and hence would not be suited for remote operation. IMS has also been combined with other techniques such as mass spectroscopy to enhance the chemical identification process [87]. The major shortcoming of IMS is the difficulty in identifying peaks when standards were not tested. Furthermore, impurities in the air have been shown to cause peak shift and broadening and the sensors are moderately expensive.

The third and final highly recommended method for chemical weapons detection in the vapor phase is by gas chromatography (GC). GC methods take a sample, vaporize it if it is not already in the vapor phase, and flow it through a column under programmable temperature control. Different chemical species exit the column at different times due to their varying interactions with the chemical species coating the inside of the column. The column design and temperature control are critical to provide required separation. After separation, various detectors (Fourier transform infrared [FTIR], mass spectrometer [MS], flame ionization, or pulsed-flame photometric) produce a signal proportional to the quantity of chemical in the sample. For all but MS, standards are required to both identify the compound as well as quantify its concentration. There are both lab scale and portable GC systems available. The one significant draw back of GC systems is their high cost [87], although they are usually the analytical method of choice for chemical warfare agents [47] as they are deemed most accurate. Also, although they have been miniaturized significantly, they are still considered very large for field use and depending of the detector selected might not even be deemed portable. In addition, carrier gases (such as helium or nitrogen) are consumed in the process along with other gases often required for detection (such as hydrogen).

Liquid Phase Sensing Evaluation

The number of possible analytes in the liquid phase is significantly larger than those occurring in the vapor phase, which makes chemical warfare agent detection in a liquid phase significantly more difficult [72]. Attempts at monitoring the vapor phase over water would be easier and a cheaper method for chemical weapon detection; however, not always practical so liquid phase sensors will also be required. The Navy would be interested in monitoring the liquid phase

- in open water (fresh and salt)
- in ports, rivers, and waterways (fresh and salt)
- in public drinking water supplies
- on shipboard drinking water supplies

As previously discussed, there have been many publications addressing the area of sensor technology for environmental analysis and monitoring of pollutants, contaminants and chemical hazards [56, 49, 87, 133, 50] for both vapor and liquid phases. The sensors selected for this study are considered the most robust for in the field use and require minimal consumables and manpower. Fiber optic, chemical resistor, and chemical oxygen demand (COD) sensors will be discussed.

Fiber optic based sensors probably show the most promise for chemical weapon detection in water as they are robust and relatively well established without the need for chemical recognition layers [58]. They are often low cost, low power and have high sensitivity [49]. Light is generated from a source and sent through the fiber to the sample which then alters the light, which is returned through the fiber and captured by a photo detector [49]. In aqueous solutions, specific fiber tip coatings are usually required to prevent the large signals from water from interfering with the sensor's sensitivity [72]. Coatings of the fiber tips with a variety of polymers and other materials have prevented the background of water from masking organic materials present [65]. The coatings do not allow water to penetrate, but do allow the absorption of organic material such as many chemical warfare agents. Fiber optics enable optical spectroscopy to be performed on site over very large distances, or even along several spots along the fiber [133]. Fibers are now available with transmission over a large spectral range and they have already found significant use in many fields such as medicine, biotechnology, environmental analysis, and the automotive industry [133]. The fiber optic techniques allow for the measurement of refractive index, absorption or emission properties of the chemical species. It is also possible to add a probe to the solution near the tip and monitor its change with the environment through fluorescence or other optical properties [49]. Very long distances may still be a problem for fiber optic sensors [49].

Chemiresistor sensors have the ability to detect chemical warfare agents in water. When the agent comes into contact with the sensor, the sensor's resistance changes and can be measured. Again, water maybe a problem with these sensors. Three types of conductometric sensors are generally employed: polymeric, catalytic beads, and metal-oxide semiconductors [49, 140]. Only the polymeric based sensors operate at ambient temperature, while the other two types operate anywhere between 200 – 800 ^{o}C and hence are deemed inappropriate for remote water sensing. With the polymeric sensors, when an agent absorbs onto or into the polymer, it swells, leading to a resistive signal monitored by the solid phase electrode upon which the polymer is coated. The process is reversible, but some hysteresis is often observed with high concentrations. These sensors are generally small, low power devices with no moving parts. One big drawback is that water can often interact with many polymers but GoreTex membranes have been used to coat the polymers, eliminating water interference [48]. They can also be used for vapor phase sensing. Another drawback is that often many chemicals will produce singles on a single polymer-electrode combination. Arrays have been developed with different polymeric conductive films deposited on different electrodes to allow for the selectivity of the sensor to be improved [53]. Identification of the proper polymer and electrodes will be critical for chemical weapon detection to prevent false positives.

Chemical oxygen demand (COD) is the third and final liquid phase senor that would be suitable to detect organic chemical warfare agents in water. With this sensor type, the total amount of organic material that can be oxidized in water is measured. This sensor is relatively cheap, but does not separate or identify specific chemical compounds and should be used in conjunction with other monitoring systems. Since water can not easily be oxidized it presents no background interference with the sensor. Various oxidizers have been developed and detection limits are being reduced continuously [71].

Sensors Conclusion

There has been significant research in the area of sensor technology for environmental analysis and monitoring of pollutants, contaminants and chemical hazards [56, 87, 133, 50]; however, the implementation and application of sensors in real-life situations remains small [72]. There is not significant data available on the lifetime of sensors in real-life situations or on malfunction rates. There also is a lack of distributing sensing studies along with the establishment of central supervising stations, intercommunication systems, and procedures to handle incoming data [137]. Testing in the environment should continue to identify sensors on the market which perform the best in real world situations. Also, alternative and new sensors should be sought out which can both provide quick identification as well as quantification of chemical warfare agents in real situations.

It is believed that suitable combinations of sensors are available or will be available shortly to meet the needs of the Navy [87] and they can be implemented quickly with the Navy setting the standard when they are not currently in existence (such as protocols, networks, and command centers). There will still be other challenges which include the robustness of the sensor, selectivity, and the complexity of the background media which may change abruptly. The senor system will need to be flexible to account for failures, new technological advances, and the changing needs of the Navy. Continuous monitoring of the background maybe required so that changes can be detected in real time. Remote sensors will provide warning, but require a mobile laboratory to quickly arrive on site to confirm detection and quantify the contaminates present and also provide containment and remediation. The portable laboratory will contain laboratory scale equipment with trained personnel to perform the required chemical analysis and selection of the equipment to meet the Navy's needs is paramount.

Remediation Introduction

An excellent 130-page report by [103] was recently published which evaluated all the proven methods for neutralizing and destroying all known chemical weapons. Dumping in any body of water, land burial, and open pit burning are not considered acceptable by the Chemical Weapons Convention (www.opcw.org) which was open for signature in January 1993, although those were some of the early and convenient methods for disposal. It is important to note that recently over 80% of the weapons destroyed have been done so by incineration with the remainder neutralized mainly though hydrolysis or reaction with bases [103]. The Navy can encounter chemical warfare agents in the air, water, or on solid surfaces. Surfaces would quickly be flushed with large quantities of water, and the aqueous run off would need to then be treated.

In World War I various chemical warfare agents were used including tear gases and other irritants (such as xylyl bromide), choking agents (such as chlorine and phosgene), blood gases (such as hydrogen cyanide), and blister agents (such as mustard). World War II saw an increase in the number of agents available and an addition of a new class of agents, nerve agents (such as tabun). Since World War II there have been the creation of many new chemical warfare agents which have been stockpiled or generated outside the United States and can present potential hazards. This report will cover chemical weapon destruction and neutralization. Biological and radiological weapons are not discussed in this part.

Remediation Concept

The basic concept presented here is the ability of the Navy to dispatch containment and treatment facilities anywhere in the world once chemical warfare agents have been detected either onboard a ship (such as a Navy vessel or passenger cruise ship), in the water (open, ports, or drinking supplies), or on land (such as in custom areas in ports). The system would have to be able to treat a wide variety of possible chemical warfare contaminates and also be mobile. The system would need to be very reliable, robust, and require minimal man power to operate. In addition, other chemical detection, such as pesticides, explosives, or ordinary organic chemical spills could also be treated with this system. There are generally two categories for treating chemical agents: high temperature and low temperature destruction methods. Each often requires effluent treatment of the gas, liquid, and possible solids produced as the byproducts of destruction are not always inert.

Remediation Evaluation

High Temperature Destruction Method Evaluation

The most common method for destroying chemical agents is through incineration whereby all chemicals containing hydrogen, oxygen, and carbon are converted to carbon dioxide and water. However, many agents have halogen atoms as well as other atoms such as sulfur, nitrogen, and phosphorous. These components are generally converted to the acid halides, nitrogen dioxide, phosphorous pentoxide, and sulfur dioxide which can be removed by scrubbing. As long as the temperature is high enough and sufficient oxidant (usually oxygen in air) is available the method is environmentally safe, robust, and allows very little escape of agent. However, aqueous solutions would be difficult to burn without the addition of significant amounts of fuel. Supercritical water oxidation units have been developed which take aqueous solutions above the critical point of water (374 ^{o}C and 246 bar) where by combustion reaction pathways can occur. These high temperature, high pressure reactors need to be made out of high nickel alloys as corrosion is often a problem when halogenated agents are treated. Furthermore, salt water would be a significant problem with these reactors as clogging and pitting often occur when salts are present. Some unique reactor designs have been developed to overcome some of the technological short comings of supercritical water reactors [51, 81].

Plasma pyrolysis methods employ the use of a plasma environment generated by an electric arc producing temperatures around 15,000 ^{o}C. Chemical agents are instantly decomposed. The effluent gas can be scrubbed and solids produced can be land filled. These reactors have been used to destroy contaminated metals and other solids and are considered very robust. Chemical agents have not been tested in the United States [103] in these reactors and hence they would not be deemed suitable.

Molten metal technologies, as the name implies, use molten metals (typically iron or nickel at temperatures around 1500 ^{o}C) to decompose chemical agents to simple inorganic molecules such as carbon monoxide, hydrogen, acid halides (HF, HCl, etc.), sulfur dioxide, nitrogen dioxide, and phosphorous pentoxide. The vapor effluent can easily be scrubbed. One drawback of the process is the requirement of a feed mixture of oxygen/methane and the cost of heating if significant amounts of aqueous contaminants are treated. The system has only been tested with known concentrations of a warfare agent requiring specific feed amounts of oxygen/methane. It is unclear how the process would work with unknown feeds. Also, the process has been limited to bench-scale systems in very controlled environments and worker safety issues are still a concern.

Hydrogen and steam can be used as a hydrogenolysis treatment process at around 850 ^{o}C whereby organic wastes are transformed into simpler substances that are less toxic. There are commercial scale reactors in use that have treated a variety of chemical wastes; however, large quantities of sulfur containing compounds (such as mustard) have not been tested. There is also concern about the secondary compounds produced and their safety. Large quantities of hydrogen are also required.

Low Temperature Destruction Method Evaluation

The most frequently used low temperature method for chemical warfare agent neutralization is through simple hydrolysis by the addition of water and slight heat (~90 ^{o}C). Contaminated surfaces and environments are often flushed with large quantities of water to dilute and wash away agents and then this waste water can be heated for treatment. Although frequently used, it is not suited for all possible agents and really has only been employed for mustard. Besides simple hydrolysis, sodium hydroxide in aqueous environments has been employed to neutralize many nerve agents. In addition, amines and other chemicals have also been added to help neutralize a variety of chemical compounds. It is important to note that all of these low temperature destruction methods are very robust but only for a select few warfare agents. In addition, complete destruction to fully oxidized compounds is not achieved and although the agent has been neutralized, the environment is still chemically contaminated. There are also several other technologies geared towards specific chemical weapons that were not discussed due to their limited applicability or sufficient testing data.

There are also several new technologies in the early testing stages which deserve some consideration. Bromberg and Hatton [19] showed that magnetic nanoparticles could destroy several nerve agent surrogates as well as pesticides in aqueous environments. It was an important discovery as many nerve agents were found to be stable over a range of pH and temperature in many hydrolysis processes. Others have also been able to degrade other pollutants using nanosized metals [84] and this new technology deserves a closer look for widespread use in warfare agent cleanup.

Remediation Conclusion

There are many options for destroying chemical warfare agents. Surfaces are often sprayed with copious amounts of water and the effluent later treated. Vapor phases will most likely dissipate before treatment can arrive and therefore aqueous phases should be of the primary concern. Liquid phases can be fully treated through incineration and mobile incinerators could quickly be dispatched to sites where agents have been detected. However, the operation and use of such processes is not trivial and safety and other issues would pose significant problems. It is believed that alternative lower temperature treatments should be investigated which have the potential to destroy chemical agents which have been released into water. These processes should be robust, be able to treat a wide variety of possible contaminants, and have the ability to function with minimal manpower. Several systems in combination might be required to adequately treat all possible contaminate situations and fast neutralization to less harmful materials might be of primary concern with full cleanup occurring over longer time periods.

A Cable Driven Monitoring and Decontamination Robotic System

Villanova University------Dr. Hashem Ashrafiuon

Introduction

Current US Naval shipboard material handling systems are manpower intensive, slow and thus not suitable for decontamination purposes. The goal of this report is to investigate the feasibility of a versatile system capable of sensing, monitoring and manipulating possible contaminants onboard a ship. It is envisioned that the system will be a reliable and autonomous robotic device capable of motion adaptation and handling materials in volatile sea conditions and hence minimizing the risk of human contamination. The system must further be transportable to access hard-to-reach locations on a ship. One possible solution that can achieve these tasks is a cable-driven robot.

Cable-driven robots are those classes of robots that actuate their end-effector via cables. These types of robots have attracted the interest of researchers as well as industry and government in the recent two decades. There are several advantages using these robots compared to traditional ones such as operation in a variety of workspace and transportability, which makes them easy to assemble or dissemble. They are also simple in form with low inertia properties and high payload to weight ratio. Although there are several advantages in using these robots, the range of motion can be limited since the cables can only operate in the tension mode. Therefore, calculations need to be carefully considered in motion planning and control of these robots in order to maintain the positive cable tension. In addition, the bulky cable configuration of the robot may not allow manipulation in tight spaces.

To date, research and development in the area of cable suspended robotics has produced several different working prototypes for use as cargo handling systems and similar operations [2-3, 124], radio telescopes [22, 80, 120-121, 138], a deep ocean search and survey system [46], air vehicle simulator [128], a motion base simulator [125], research laboratory robots [43, 94-96, 113], aerial camera systems [25, 92], and a neuro-rehabilitation device suggested for lower limbs [82].

One of the early cable-driven robots, called ROBOCRANE, was introduced by the National Institute of Standards and Technology [2-3, 124]. ROBOCRANE is a six-cable six degree-of-freedom cable-driven robot geometrically designed similar to a Stewart platform to provide a complete six-degree-of-freedom rigid body motion. Such devices have been of particular interest to the commercial shipping and NAVY for cargo handling. The main justification has been the need for a device that can handle volatile sea conditions. Cable Array Robot [43, 113], a 4-cable robot was developed at the Pennsylvania State University in order to manipulate cargo containers' position and orientation. A Stewart platform configured six-cable suspended robot has also been designed and assembled at the University of Delaware [94-96]. Skycam® which is an aerial robotic camera was developed by Cone [25] to provide three-dimensional mobility to television and motion pictures and is mainly used in sports facilities. A similar device has been recently developed [92] which takes advantage of the Stewart platform to provide a wider range of motion and more versatility for such a camera. Cable-driven robots with Stewart platform configurations have also been suggested as future radio telescopes with awesome potential [43, 94-96, 113]. Such a telescope will have 100 times more sensitivity than the largest currently operational telescopes. Tadokoro, et al. [125] designed a base motion simulator for virtual sensation of motion using physical and psychological stimuli and suggest such a device for rehabilitation application as well as virtual experience of amusement park simulators. Usher, et al. [128] developed a cable array robot and used it as an air vehicle simulator. They used the device for effective testing of sensing and control strategies before experimentation with a free flying helicopter type unmanned vehicle.

Research in the cable-suspended robotics has been mainly focused in workspace analysis and motion control, due to difficulties introduced in keeping the cables in tension mode only. Gosselin and Wang [44] introduced a method for determining the static and dynamic workspace of cable-driven mechanisms. Bosscher [17-18] introduced a wrench-base analysis for geometric calculation of the boundaries of the feasible workspace subject to cable tension mode constraint. Redundant cables have also been suggested as a remedy to improve the workspace by avoiding singularities caused by the cables tension-only mode [44, 95]. Oh and Agrawal used a set point sliding mode approach [96] to control a cable suspended robot. In their work, the admissible workspace of the system was calculated in terms of set points. They also used feedback linearization [94-95] to design a positive tension controller for a planar cable suspended robot developed at the University of Delaware. The disturbance robustness and workspace generation of single body and multibody cable robots has also been addressed in [17-18]. Anti-sway and stabilization problem for systems carried by cranes have also been the subject of several investigation by several researchers [15, 66, 79, 97-99, 102, 106, 121, 138, 141].

There are three major difficulties that have hindered the progress of cable-driven robots in volatile environments. The first is the workspace limitation due to continuous maintenance of cable tension resulting in limited rigid body motion particularly in some of the six degrees of freedom motion such as sway and yaw. The second difficulty is due to lack of flexibility required in some applications such as those where the robot must get into tight spaces. The third difficulty arises from the suspension of the whole robotic system from the crane cable in volatile environments leading to instability.

While there has been a relatively wide range of research addressing kinematics, workspace, dynamics, design, and control of cable-driven robots, the difficulties mentioned above have not been effectively addressed. There has not been any research to significantly increase the workspace with the exception of adding redundant cables [44, 95]. There has been little research addressing obstacle avoidance by such a robot, which can be of particular importance if it needs to get into tight spaces. Further, while there has been some research in vibration isolation of such robots, the more difficult problem of rejecting large-scale disturbances when a six-cable system is suspended from a standard shipboard crane cable and supported only by taglines has not been addressed.

Concept

In this study, we propose and investigate a cable-driven platform that can provide six-degree-of-freedom rigid body motion and carries a robotic arm. Such a system is a viable solution to the difficulties normally associated with cable-driven robots such as workspace limitation, inability to get into tight spaces, and rejection of large disturbances. The robotic system consists of two platforms, one suspended from the other and controlled by six cables designed in a Stewart platform configuration to achieve full three-dimensional position and orientation controlled motion. The suspended platform will include a camera system to provide vision, chemical sensors for contaminant identification, and a robotic arm with a mechanical or magnetic gripper to get into tight spaces and handle/manipulate contaminants and other hazardous objects. The robot can be transported to specific locations on a ship via existing cranes or other forms of cable-trolley system.

Figure 11 shows the conceptual design of the robotic system carried by a typical shipboard crane. The crane carries the upper platform, which carries the motors, winches, and other electronics required to control the motion of the six cables. The cables provide six-degree-of-freedom rigid body motion of the lower platform through a Stewart platform type configuration.

In order to design and develop a prototype of the system, we need to develop a kinematic model, a dynamic model, and a robust position control law that can properly position the robot while rejecting environmental disturbances such as wind forces. The kinematics of the two platforms system can be represented by 12 degrees of freedom. Each of the two platforms possesses six rigid body degrees of freedom. In addition, the robotic arm also possesses several degrees of freedom. The dynamics of the system may be modeled by deriving the equations of motion of the two platforms subject to cable forces and environmental disturbances plus the equations of motion of the robotic arm. The control law can be developed using the system dynamic model. Sliding mode control approach [114, 129] may be used to develop the control law for precise and robust control of lower platform linear and rotational motion and robot arm manipulations. The control law must guarantee stability of the overall system, maintain cable tension, reject environmental disturbances and accurately position the robotic system for monitoring and handling of contaminants and other objects. Furthermore, some of the basic geometric, inertia, and material properties of the system may be designed based on simulation of the system dynamic mode and the suggested control law.

In order to simplify the problem, we present the kinematic and dynamic models of the cable-driven robot without the robotic arm and develop a preliminary control law that provides stability while the crane is in motion and accurate lower platform position and orientation when the crane has stopped.

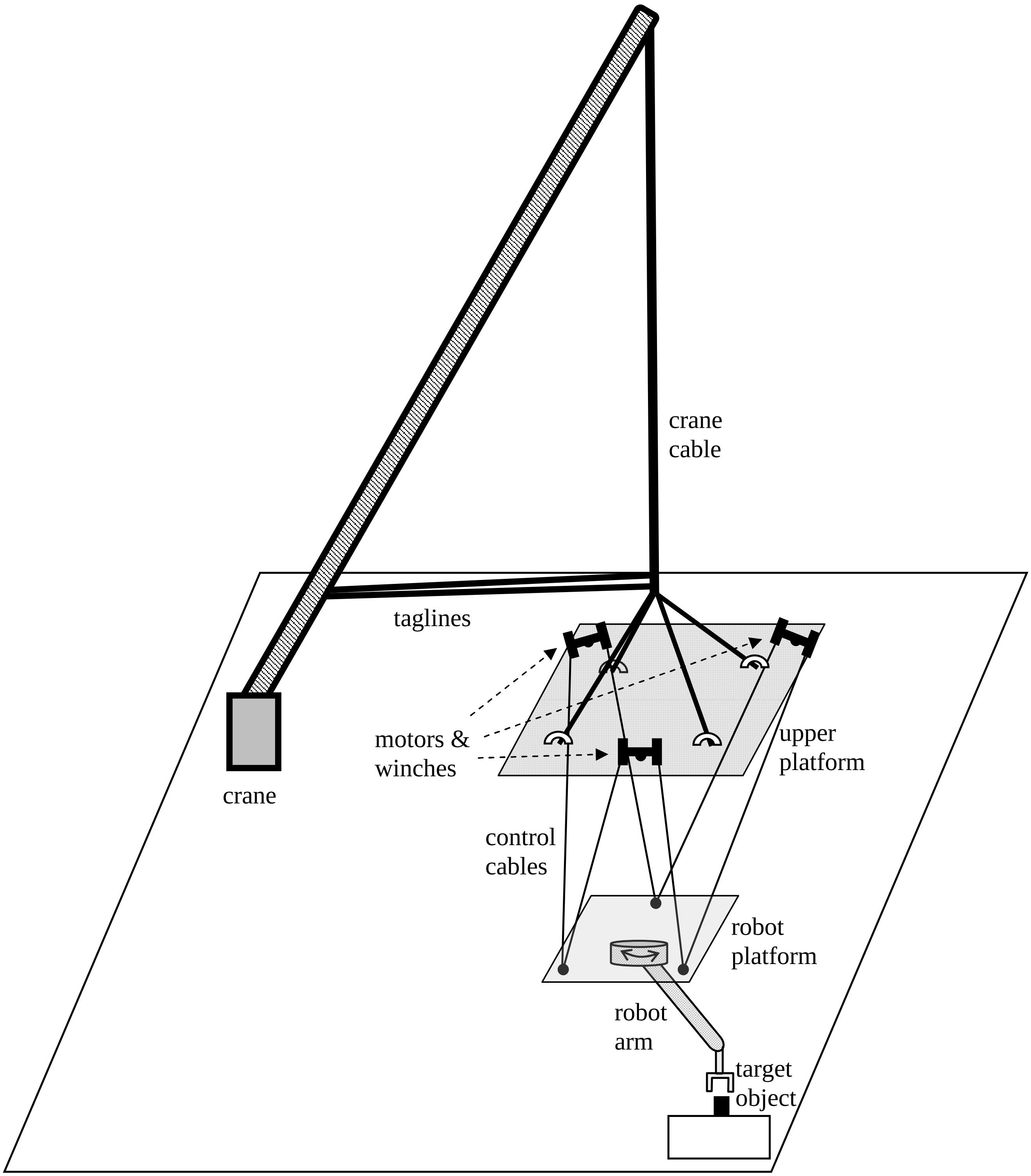

Figure 11: A cable driven monitoring and decontamination system with a robotic arm

Kinematic Representation

Kinematic representation mainly consists of motion of the two rigid bodies, upper and lower platforms, in space, as shown in Figure 12. Each rigid body motion is represented by six degrees of freedom. A reference frame is attached to the center of mass of each rigid body to represent its linear motion and orientation. We represent the linear motion with surge (*x*), sway (*y*), and heave (*z*) and rotational motion by roll, pitch, and yaw, collectively called the Euler angles. The position vector and Euler angles for the lower and upper platforms are written as:

$$\begin{aligned} \boldsymbol{r}_l &= [x_l \quad y_l \quad z_l]^T, \quad \boldsymbol{\theta}_l = [\theta_{lx} \quad \theta_{ly} \quad \theta_{lz}]^T \\ \boldsymbol{r}_u &= [x_u \quad y_u \quad z_u]^T, \quad \boldsymbol{\theta}_u = [\theta_{ux} \quad \theta_{uy} \quad \theta_{uz}]^T \end{aligned} \tag{1}$$

The angular velocities and accelerations are related to Euler angle rates as:

$$\boldsymbol{\omega}_j = B_j \dot{\boldsymbol{\theta}}_j, \quad \dot{\boldsymbol{\omega}}_j = B_j \ddot{\boldsymbol{\theta}}_j + \dot{B}_j \dot{\boldsymbol{\theta}}_j, \quad j = l, u \tag{2}$$

$$\begin{aligned} B_j &= \frac{\partial \boldsymbol{\omega}_j}{\partial \dot{\boldsymbol{\theta}}_j} = \begin{bmatrix} 1 & 0 & -S\theta_{jy} \\ 0 & C\theta_{jx} & S\theta_{jx}C\theta_{jy} \\ 0 & -S\theta_{jx} & C\theta_{jx}C\theta_{jy} \end{bmatrix}, \quad j = l, u \\ \dot{B} &= \begin{bmatrix} 0 & 0 & -C\theta_{jy}\dot{\theta}_{jy} \\ 0 & -S\theta_{jx}\dot{\theta}_{jx} & C\theta_{jx}C\theta_{jy}\dot{\theta}_{jx} - S\theta_{jx}S\theta_{jy}\dot{\theta}_{jy} \\ 0 & -C\theta_{jx}\dot{\theta}_{jx} & -S\theta_{jx}C\theta_{jy}\dot{\theta}_{jx} - C\theta_{jx}S\theta_{jy}\dot{\theta}_{jy} \end{bmatrix}, \quad j = l, u \end{aligned} \tag{3}$$

where we have used the notation $S\theta \equiv \sin\theta$ and $C\theta \equiv \cos\theta$.

The cables position vectors from their connection points on the lower platform to their winch locations on the upper platform are defined as:

$$\boldsymbol{d}_i = \boldsymbol{r}_u + A_u \boldsymbol{a}_{ui} - (\boldsymbol{r}_l + A_l \boldsymbol{a}_{li}), \quad i = 1, \ldots, 6 \tag{4}$$

where $\boldsymbol{a}_{li}$ and $\boldsymbol{a}_{ui}$ are the position vectors of the i^{th} cable connection point on the lower and upper platforms in their local reference frames, respectively. A_l and A_u are the direction cosine matrices of the local frames of upper and lower platforms, respectively. Cable velocities are derived by taking the time derivative of Eq. (4):

$$\dot{\boldsymbol{d}}_i = \dot{\boldsymbol{r}}_l + A_u \tilde{\boldsymbol{\omega}}_u \boldsymbol{a}_{ui} - (\dot{\boldsymbol{r}}_l + A_l \tilde{\boldsymbol{\omega}}_l \boldsymbol{a}_{li}) \tag{5}$$

where "~" is used for cross product and indicate $\tilde{\boldsymbol{\omega}} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$.

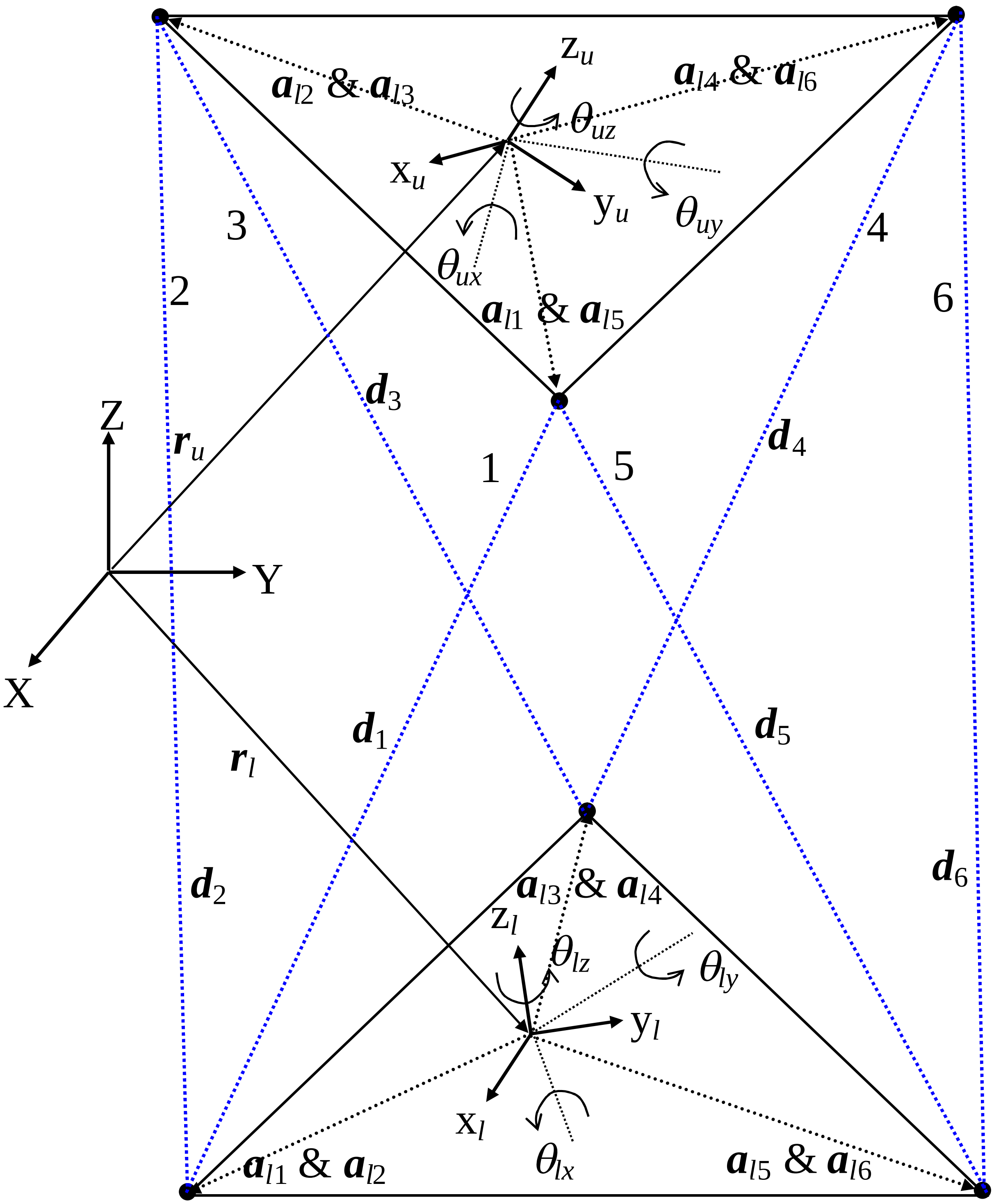

Figure 12: Kinematics of the upper and lower platforms with cable connections

Dynamic Model

The cable forces that act on the camera platform and with equal magnitude and opposite direction on the trolley platform are given in terms of control forces as:

$$\boldsymbol{f_i} = \frac{\boldsymbol{d_i}}{|\boldsymbol{d_i}|}u_i \ , \ i = 1...6 \tag{6}$$

where u_i is the i^{th} (positive) cable control/tension force. Based on the kinematic representation, we may derive the Lagrangian equations of motion in terms of the 12 degrees of freedom defined in Eq. (1) as:

$$m_l \ddot{\boldsymbol{r}}_l = (\sum_{i=1}^{6} \frac{\boldsymbol{d_i}}{|\boldsymbol{d_i}|}u_i) - m_l \boldsymbol{g} + \boldsymbol{f}_l' \tag{7}$$

$$M_{l\theta}\ddot{\boldsymbol{\theta}}_l = B_l^T (\sum_{i=1}^{6}(A_l \tilde{\boldsymbol{a}}_{\boldsymbol{li}}) \frac{\boldsymbol{d_i}}{|\boldsymbol{d_i}|}u_i) - \boldsymbol{f}_{\boldsymbol{l\theta}} + \tau_l' \tag{8}$$

$$m_u \ddot{\boldsymbol{r}}_u = -(\sum_{i=1}^{6} \frac{\boldsymbol{d_i}}{|\boldsymbol{d_i}|}u_i) - m_u \boldsymbol{g} + \boldsymbol{f}_u' \tag{9}$$

$$M_{u\theta}\ddot{\boldsymbol{\theta}}_u = -B_u^T (\sum_{i=1}^{6}(A_u \tilde{\boldsymbol{a}}_{\boldsymbol{ui}}) \frac{\boldsymbol{d_i}}{|\boldsymbol{d_i}|}u_i) - \boldsymbol{f}_{\boldsymbol{u\theta}} + \tau_u' \tag{10}$$

where m_l & m_u are the total masses of the lower and upper platforms, $\boldsymbol{g} = [0 \quad 0 \quad g]^T$ the acceleration due to gravity, and $\boldsymbol{f}_l', \tau_l', \boldsymbol{f}_u', \tau_u'$ represent the disturbance forces and moments acting on the lower and upper platforms. Also, noting J_l & J_u as the inertia matrices for the lower and upper platforms:

$$M_{j\theta} = B_j^T J_j B_j \ , \quad \boldsymbol{f}_{\boldsymbol{j\theta}} = B_j^T J_j \dot{B}_j \dot{\boldsymbol{\theta}}_j + B_j^T \tilde{\boldsymbol{\omega}}_j J_j \boldsymbol{\omega}_j \ , \quad j = l, u \tag{11}$$

Sliding Mode Control Law

Sliding mode control is a simple and robust method well suited for real time control of mechanical systems [114]. The goal of sliding control approach is to define asymptotically stable surfaces such all system trajectories converge to these surfaces and slide along them until they reach their desired destination. Here, we define 6 first order surfaces to determine the control laws for the 6 cables. The surfaces may be defined based on the type of task to be performed. When the crane is transporting the system to a location, the main objective is to keep the system stable. Hence the surfaces are defined such that the lower platform maintains its relative position to the upper platform. In this case, the surfaces are defined as:

$$\boldsymbol{s_r} = \dot{\boldsymbol{r}}_l - \dot{\boldsymbol{r}}_u + \lambda_r(\boldsymbol{r}_l - \boldsymbol{r}_u) , \quad \boldsymbol{s_\theta} = \dot{\boldsymbol{\theta}}_l - \dot{\boldsymbol{\theta}}_u + \lambda_\theta(\boldsymbol{\theta}_l - \boldsymbol{\theta}_u) \tag{12}$$

When the crane has stopped, the objective is to accurately position the lower platform. In this case, the surfaces are defined in terms of tracking linear and angular position and velocity errors of the lower platform:

$$\boldsymbol{s_r} = \dot{\boldsymbol{r}}_l - \dot{\boldsymbol{r}}_{\boldsymbol{ld}} + \lambda_r(\boldsymbol{r}_l - \boldsymbol{r}_{\boldsymbol{ld}}) , \quad \boldsymbol{s_\theta} = \dot{\boldsymbol{\theta}}_l - \dot{\boldsymbol{\theta}}_{\boldsymbol{ld}} + \lambda_\theta(\boldsymbol{\theta}_l - \boldsymbol{\theta}_{\boldsymbol{ld}}) \tag{13}$$

where subscript "*d*" indicates the desired trajectories.

We derive the nominal control law by setting the time derivatives of the surfaces equal to zero. The robust sliding mode control law is derived by adding a weighted “sign” function of each surface to the nominal one. Hence, the six cable control forces may be written as:

$$\boldsymbol{u} = M^{-1}[\boldsymbol{f} - \boldsymbol{k}\,\mathrm{sgn}(\boldsymbol{s})], \quad \boldsymbol{k} = \boldsymbol{\eta} + \boldsymbol{D} \tag{14}$$

where $\boldsymbol{\eta}$ is a vector if positive numbers representing the effort required for the system trajectory to the reach surfaces and $\boldsymbol{D}$ the bound for unknown disturbances and modeling uncertainties. The detailed equations for M and $\boldsymbol{f}$ depend on the type of surface and are presented in [92] for surfaces defined in Eq. (13).

Evaluation

Over the last few decades there has been numerous scenarios involving contamination due to chemical, biological, nuclear, radiological, and explosive agents either onboard ships or at ports that would benefit from a Scalable Emergency Response System for Oceangoing Assets. A cable-driven robotic device is a versatile system capable of sensing, monitoring and manipulating possible contaminants onboard ships and at ports. The system will be a reliable and autonomous robotic device capable of motion adaptation and handling materials in volatile sea conditions and hence minimizing the risk of human contamination. The system has the advantage of reaching locations otherwise hard to access via existing shipboard and on port cranes. Other potential applications of the system are general military and commercial ship-to-ship and ship-to-shore cargo and material handling and possible underwater monitoring, damage assessment, and repair operations for ships. The main technical concern about the system is maintaining tension in control cables and ensuring the overall system stability under volatile sea conditions.

Conclusion

We need to develop the complete kinematic and dynamic model of the cable-driven robotic system including the robotic arm to properly evaluate its performance. A robust control law must be developed that can guarantee system stability under volatile sea conditions. The control must also allow for precise manipulation of the robotic arm. Specifically, software must be developed for robust motion control and design and performance specifications through simulations. Further, experiments must be carried out to validate the simulations results.

Terahertz Imaging Technique for Bio-defense

University of Delaware-----Latha Nataraj

Introduction

Current US Naval shipboard material handling systems do not have a detection mechanism for agents of biological warfare. The goal of this project is to investigate the feasibility of the highly promising technique of terahertz (THz) imaging for sensing and monitoring possible biological contamination in a fast, non-invasive, and cost effective manner. It is envisioned that this reliable technique, which would minimize the risk of human exposure to lethal biological agents, could lead to the development of an autonomous system capable of reliably detecting various biological agents, thus resulting in an extremely valuable tool for the homeland security effort.

Terahertz (THz~10^{12} Hz) lies between the Far-IR and the microwave frequencies, roughly from 300GHz to 10 THz, or about 1 to 40 meV in photon energy. Some materials interact strongly at THz frequencies, making them a great way to gain information that is otherwise not possible with conventional optical techniques, X-Ray, or NMR [100]. Terahertz can also serve as a carrier wave in telecommunication applications for larger bandwidth [28]. These promising potentials attract intense R&D efforts worldwide.

Biomolecules such as DNA and proteins exhibit a wealth of modes in the THz range from the rotational, vibrational and stretching modes of biomolecules. Therefore, it can be used as a powerful tool for biomolecular sensing and biomedical analysis. Experiments have been carried out at the University of Delaware to study the absorption of various samples of DNA using FTIR spectrometer and Time Domain Spectroscopy (TDS) system.

Concept

Label-free DNA detection has attracted tremendous research effort in recent years for its non-invasive, fast and low cost advantages [35, 41, 27]. In this study, we propose to investigate and characterize the responses of DNA samples from various agents of biological warfare to Terahertz frequencies. Various modes such as rotation, vibration and stretching are exhibited by biomolecules such as DNA and proteins in the Terahertz (THz) range of frequencies. Therefore, it can be used as a powerful tool for biomolecular sensing and biomedical analysis.

Sensing of Biomolecules

Experiments were conducted at the University of Delaware to investigate the potential of THz in DNA sensing and results have been presented to indicate that using THz imaging techniques for DNA sensing could be highly effective. This study has explored the possibility of gaining information about the DNA through its interaction with Terahertz radiation.

A Thermo Nicolet 870 FTIR spectrometer equipped with a liquid Helium cooled silicon bolometer (IRLabs Inc.) was used to study the absorption characteristics of DNA molecules. The 20bp and Lambda DNA were purchased from Invitrogen Inc. in a lyophilized power form. The 470bp and 1200bp DNA were synthesized at the University of Delaware. The DNA powder was then dissolved in DI water and 20μL of the solution was deposited with a precision micropipette on Au-plated Si substrates. The sample was subsequently vacuum-dried. The resulting DNA film has a thickness of about 10μm. A piece of gold-plated Si with no DNA film was used to serve as the reference background. The reflection spectrum was obtained from the ratio between the DNA film spectrum and the reference one. Before each measurement, the FTIR chamber was purged for two hours with Nitrogen to get rid of moisture. IR spectroscopy was carried out in the 600 – 50 cm^{-1} range (20 – 1.6 THz) at a resolution of 4 cm^{-1}. The DNA spectra obtained from these films were consistently reproducible and showed features that were unique to different DNA molecules (length and sequence). Figure 13 shows the reproducibility of the measurement.

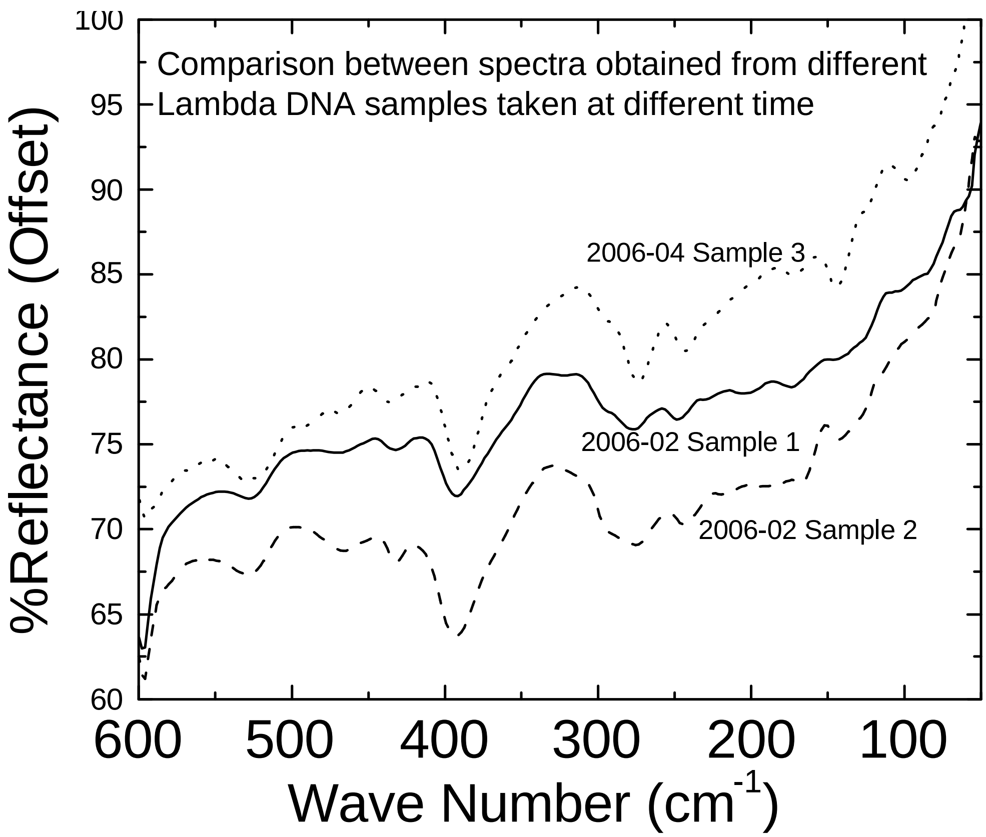

Figure 13: Three spectra obtained from different samples prepared using Lambda DNA The spectra share most of the features even though they were taken at different times from different samples. It shows the reproducibility of the measurements is very good.

Using the same lambda DNA, three different samples were prepared and measured at different times. These spectra are nearly identical except that some resonance shows up stronger on one sample than on the other two. Spectra were also obtained from DNA with varying lengths. Figure 14 shows the spectra for DNA molecules of 4 different lengths: 20 base pairs (bp), 470 bp, 1200 bp and 48 kbp. Woolard et al. al. [27] published a spectrum on Herring sperm Tyhpe XIV DNA between 500 and 100cm^{-1} and showed similar spectra.

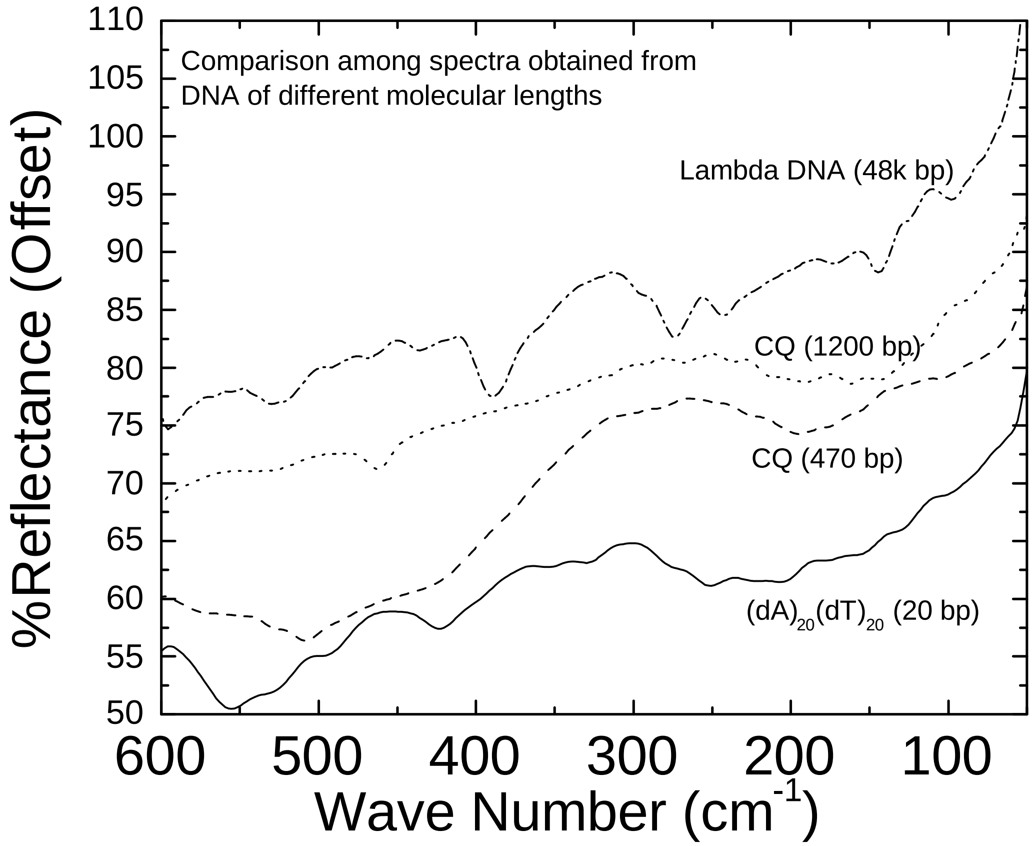

Figure 14: Comparison among four types of DNA molecules of different lengths ranging from 20bp to 48kbp. These spectra have been vertically offset for clarity. Three resonant-absorption features exhibit length-related changes. These absorption peaks are marked by pointers in the graph

In Figure 14, from the bottom spectra to the top one, the DNA molecules became longer (more basepairs) and certain resonant-absorption peaks showed trend changes with longer molecule. For example, the 555cm^{-1} absorption peak in the 20bp spectra moves to 507cm^{-1} for 470bp, 463cm^{-1} for 1200bp and 390cm^{-1} for 48kbp. The 494cm^{-1} dip in 20bp spectra moves to the 363cm^{-1} for 1200bp and 274cm^{-1} dip for the 48kbp. This feature in 470bp spectra is greatly suppressed. The broad dip at 231cm^{-1} in the 20bp spectra moves to 190cm^{-1} for 470bp, 165cm^{-1} for 1200bp and 121cm^{-1} for 48kbp. To visualize this finding,

Figure 15 plots (log-log plot) the position of feature vs. DNA molecular length. Each curve shows each series of absorption peaks in different spectra that were believed to be length-related.

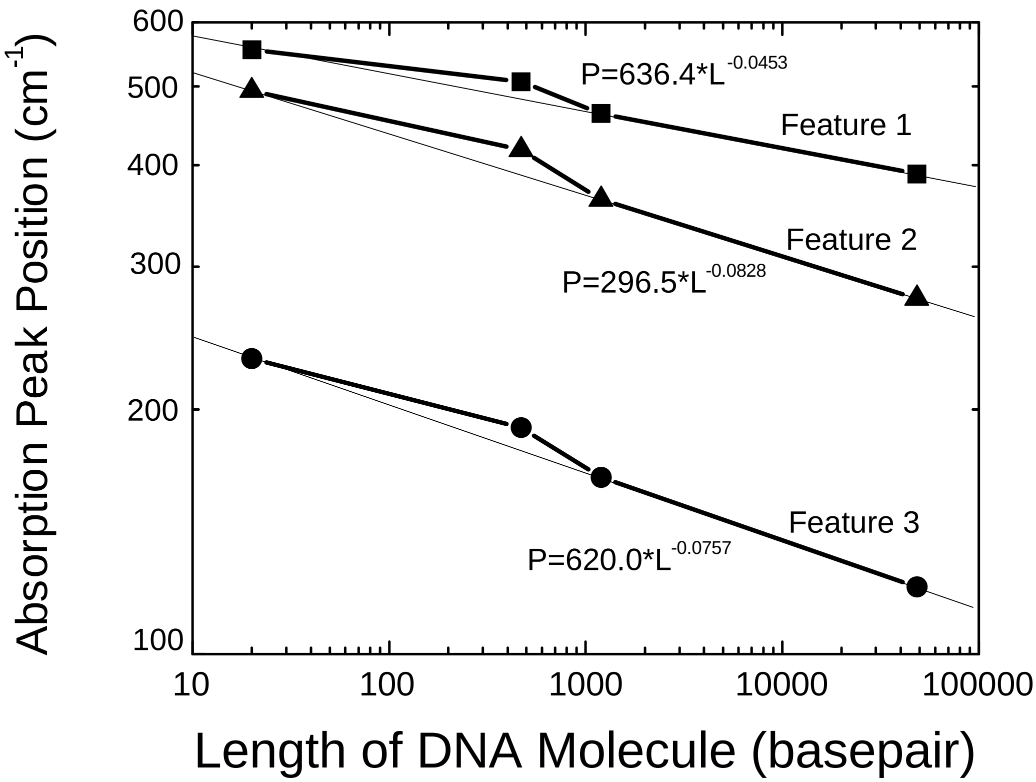

Figure 15: Log-log plot of position of absorption peaks versus lengths of DNA molecules. The thick line connects all the data points while the thin line is a perfect linear straight line connecting the resonant peaks from 20bp, 1200bp and 48kb.

In Figure 15, it seems that all the features belonging to the 470bp DNA molecule show abnormal in the curve while the features from other three lengths DNA showed linear behaviors. In a log-log plot, linear behavior means one variable is proportional to the power of the other variable. The abnormal behavior from the 470bp spectrum could result from a number of possible reasons such as errors in determining the molecular lengths during electrophoresis. Curve-fitting results (less the non-linear points) in the equation in the form of $Peak = C_1 \cdot Length^{C_2}$ and were shown next to each curve in Figure 15. The thin lines in the graph were the result of the curve fits. The slopes of these three lines (C_2) were approximately in the same range (-0.0453, -0.0828 and -0.0757). Both constants (C_1 and C_2) are believed to be related to fundamental DNA molecular parameters such as length and sequence. If we could collect spectra from large quantities of different lengths DNA molecules combining the use of clustering methods, a correlation could be made between spectral features and DNA molecular information such as lengths and even hybridization states and sequence.

Summary

Experiments to study responses of various types and lengths of DNA have been reliably performed at the University of Delaware using FTIR in the 600-50 cm^{-1} spectral region and several features have been identified to be type and molecular length related, indicating that this could be a promising approach to detect agents of biological warfare.

Evaluation

Over the last few decades there have been numerous incidences and threats involving contamination due to chemical, biological, nuclear, radiological, and explosive agents either onboard ships or at ports. A reliable system capable of sensing and monitoring possible biological contaminants onboard ships and at ports would be extremely valuable in fighting bio-terrorism and minimizing the risk to human life.

Other potential applications of the system could be general military and commercial ship-to-ship and ship-to-shore cargo and material handling and possible underwater monitoring. A bio-detector system based on THz imaging techniques could also have potential medical applications for non-invasive diagnosis of various bacterial and viral infections.

Conclusion

Various studies show that THz imaging techniques could be a highly promising approach in order to achieve this. This experimental study intends to establish the feasibility of the utilization of this technique for bio-defense by characterizing the responses of DNA samples from various biological agents to THz frequencies. It is envisioned that this reliable technique, which would minimize the risk of human exposure to lethal biological agents, could lead to the development of an autonomous system capable of reliably detecting various biological agents, thus resulting in an extremely valuable tool for the homeland security effort.

Emergency Response Decontamination Ship

Ship Recycling Research Institute

Introduction

While terrorism grabs headlines and focuses attention, accidents are a much more likely CBRN risk. The paper outlines a phased emergency response procedure to either terrorist or accidentally caused CBRN events, assesses gaps between suggested methodology and current practice and proposes a series of equipment and procedural adaptations to limit the current vulnerability. Additionally, it introduces the concept of a modified auxiliary crane ship to perform at-sea decontamination of vessels to protect populations and environments, and addresses strategic issues surrounding the creation of a Navy decontamination operations center at the Port of Philadelphia with forward operating bases for the most thorough protection and response.

In 2005 a Presidential WMD commission concluded “at the time of the commencement of the war in Afghanistan, Al-Qaeda biological weapons program was both more advanced and more sophisticated than analysts had previously assessed” [148]. Terrorism by its horrific, theatric nature tends to capture headlines, grabs hold of conversations and colors perceptions. However, a detailed review of prior maritime incidents and analysis of naval scenarios, suggests strongly that the more prevalent risk is accidents, not terrorism. Further, the Congressional Research Service, along with similar reports by the CIA and the Department of Defense, concludes that the likely occurrence of a CBRN act caused by terrorism is very low [145]. By contrast reports from the US Department of Transportation document more than 221 maritime incidents involving hazardous materials within just the last 10 years [155].

An example of a typical accident occurred in October 1996 off the coast of North Carolina when the guided-missile cruiser Leyte Gulf (CG-55) crashed into the aircraft carrier Theodore Roosevelt (CVN-71) during a training exercise. Another such accident took place in February 1999, as the USN destroyer Radford (DD-968) crashed into a Saudi cargo ship, the Riyadh, outside of Virginia Beach while calibrating electronic warfare equipment. Together, these two accidents resulted in $44 million in damage and posed both chemical and nuclear hazards to the vessels and crew (see Appendix D). During the three years between the Radford and the Leyte Gulf incidents there were no terrorist attacks on US Naval or commercial vessels, yet dozens of Navy accidents and more than 100 commercial accidents took place [157].

Since at least WWI, the Navy has recognized the threat posed first by chemical, then radiological and nuclear, and more recently biological weapons. The Navy has become increasingly prepared for CBRN incidents [161]. The Interim Biological Agent Detector (IBAD) is now deployed while another detection system, the Joint Biological Point Detection System (JBPDS), is being developed and tested for deployment to surface ships and high priority shore installations [167]. Personnel protection includes the use of the Joint Service General Purpose Mask (JSGPM) and the Joint Service Lightweight Integrated Suit Technology (JSLIST). The United States Marine Corps in 1996 created the Chemical Biological Incident Response Force (CBIRF) "which is the only DOD unit that has major decontamination ability" [154]. As a part of these efforts, vaccines and antibiotics are available for medical emergencies.

While the Navy is more prepared than ever, persistent gaps remain in its ability to respond to a CBRN incident. According to the National Research Council these gaps stem primarily from what they consider an over concentration on preventing contamination at the expense of decontamination [164]. Especially needed are capabilities to decontaminate interior spaces of vessels and sensitive equipment. Moreover, only a minority of active naval vessels have Collective Protection Systems (CPS) for contamination control, thus making large scale decontamination capacity an ongoing, and as of yet, unmet need. Interestingly, most joint service programs focus on land centric solutions. Should a CBRN incident occur onboard a Navy vessel, the lack of post-contamination planning and response technology increases the dangers posed to the vessel and its crew and cargo. The following proposed response procedure helps to address these enduring gaps and works to resolve the outstanding issues surrounding adequate decontamination response.

Concept

Event Phases

CBRN events have broadly similar patterns of divisible phases. In most cases the incident is sudden: caused by a fire, an explosion, a rapid change in pressure, an attack, a rupture (see Appendix E). This acute phase must be successfully managed to limit the loss of life and human injury, to keep the ship afloat and as functional as possible, and to contain the incident initially. The second phase brings outside resources to the incident to forward containment, protection, and treatment. These resources (equipment and personnel) are logistically or cost prohibitive to have on each vessel at the start. The third and fourth phases involve more substantial, longer term efforts (see Appendix F). They involve specialized equipment and personnel who must be able to conduct the more intensive clean up procedures while limiting risk and exposure to other ships and people, minimizing disruption, and culminating in the return of the ship(s) to active duty.

Through research and project team brainstorming, the study group came to understand this phasing better, and to believe that the best approach would be to match decontamination resources to incident phases (see Appendix C). By doing so, we are able to separate out and more easily identify decontamination gaps, promote greater efficiency and effectiveness by designing the concept to match resources to tasks, as laid out below. Phases one and two exist currently at least to some degree; phases three and four, involving more substantial decontamination efforts, will be a major focus of the next phase of the Team's investigation.

Response Phases – The Core Concept

The following represents the core concept of the Team's efforts. As currently practiced, in the first phase of CBRN response a threat is reported either by an on-board detection system or crewmember. The commanding officer of the vessel is notified and a designated CBRN team is deployed to the contaminated areas in order to evaluate the extent and severity of the incident. The areas are quickly contained by the CBRN team and sprayed down with water, bleach, foam, or a related substance. While this immediate response is underway, the vessel's commanding officer passes information of the event on to the chain of command, which notifies the centralized CBRN response coordinator—either StratCom or DTRA.

In the second phase of response this coordinator dispatches a quick response team via airlift and/or a USCG-style cutter ship to the vessel's location. These approaches are currently available to the Navy. Once onboard, quick response personnel evaluate the incident and determine whether the contaminated vessel must be pulled from operations. If the incident is contained and remediated, then the effort is essentially over. If more substantial decontamination efforts are deemed necessary, the response team would then request dispatch of a (proposed) converted auxiliary crane ship (ACS) to the site.

In the third phase of response the ACS departs from port with relevant modules onboard based on reports received from the quick response team. The converted ACS is envisioned akin to a "floating hazmat truck," carrying a series of designated TEU (twenty-foot equivalent units, IMO standard shipping containers) modules. These standard-sized modules are designed for easy transport and setup at the site of the incident, and offer a range of configurations, to be selected based on the specific situation to which the vessel is responding. For example, a typical situation might require the ACS to carry: the forensics TEU and a team from the FBI; a high level laboratory unit and a team from the CDC; and a special engineering TEU with a team of engineers and technicians to remove classified communications or similar equipment from the damaged vessel. The ACS carries a decontamination lab for sensitive equipment, as well as an isolation chamber for storing contaminated material and clean up related debris until they can be disposed of safely. Other TEU-based space, such as a habitability module with additional living space could be part of the complement.

In addition to physical modules based on TEUs the ACS would have access to specially trained and equipped teams from a variety of agencies. These teams could be called up to staff the ACS depending on the situation and the TEU modules being taken.

Upon arriving at the contaminated vessel, the ACS uses sensors and robotics to conduct a scan of the affected areas. A testing unit confirms the prior evaluations of the incident and the TEU-based modules are offloaded onto the contaminated vessel. A dedicated clean area onboard the vessel is allocated to handle personnel and equipment as the ACS operations move back and forth. While the vessel is being decontaminated, the ACS is also able to provide housing for the affected personnel via TEU-based units as well as utility services such as electricity, water, and communications to the contaminated vessel.

In the fourth and final phase of response the special equipment used for decontamination is loaded back onto the ACS. Upon returning to port, the equipment will be cleansed and prepared for redeployment. Meanwhile, the decontaminated vessel returns to active duty, no longer a risk to seaports, populations, or the rest of the Navy fleet.

Operations Center

The matrix of risk and threat profiles strongly suggest that the Navy decontamination operations center (NDOC) should be based at a location that is both easily accessible to the Norfolk/Newport News/James River area, but removed from the target rich environment this heavily trafficked Naval area represents.

The NDOC location should meet certain criteria:

1. Geographic proximity to Norfolk, Washington, D.C. and NYC.
2. Geographic separation from the James River / Chesapeake waterway and ideally also from the Port of NY/NJ.
3. Readily-available Navy land and facilities in order to limit cost and local objections.
4. Proximity to a strong technology base, particularly in life sciences and pharmaceuticals, in order to continue to improve bio detection and response capabilities and partner with corporate and university assets.

The Port of Philadelphia represents a good logical fit to host the NDOC. It is only 266 nautical miles from Newport News; if needed, the ACS could arrive in the area within 13 hours. Further, Philadelphia lies in a central location on the Atlantic Coast thus allowing the ACS to move to any east coast port quickly and easily. Further:

- Philadelphia is isolated from the waters most likely to encounter a CBRN incident. The Delaware River flows into Delaware Bay, which flows into the Atlantic Ocean. Therefore, any contamination of the Chesapeake would be unlikely to affect a Philadelphia-based operations center.

- As one of the nation’s leading life sciences clusters, Philadelphia offers a unique opportunity to utilize a vast amount of resources and expertise in medical science and biotechnology. The region is home to many centers of research including universities, teaching hospitals, medical laboratories, and technology-based venture capital firms. Philadelphia is a substantial base for the pharmaceutical industry and is the only East Coastal city with a veterinary school. The Greater Philadelphia Area is home to an experienced life sciences workforce that would provide the skilled labor necessary to this project.

- In addition, the former naval shipyard provides land and docking space, surrounded by business/industrial (rather than residential) operations. Local and state governments would support the increased economic activity the program represent, and in particular because the base has been designated a Keystone Innovation Zone, designed to encourage bio and life sciences to locate and grow there [166]. It would be relatively straightforward to create an on-site, state-of-the-art, bio-tech development community there to support the project.

Evaluation

The project goal is to create and evaluate a scalable emergency response system for oceangoing assets. The concept presented above brings several important benefits to project objectives. The matched phasing, for example, not only ties better with the nature of a CBRN event, but allows for more efficient dedication and use of resources applied to the problem. The concept as stated also allows the project to respond to any CBRN event involving an oceangoing vessel, including the large number of dangerous events affecting civilian craft.

Creating a system whereby decontamination efforts take place at sea reduces exposure and contact with hazardous materials by other vessels and crewmembers. Risks to civilians and population centers are nearly eliminated. Consequently, the impact of the CBRN event outside of the incident site is lessened. Additionally, at-sea decontamination saves time otherwise lost transporting the contaminated vessel to port. Each response team offers an additional opportunity for expert evaluation. The teams and their equipment can offer better isolation and contamination control than teams onboard the affected vessel can reasonably be expected to provide. No longer restricted to friendly ports, decontamination can now take place in a multitude of at-sea locations based on area conditions and convenience. Additionally, the ACS offers a platform for handling sensitive equipment and special materials from the interior of the contaminated vessel. Moreover, it can provide housing for affected personnel during the process as well as basic utility services (electrical, water, communications) for the contaminated vessel.

The multiple phases of this response approach can be scaled to the needs of each individual incident and can work in conjunction with a wide variety of hazardous situations. While accidents are the most prevalent risk, the phased response system will also be equipped to manage response to maritime terrorism aimed at both military and civilian targets. Additionally, at-sea decontamination can be utilized on military vessels in times of warfare in the event of an attack.

There are several concerns that should be considered in the phased emergency response plan. The success of each of the phases of the process builds upon and relies heavily on the actions taken, and the conclusions made, in prior phases. Therefore, a large responsibility is placed on the vessel's CBRN team and the quick response team in determining the severity of the incident and reporting on the specific conditions. With inaccurate or incomplete information, the ACS could depart from port with inadequate modules. The better each team and official along the chain of command is trained for CBRN incidents, the less the impact of this timing concern.

A ship like the ACS, designed to hold, move, and manipulate cargo and other equipment of this magnitude will be slow. The ACS, with a speed of 20 knots, may take up to two days to arrive at the scene of an East Coast incident with its supporting crew and equipment [143]. This issue is mitigated by the staggered response design of the proposal. While the ACS is in transport, the quick response team takes preliminary measures to isolate and contain the contaminated area. In addition, the fully developed concept should include preliminary considerations for forward operations.

There are likely to be several commercial and military applications of research and development from this project. The first and most obvious implication is for civilian shipping, protecting personnel, environment, and cargo through better matched and more effective at-sea decontamination capability.

A substantial opportunity exists in using the ACS decontamination ship and capability to address the clean up of decommissioned US Navy ships currently docked in domestic ports. Rotting, toxic ships too hazardous and deteriorated for transport can be decontaminated on site reducing environmental damage and beginning the process of reclaiming and reusing valuable coastal areas. In addition, this decontamination opportunity fits well into the training of ACS and other crews.

The research that will be enhanced in chemical and biological decontamination procedures and products has the potential to create substantial spin-off opportunities. The universities, medical, and pharmaceutical institutions in the Philadelphia area are well-positioned to maximize the benefits and to commercialize this research, in an area the Milken Institute labels one of the hotbeds of bio and life sciences [152].

The potential exists for some form of partnership with cargo lines and other sectors of the ocean transport industry to allow for cost, resource and/or knowledge sharing as the risk potential is even greater for commercial vessels as they lack many of the counter measures that the Navy has. In addition, there is a good deal to be learned about TEU design and configuration for these uses, and a unique opportunity to test and improve crane technology, with potentially far-ranging commercial and industrial impacts.

Conclusion

There is a clear case for a robust, flexible, US Navy CBRN emergency response capability with the ability to handle both maritime accidents as well as terrorism through an ACS-based system matched to phases of an event. This creates a range of benefits including limiting perceived public exposure and resulting public outcry, cuts down on the down time of damaged or affected vessels and limits exposure to the rest of the fleet.

As this project moves forward it will be necessary to focus efforts on the particulars of the ACS and the NDOC. Module types required, related design enhancements, and crane technology are key issues to be explored further, as are the operational issues related to maximizing biological and chemical technology, and the leveraging of the technical and industrial capacities of a projected geography .

As this project progresses from brainstorming and concept to implementation, it will be necessary to focus on several key issue areas. The capabilities of modular units will present real-world issues, constraining and better directing the design, construction, and modification of these TEU shipping containers to maximize the effectiveness of the bio-chemical labs and other equipment contained inside. The equipment itself will have sensitivities to factors such as ventilation, movement, and water, and must be evaluated in this context as well. Attention to crane technology will allow for better utilization of the TEU modules and possibly limit the risk/exposure to humans via leveraged usage of cranes, such as enhanced detection and/or monitoring capability mounted on a crane's spreader bar.

This concept has advanced using the Keystone state class ACS ships as a notional basis. Specific carrying capacities, maneuverability, and other design requirements now will come into focus, and the ship must be evaluated for its suitability, and the availability and condition of likely ships must be considered.

Additional research into the current practices and procedures of Navy personnel involved in ship damage and CBRN events may be useful, in order to best fit the expanded phases into current practices.

In order to leverage the strengths of the Philadelphia area in research (biological, medical, chemical, and engineering), economics, industrial/commercial, and university and other institutions to create an innovative cluster community tied to the Operations Center, the team must engage in a deeper and more detailed survey of the region's relevant assets.

Summary

The *Emergency Response Decontamination Ship* presented by the Ship Recycling Research Institute will be sponsored under this contract for further development of the feasibility of the concept.

Separate cost proposals were submitted to further the development of each of the six (6) University Science and Technology concepts. These proposals were evaluated by a small panel of experts assembled from the participants of the Brainstorming Workshop. The evaluation process included a Microsoft Excel workbook which calculated a total score for each of the proposals based on specific categories which were weighted then rated on a scale of one (1) to five (5) by each panel reviewer. The top rated proposals are those that meet the immediate needs of the project and the concepts contained in the proposals will continue to be refined under the current project, as funding allows. The remaining concepts, which do not require immediate attention, will be recommended for further development under future projects.

Based upon the results of the proposal evaluation, the following University Science and Technology concepts will be sponsored under this contract to further development:

1. *Microarray Identification*, Dr. Metin Duran, Villanova University
2. *Chemical Warfare Agent Sensing and Remediation*, Dr. Randy Weinstein, Villanova University
3. *Optical Fibers for Detection of Radionuclide Contamination*, Dr. Rosalynn Wynne, Villanova University

In a parallel effort to the formal concept evaluations, a complementary concept brainstorming and evaluation session was performed on March 23rd and 24th by a core group focusing on mechanical and electronic technology concept solutions based upon the project scenarios and comments made at the Brainstorming Workshop. These additional concepts will be further refined and evaluated with the most promising concepts being funded under the current contract. Details of these concepts will be provided under separate reports. The concepts include: (in no particular order).

1) <u>Cargo Sentry: </u>a portable instrumentation carrier able to be outfitted with sensors. The system will work with any standard spreader bar. The system would provide the ability to detect CBRN on ISO containers during on-loading and off-loading operations without reducing the productivity.
2) <u>Bee Stinger</u>: a highly portable device which will be able to penetrate steel (e.g. ISO container, sealed compartment on ship) creating a small hole which foam, decontamination fluids (i.e. Decon Green) or an aerosol could easily be passed via a sealed coupler. *Alternate variation*: fluid or aerosol could be sampled. *Alternate variation*: adapted with fiber optic camera and sensor detection.
3) <u>Hull Crawler</u>: a portable tow sled which will allow divers to transverse the exterior, including the underside, of a vessel or submarine hull to inspect, repair or maintain the ship.

4) Hull Band-Aids: a highly portable apparatus which will assist in the temporary repair of damage to the haul of a vessel until a permanent repair is made. The band-aid would be made out of non-permeable fabric attached by industrial magnets.
5) Expandable plug: a highly portable device which will assist in the temporary repair of damage to the haul of a vessel until a permanent repair is made. The plug would be made out of non-permeable fabric filled with expansion foam/sponge that would fill and seal the area.
6) Magnetic Carabineer System: personnel equipment to allow inspection or maintenance teams the ability to easily and safely ascend and descend a stack of ISO containers or a hull of a vessel. *Alternate variation*: adapt for scaffolding system.
7) CBRN Expert System: a suite of expert systems to assist in rapid decision making throughout the "crisis". The domains range from determining what resources must be gathered to bring to the site and how to best transport the resources, to portable handheld expert systems to determine how to treat contain the damage and how to perform triage on any victims.
8) Segmented Robot: a highly versatile segmented robot which can exhibit a human function factor that can traverse varying terrain with the ability to climb stairs and ladders found in vessels and submarines. Potentially assist in extraction, data collection, surveillance, and decontamination operations. *Alternate variation*: adapted to crawl the exterior of vessel or submarine hull.
9) Bag-o-Foam: a highly portable device that will enable the ability to seal an ISO container of vessel compartment for containment.
10) AACTS: (Automated All-Weather Cargo Transfer System) a robotic crane with fuzzy logic control systems for an advanced cargo handling system for pier-side, off-shore and in-stream container transfers.
11) Sensor Jellyfish: an autonomous system which would be capable of sensing and providing communications; will be able to measure such environmental factors as wave height, direction, period of waves, air temperature, water temperature, depth, salinity as well as chemical, biological and radiation levels.
12) Cell Elevator: container cell elevator system which will raise the top container in each hatch cell to deck level where the crane can easily access the container; once the crane removes the container, the in-cell device would retrieve the next container and raise it above deck. This device would also support loading operations.
13) Bunker Container: an ISO container with the ability to contain and isolate a variety of materials including contaminated items and unexploded bombs.
14) Floating decontamination station: a general decontamination facility that is easily transported and deployable in port and in the ocean able to perform basic decontamination, and containment activities.

Appendices

Appendix A - References

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Appendix B - Equations of Motion of a Rigid Body in Three Dimensions

Basic Terms Defined

In order to make this report somewhat intelligible, some relevant terminology (well known in the robotics literature) is defined here. They can found in standard sources. With regard to systems in motion, two concepts are used: *Kinematics*, which is a geometric description of motion, and *kinetics*, which is a description of forces that cause the motion. *Dynamics* includes kinematics, kinetics and Newton's Laws to create a mathematical model for the motion (linking cause and effect). For example, it is possible to analyze the problem of parking a car in a confined space and to carry out a kinematic analysis and predict that it is possible to park it given the size and shape of the car, the tires and its steering linkage. It would however take a *dynamic* analysis to actually determine if the driver has sufficient muscular strength and to predict how the car would respond to the forces. Hence, we need dynamic analysis to ensure that the system would work in real life.

The motions of a robot are called *trajectories*, and consist of a sequence of desired positions, velocities and accelerations of a specific point on the robot. Given such a trajectory, as well as the forces that have to be exerted at a certain point, it is possible to determine the torques that should be exerted by the actuators in order to move it in a desired manner. This is called *inverse dynamics*. In practice, such computed torques will invariably lead the robot to stray from the desired path because of the cumulative effects of unpredictable disturbances and modeling inaccuracies. We remedy this by measuring the actual motion and using *feedback control* techniques to correct for errors.

Kinematics of Rigid Body Motion

Consider a rigid body in three-dimensional space that is possibly translating and rotating as shown in Figure 16. *XYZ* is a fixed reference at *O*, and *abc* is a frame of reference that is fixed to the body at point *A*. Let *B* be any other point on the rigid body.

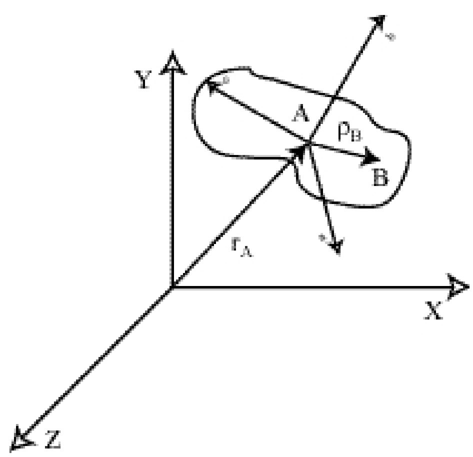

Figure 16: Rigid Body Kinematics

$$\begin{aligned} r_A &= X_A\hat{i} + Y_A\hat{j} + Z_A\hat{k} \\ r_B &= X_B\hat{i} + Y_B\hat{j} + Z_B\hat{k} \\ \rho_B &= a_B\hat{i} + b_B\hat{j} + c_B\hat{k} \end{aligned} \tag{1}$$

r refers to the position vector of a point with respect to the origin of the *XYZ* reference, and ρ is the position vector of a point with respect to the origin of the *abc* reference.

We have

$$r_B = r_A + \rho_B \tag{2}$$

Differentiating,

$$\frac{d}{dt}(r_B)_{XYZ} = \frac{d}{dt}(r_A)_{XYZ} + \frac{d}{dt}(\rho_B)_{XYZ} \tag{3}$$

Or

$$v_B = v_A + \omega \times \rho_B \tag{4}$$

where, ω is the angular velocity of the body expressed in body-fixed coordinates as

$$\omega = \omega_a\hat{i} + \omega_b\hat{j} + \omega_c\hat{k} \tag{5}$$

Note that, since ρ_B is fixed, $\dot{\rho}_B = 0$.

Differentiating again,

$$\frac{d}{dt}(v_B)_{XYZ} = \frac{d}{dt}(v_A)_{XYZ} + \frac{d}{dt}(\omega \times \rho)_{XYZ} \tag{6}$$

Or

$$a_B = a_A + \left(\frac{d\omega}{dt}\right)_{XYZ} \rho_B + \omega \times (\omega\rho) \tag{7}$$

<u>Special Case: Plane Motion</u>

Consider the case of the body being confined to the *YZ* plane.
Then, we have

$$\begin{aligned} r_A &= Y_A\hat{j} + Z_A\hat{k} \\ r_B &= Y_B\hat{j} + Z_B\hat{k} \\ \rho_B &= b_B\hat{j} + c_B\hat{k} \end{aligned} \tag{8}$$

The angular velocity is along the *X*-axis; or,

$$\omega = \omega\hat{i} \tag{9}$$

The velocity and acceleration of point B are

$$v_B = \dot{Y}_A \hat{j} + \dot{Z}_A \hat{k} + \omega b_B \hat{k} - \omega c_B \hat{j} \quad (10)$$

$$a_B = \ddot{Y}_A \hat{j} + \ddot{Z}_A \hat{k} + \dot{\omega} b_B \hat{k} - \dot{\omega} c_B \hat{j} - \omega^2 b_B \hat{j} - \omega^2 c_B \hat{k} \quad (11)$$

Newton's Equations of Motion

From a consideration of a rigid body as an assemblage of particles held together by rigid constraints and by applying Newton's laws to the particles, the equations of motion governing the motion of a rigid body can be derived.

From Newton's II Law, each particle in the rigid body is governed by the equation

$$F_i = \frac{d}{dt} P_i \quad (12)$$

where, P_i is the linear momentum of each particle.

The total linear momentum in the rigid body is obtained from

$$\begin{aligned} P &= \iiint (v_C + \omega \times \rho) dm \\ &= v_C \iiint dm + \omega \times \iiint \rho dm \\ &= m v_C \end{aligned} \quad (13)$$

Summing the forces and applying Newton's equations to each particle, we get the following equation for the rigid body.

$$F = \frac{d}{dt} P = m a_c \quad (14)$$

Note that the force equation is related to the acceleration of the point C, the center of mass of the body.
Taking moments of the particle equation leads to the following.

$$M = \dot{H}_C \quad (15)$$

where, the moment equation is valid when the reference point is the center of mass of the body (it could also be a fixed point in an inertial frame of reference). H_C is the angular momentum of the body with respect to the center of mass defined by

$$\begin{aligned} H_C &= \iiint \rho \times dP \\ &= \iiint \rho \times (\omega \times \rho) dm \end{aligned} \quad (16)$$

Substituting for ρ and ω in body-fixed coordinates,

$$\begin{aligned} \rho \times (\omega \times \rho) = & \left[\omega_a (b^2 + c^2) - \omega_b ab - \omega_c ac\right]\hat{i} \\ & + \left[\omega_a ca - \omega_b cb + \omega_c (a^2 + b^2)\right]\hat{j} \\ & + \left[\omega_a ca - \omega_b cb + \omega_c (a^2 + b^2)\right]\hat{k} \end{aligned} \quad (17)$$

Hence, the angular momentum can be expressed in the following matrix relation.

$$\begin{bmatrix} H_a \\ H_b \\ H_c \end{bmatrix}_C = \begin{bmatrix} I_{aa} & -I_{ab} & -I_{ac} \\ -I_{ba} & I_{bb} & -I_{bc} \\ -I_{ca} & -I_{cb} & I_{cc} \end{bmatrix}_C \begin{bmatrix} \omega_a \\ \omega_b \\ \omega_c \end{bmatrix} \tag{18}$$

Or

$$\{H\}_C = [I]_C \{\omega\} \tag{19}$$

$[I]_C$ is the mass moment of inertia tensor each of whose elements are defined by the following relations.

$$\begin{aligned} I_{aa} &= \iiint (b^2 + c^2) dm, \quad I_{ab} = I_{ba} = \iiint (ab) dm \\ I_{bb} &= \iiint (c^2 + a^2) dm, \quad I_{bc} = I_{cb} = \iiint (bc) dm \\ I_{cc} &= \iiint (a^2 + b^2) dm, \quad I_{ca} = I_{ac} = \iiint (ac) dm \end{aligned} \tag{20}$$

Now, from the moment equation, we have

$$\begin{aligned} M &= \left(\frac{d}{dt} H \right)_{XYZ} \\ &= \left(\frac{d}{dt} H \right)_{abc} + \omega \times H \\ &= \dot{H}_a \hat{i} + H_a \underbrace{\left(\frac{d}{dt} \hat{i} \right)_{XYZ}}_{\omega \times \hat{i}} + \dots \end{aligned} \tag{21}$$

This then leads to three scalar equations.

$$\begin{aligned} M_a &= \dot{H}_a - \omega_c H_b + \omega_b H_c \\ M_b &= \dot{H}_b - \omega_a H_c + \omega_c H_a \\ M_c &= \dot{H}_c - \omega_b H_a + \omega_a H_b \end{aligned} \tag{22}$$

If the body-fixed axes coincide with the principal axes of inertia of the body (then the products of inertia, $I_{ab} = I_{bc} = I_{ca} = 0$,

$$H_a = I_{aa}\omega_a \quad H_b = I_{bb}\omega_b \quad H_c = I_{cc}\omega_c \tag{23}$$

The moment equations then simplify to the following.

$$\begin{aligned} M_a &= I_{aa}\dot{\omega}_a + (I_{cc} - I_{bb})\omega_a \omega_b \\ M_b &= I_{bb}\dot{\omega}_b + (I_{aa} - I_{cc})\omega_b \omega_c \\ M_c &= I_{cc}\dot{\omega}_c + (I_{bb} - I_{aa})\omega_a \omega_c \end{aligned} \tag{24}$$

These are called *Euler's Equations of Motion.*

Euler Angles

In order to orient the rigid bodies we define what are called Euler angles. The ones we use here are often called Tait-Bryan angles @@@\cite{goldstein1951}. These are sometimes called Set B Euler angles @@@\cite{moon1998}.

First, we have a fixed set of axes *XYZ*. A rotation, ψ, about the *Z* axis leads to a new set of axes, $x_1y_1z_1$. The rotation is shown in Figure 17 and the coordinate transformation is listed in Equation 25.

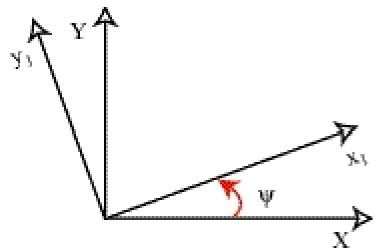

Figure 17: Rotation about *Z axis*

$$\begin{bmatrix} \hat{i}_1 \\ \hat{j}_1 \\ \hat{k}_1 \end{bmatrix} = \begin{bmatrix} +\cos\psi & +\sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{i} \\ \hat{j} \\ \hat{k} \end{bmatrix} \tag{25}$$

Next, we carry out a rotation, θ, about y_1. This is shown in Figure 18 and the transformation is listed in Equation 26.

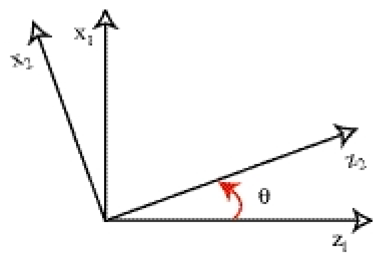

Figure 18: Rotation about y_1 *axis*

$$\begin{bmatrix} \hat{i}_2 \\ \hat{j}_2 \\ \hat{k}_2 \end{bmatrix} = \begin{bmatrix} +\cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \hat{i}_1 \\ \hat{j}_1 \\ \hat{k}_1 \end{bmatrix} \tag{26}$$

Finally, we carry out a rotation, ϕ, about x_2. This is shown in Figure 19 and the transformation is listed in Equation 27.

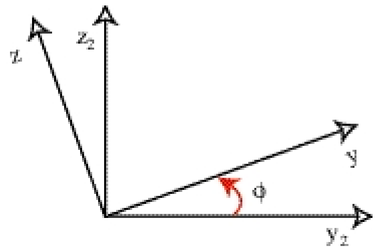

Figure 19: Rotation about x_2 axis

$$\begin{bmatrix} \hat{i}_3 \\ \hat{j}_3 \\ \hat{k}_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \hat{i}_2 \\ \hat{j}_2 \\ \hat{k}_2 \end{bmatrix} \tag{27}$$

The angular velocity of the final set of axes is given by

$$\begin{aligned} \overline{\omega} &= \dot{\psi}k1 + \dot{\theta}j2 + \dot{\phi}i2 \\ &= \left(\dot{\phi} - \dot{\psi}\sin\theta\right)\hat{i} + \left(\dot{\psi}\cos\theta\sin\phi + \dot{\theta}\cos\phi\right)\hat{j} + \left(\dot{\psi}\cos\theta\cos\phi - \dot{\theta}\sin\phi\right)\hat{k} \end{aligned} \tag{28}$$

Suppose θ and ψ are small quantities. Then, the angular velocity components can be approximated as follows.

$$\begin{aligned} \omega_a &= \dot{\phi} - \dot{\psi}\theta \\ \omega_b &= \dot{\psi}\sin\phi + \dot{\theta}\cos\phi \\ \omega_c &= \dot{\psi}\cos\phi - \dot{\theta}\sin\phi \end{aligned} \tag{29}$$

Kinetic Energy

The kinetic energy in the rigid body can be determined by integrating over the individual particles.

$$T = \frac{1}{2}\iiint (v \cdot v)dm \tag{30}$$

The velocity at any position in the rigid body can be written as

$$v = v_c + \omega \times \rho \tag{31}$$

Substituting,

$$\begin{aligned} T &= \frac{1}{2}mv_c \cdot v_c + \frac{1}{2}\iiint (\omega \times \rho) \cdot (\omega \times \rho)dm \\ &\quad + v_c \cdot \omega \times \iiint \rho dm \end{aligned} \tag{32}$$

Note that the integral in the second term is the definition of the angular momentum about the center of mass.

Hence, the kinetic energy can be written as the sum of translational and rotational terms.

$$
\begin{aligned}
T &= T_{trans} + T_{rot} \\
&= \frac{1}{2} m v_C^2 + \frac{1}{2} \{\omega\}^T [I] \{\omega\}
\end{aligned}
\tag{33}
$$

Lagrange Equations

Lagrange Equations for N generalized coordinates is

$$
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i, \quad i = 1, 2, \ldots N
\tag{34}
$$

where, q_i are the generalized coordinates, and Q_i are generalized forces, and $L=T-V$, where, T is the kinetic energy of the system, and V is the potential energy.

Kinematic Model

If we ignore dynamics, the motion of a rigid body in three dimensions is still governed by differential kinematical equations that are as follows (after application of the above principles).

$$
\begin{aligned}
p &= \dot{\phi} - \psi \sin t \\
q &= \dot{\theta} \cos p + \dot{\psi} \cos t \sin p \\
r &= \dot{\psi} \cos t \cos p + \dot{\theta} \sin p \\
\dot{\phi} &= p + (q \sin p + r \cos p) \tan \theta \\
\dot{\theta} &= p \cos p - r \sin p \\
\dot{\psi} &= (q \sin p + r \cos p) \sec \theta \\
\dot{x} &= u \cos\theta \cos\psi + v(\sin p \sin t \cos s - \cos p \sin s) \\
&\quad + w(\cos p \sin t \cos s + \sin p \sin s) \\
\dot{y} &= u \cos\theta \sin s + v(\sin p \sin t \sin s + \cos p \cos s) \\
&\quad + w(\cos p \sin t \sin s - \sin p \cos s) \\
\dot{z} &= -u \sin t + v \sin p \cos t + w \cos p \cos t
\end{aligned}
\tag{35}
$$

Dynamic Model

The following force and moment *dynamic* equations have added to the kinematic equations presented earlier.

$$
\begin{aligned}
m(\dot{u} + qw - rv) &= X \\
m(\dot{v} + ru - pw) &= Y \\
m(\dot{w} + pv - qu) &= Z
\end{aligned}
\tag{36}
$$

$$
\begin{aligned}
&I_x \dot{p} - I_{yz}(q^2 + r^2) - I_{zx}(\dot{r} + pq) - I_{xy}(\dot{q} - rp) - (I_y - I_z)qr = K \\
&I_y \dot{q} - I_{zx}(r^2 + p^2) - I_{xy}(\dot{p} + qr) - I_{yz}(\dot{r} - pq) - (I_z - I_x)rp = M \\
&I_z \dot{r} - I_{xy}(p^2 + q^2) - I_{yz}(\dot{q} + rp) - I_{zx}(\dot{p} - qr) - (I_x - I_y)pq = N
\end{aligned} \tag{37}
$$

If the axes x,y,z are assumed to be symmetry axes, the rotational equations simplify.

$$
\begin{aligned}
&I_x \dot{p} - (I_y - I_z)qr = K \\
&I_y \dot{q} - (I_z - I_z)rp = M \\
&I_z \dot{r} - (I_z - I_y)pq = N
\end{aligned} \tag{38}
$$

Forces & Moments

The forces and moments in the above equations arise from gravity, air, water, propulsion and actuation which will have components about all the three axes. These forces are typically nonlinear functions of the motion variables; in addition, there is always some uncertainty associated with their functional form and parametric values.

Hydrodynamic Forces

The hydrodynamic forces arise due to a combination of flow situation and fluid property, and can be categorized as follows.

- Inertia forces involving fluid density.
- Viscous forces in the form of friction involving viscosity.
- Wave forces due to gravitational waves near to or on the surface.
- Circulation forces due to the addition of a fluid rotation about the body.

Appendix C - Scenario Planning

Scenario Number	Scenario Description	Probability of Occurrence	Potential for Further Contamination of Area	Level of Damage to Vessel(s)	Population Exposure or Strategic Concern (1=yes)	Cumulative Weighted Impact Rating	Proposed Project's Potential Applicability	Type of Location	Contamination Type	Description of Contaminated Area	Vessel's Level of Functioning	Type of Threat (Irregular, Catastrophic, Conventional, Disruptive,	Owner	Geographic Location
1	Vessel carrying toxic chemicals reports leaking cargo containers	5	3	3	1	5.28	High	harbor/ population center	chemical	vessel, crew, and cargo	High	Accidental	commercial	Outside LA/Long Beach port
2	Aircraft carrier collides with HAZMAT barge at night in heavy fog	4	5	4	1	5.04	High	harbor/ population center	biological, chemical and unknowns	vessels, crews and cargo	Limited	Accidental	commercial / military	Chesapeake Bay
3	Ship runs aground on coral reef	5	1	2	1	4.68	Moderate	harbor/ population center	chemical	vessel	Dependent on situation	Accidental	commercial / military	San Juan Harbor
4	Surfacing submarine collides with merchant ship	5	2	3	0	4.20	Moderate	open ocean	nuclear, chemical, unknowns	vessels, crews, and cargo	Limited	Accidental	commercial / military	Caribbean Sea
5	Navy Ship Collides with Civilian cargo ship, collision results in chemicals packed and stored separately mixing	3	5	4	1	4.20	High	25 miles from port/popula tion center	chemical, biological	civilian cargo ship and hole in Navy vessel	Limited	Accidental	commercial/ military	Outside Kaohsiung Harbor, Taiwan
6	Structural Problem for tanker and/or cargo ship	4	4	4	0	4.00	Moderate	open ocean	chemical and unknowns	vessel	Limited	Accidental	military	Mediterranean Sea
7	Plane crashes on aircraft carrier deck	4	3	3	0	3.70	Low	open ocean	nuclear	vessels and crew	Impaired but seaworthy	Accidental	military	Pacific Ocean 400 miles SW of Hawaii
8	Engine room fire causes release of toxic cloud	4	2	4	0	3.60	Unclear	open ocean	chemical	vessel, crew, and cargo	Limited	Accidental	commercial / military	North Atlantic west of the Azores

9	Guided missile cruiser and submarine collision	4	2	2	0	3.40	Moderate	open ocean	nuclear and unknowns	vessels, crews, and cargo	Limited	Accidental	military	Western Mediterranean
10	Piracy of chemical tanker	2	5	2	1	3.12	Low	strait/population center	chemical	vessel, crew, and cargo	High	Irregular	commercial	Strait of Malacca
11	Shipping container found to carry rare disease	2	5	1	1	3.00	High	harbor/population center	biological	vessel and crew	High	Accidental / Irregular	commercial	New York Harbor
12	SARS-like outbreak on ship or cruise ship	2	5	1	1	3.00	High	strait	biological	vessel and crew	High	Accidental	commercial	Istanbul Strait
13	Bioweapon in cargo container	2	5	1	1	3.00	High	harbor/ population center	biological	vessels, crews, and cargo	High	Irregular	commercial	Rotterdam Harbor, Netherlands
14	Chemical weapon launched from land hits navy vessel operating just beyond coastal waters	2	4	3	1	3.00	High	ocean (littoral)	chemical and unknowns	vessel, crew, and cargo	High	Irregular	military	Cape of Good Hope
15	Missiles in shipping container break during ship-to-ship resupply	3	3	2	0	2.90	Low	open ocean	nuclear	vessels, crews, and cargo	High	Accidental	military	Pacific Ocean 200 miles N of Hawaii
16	Torpedo jams in tube	3	2	3	0	2.80	Low	open ocean	nuclear	vessel and cargo	High	Accidental	military	Off coast of North Carolina
17	Ship hits a contact mine	2	5	4	0	2.80	Unclear	open ocean	chemical	vessel, crew, and cargo	Limited	Accidental / Irregular	military	Persian Gulf
18	Explosive-laden boat rams oil tanker	2	4	4	0	2.60	Low	open ocean	chemical and unknowns	vessel, crew, and cargo	Limited	Irregular	military	Gulf of Aden off coast of Yemen
19	Nuclear-powered ship suffers radiation leak	1	5	2	1	2.28	High	harbor/population center	nuclear	vessel, crew, and cargo	Limited	Accidental	commercial	Cape Horn
20	Interception of nuclear material during transport	1	5	1	1	2.16	Unclear	open ocean	nuclear	vessel and crew	High	Irregular	foreign military	Sea of Japan
21	Bombing of an Oil Platform	1	5	4	0	2.10	Low	open ocean	nuclear or chemical	platform and crew	N/A	Irregular	commercial	Gulf of Mexico 150 miles SE of New Orleans

22	Ship contamination resulting from India/Pakistan nuclear exchange	1	5	2	0	1.90	High	open ocean	nuclear	Indian naval vessel and crew	Nonfunctional	Catastrophic	foreign military	Indian Ocean

Cumulative Weighted Impact Rating Calculation Table

Formula	**Weighting**[1]
Probability of occurrence	70.0%
Potential for further contamination	20.0%
Level of damage	10.0%
	Additional increase
Population Exposure or Strategic Concern	20.0%

[1] 0.7* probability + 0.2* further contamination + 0.1* level of damage) * 1 or 1.2 for population/strategic

Appendix D - Military Incident Report

Incident Name	Date	Location	Incident Description	Incident Response	Risk
USS Hartford (SSN 768)	25-Oct-03	Mediterranean Sea north of Sardinia	Los Angeles class nuclear submarine ran aground		Chemical/Nuclear
USS Paul Hamilton (DDG-60)	6-Dec-02	North Arabian Gulf	Collision w/ unidentified vessel	ship suffered a non-threatening hole in its side above waterline	Chemical
USS Oklahoma City (SSN 723)	13-Nov-02	Western Mediterranean	nuclear powered attack sub collided w/merchant ship	damaged the sub's sail and periscope	Nuclear/Chemical
USS Cole (DDG-67)	12-Oct-00	Aden, Yemen	a small craft known as a dhow loaded with explosives and several suicide bombers pulled up alongside the Cole and detonated killing 17 and injuring 39	Cole was transported back to States via semi-submersible heavy transport and repaired over 14 months in dry-docks	Nuclear/Chemical
LaMoure County (LST-1194)	12-Sep-00	Coast of Chile	Grounding, struck a reef while conducting a tank-landing operation.	data not available	Chemical
Denver (LPD-9) & Yukon (TAO-202)	13-Jul-00	Western Pacific	amphibious transport dock Denver, ran into the stern of the oiler Yukon on July 13 in the Western Pacific at the onset of a refueling operation	Denver sustained significant damage to its bow, with stern damage to the Yukon. Damage estimates were $2.9 million	Chemical/Nuclear
Yukon (TAO-202)	27-Feb-00	Persian Gulf	Collision with a civilian vessel		Chemical
Shreveport (LPD-12)	16-Feb-00	Suez Canal	transport dock Shreveport ran aground in the Suez Canal		Chemical
Radford (DD-968)	4-Feb-99	25 miles east of Virginia Beach	the destroyer Radford crashes into the Saudi Riyadh (cargo ship) while Radford is circling a buoy to calibrate electronic warfare equipment	Radford suffered $32 million in damage, and one sailor was injured	Chemical/Nuclear
Seattle (AOE-3) & America (CV-66)	18-Aug-98	leaving the slip in Philadelphia	the Seattle collided with the America while leaving the slip		Chemical
USS. Enterprise (CVN-65)	8-Nov-98	off coast of Virginia	EA-6B Prowler crashed into an S-3 Viking on the flight deck causing a fire to break out involving both aircraft		Chemical/Nuclear

Roosevelt (CVN-71) & Leyte Gulf (CG-55)	14-Oct-96	off the North Carolina coast	guided-missile cruiser Leyte Gulf crashes into the aircraft carrier Theodore Roosevelt during a training exercise	crash ripped open front of Leyte Gulf and damaged rear of Theodore Roosevelt, $12 million in damage	Chemical/Nuclear
Gettysburg (CG-64)	13-Oct-96	northern Arabian Gulf.	Gettysburg was acting as plane guard for the USS Enterprise when struck the Iranian corvette, Bayandor		Chemical
Jacksonville (SSN-699)	17-May-96	Chesapeake Bay	attack submarine USS Jacksonville crashes into the Saudi Makkah cargo ship in thick fog	Both ships suffered significant damage, but no one was injured.	Chemical/Nuclear
USS Monongahela (AO-178)	1-Nov-89	off the coast of Spain	fire in engine room, 9 sailors injured		Chemical
USS Dwight D. Eisenhower (CVN-69)	31-Oct-89	90 miles off Cape Hatteras, NC	38 non nuclear missiles and 3 sailors washed overboard by a wave during nighttime cargo loading		Chemical
USS Reeves (CG-24)	30-Oct-89	32 miles south of Diego Garcia	F/A 18 Hornet from USS Midway accidentally dropped 500 pound bomb creating 5 foot hole in bow and small fire		Chemical
USS Iowa (BB-61)	19-Apr-89	off coast of Puerto Rico	47 sailors killed during gunnery practice when gun turret number 2 explodes		Chemical/Nuclear
USS Norfolk (SSN-714) & USS San Diego ((AFS-6)	17-Jan-89	Norfolk, VA	ships collided near Chesapeake bay tunnel and bridge while heading out to sea		Chemical/Nuclear
Oil Tanker Western Sun	30-Jul-86	60 miles east of Norfolk, VA	F-14 Tomcat Fighter fires sidewinder air to air missile during a training exercise striking the Western Sun causing gash in ship and several small fires	no information available	Chemical/Nuclear
USS Coral Sea (CV-43)	11-Apr-85	45 m. S. of Guantanamo Bay Cuba	Coral Sea Collides with tanker Napo causing a 30 foot hole in carriers bow holed above waterline and spills 8,000 barrels of oil	towed to dry-dock at Norfolk for repairs	Chemical/Nuclear
USS Kitty Hawk (CV-63)	12-Mar-84	Sea of Japan	Kitty Hawk carried 2-4 dozen nuclear weapons collides with a Soviet sub carried two nuclear torpedoes.		Nuclear/Chemical

USS Albany (CG-10)	16-Apr-76	unknown	experienced a nuclear weapons incident -- known as a "Dull Sword" -- when a TALOS surface-to-surface missile's nuclear warhead was damaged.		Nuclear
USS JFK (CV-67) & USS Belknap (CG-26)	22-Nov-75	70 miles East of Sicily	Collision in rough seas during air exercises results in 7 hours of fire on Belknap the deaths of 7 sailors and a broken arrow report	Belknap suffers serious damage and is towed back to US for 4 years of repairs no radiation hazard declared	Chemical/Nuclear
USS Guardfish (SSN-612)	21-Apr-73	370 miles SSW of Puget Sound	primary coolant leak while submerged sub surfaces where it is ventilated and decontaminated four crewmembers are transferred off for monitoring		Chemical
USS Dace (SSN-667)	29-Dec-71	Thames River, New London CT	during a submarine to ship water transfer the Dace discharged 500 gallons of water used as coolant for its nuclear reactor	USN claimed no negative impact	Nuclear/Chemical
USS Bon Homme Richard (CVA-31)	10-Feb-70	Naval Station San Diego, CA	Bullpup missile cracks leaking toxic gases and liquids, crew of 200 crew evacuated while rest of 3500 crew prepare to head to sea if needed		Chemical
USS Enterprise (CVN-65)	14-Jan-69	70 Miles off of Honolulu, HI	MK-32 Zuni rocket fixed to an F-4 Phantom overheated due to the exhaust of a nearby aircraft causing the rocket to explode, setting off a chain reaction of explosions (28 deaths, 314 injuries), and resulting in 2 months of repairs in Pearl Harbor		Chemical/Nuclear
USS Scorpion (SSN-589)	27-May-68	400 miles SW of the Azores	sub sinks killing all 99 sailors sub goes under with at least 2 ASTOR nuclear armed torpedoes		Nuclear/Chemical
USS Ticonderoga (CVA-14)	5-Dec-65	80 miles E of Ryukyu Islands Japan	A-4E with B-43 nuclear weapon rolled off the elevator and the plane aviator and bomb went under in 16,000 feet of water		Nuclear/Chemical
USS Tingey (DD-539) & USS Vammen (DE-644)	2-Aug-63	Pacific 200 miles off S. California	collided during naval reserve exercises Tingey is partly flooded, Vammen suffers damaged bow	both ships limp back to their homeports	Chemical

USS Salmon (SS-573)	4-Jul-63	unknown	shipboard accident causes release of mercury and interaction with a hot grid resulting in toxic mercury vapor cloud	14 sailors contaminated and treated	Chemical/Nuclear
USS Thresher (SSN-593)	10-Apr-63	Atlantic 220 miles east of Boston	engine room flooding causes piping failure and submarine to sink in 8,400 feet of water 129 sailors die submarine is never recovered		

Appendix E - Civilian Incident Report

Incident	Date	Location	Incident Description	Incident response	Risk
Barge	17-Sep-06	Tampa, FL near buoy 11 in the Edgemont channel	barge ran aground containing 70,000 barrels of molten sulfur causing some of the barrels to break open	attempts to free the barge were unsuccessful and a salvage operation undertaken	Chemical
Barge 7304	26-Aug-04	Lower Mississippi River near Brusly, LA	barge containing benzene and C5 gas was found leaking	two schools in the area were evacuated and most of the navigable portion of the Mississippi channel was closed to traffic	Chemical
Barge KTC 115	28-Jul-04	Saint Lawrence River	barge being towed by tug when tug lost steering and the barge ran aground spilling calcium chloride into the water and over the barge	divers repaired the damaged barge while the accident nescesitated closing the river to traffic before the barge could be moved for further work	Chemical
M/T Bow Mariner	28-Feb-04	Atlantic Ocean near Assateague, VA	fire and explosion on board the Bow Mariner while carrying 11,000 metric tons of Ethanol and a crew of 27	Coast Guard and local fisherman rescue 9 and 19 go down with the ship	Chemical
Barge	3-Nov-03	Houston Shipping Channel	barge containing 225,000 gallons of sulfuric acid capsizes and starts to leak into the water creating highly explosive hydrogen gas	Coast Guard evacuates area and monitors vessel via cameras holes are drilled to vent the gas and nitrogen used to inert the barge	Chemical
M/V Kent Relliant	18-Sep-03	San Juan Harbor	double bottomed freight vessel carrying 2.6 million gallons of IFO 180 runs aground in harbor	double bottom prevents leaking and vessel is off loaded to refloat it	Chemical
M/V HollandicConfidence	4-Mar-99	30 Miles W of Cape Mendocino, CA	Rough weather ripped hatch cover of a cargo hold off causing ship to take on water risking loss of 17.5 metric tons of sulfur	Ship limped into SF Bay under Coast Guard watch	Chemical

Sea Barge Trader	11-Nov-98	150 miles N of Dominican Rep.	Trader, a hazmat transport barge, ran into rough seas 12 containers went overboard and remaining containers were broken and leaking	Barge limped into San Juan and cargo was monitored	Chemical
M/V Manzur	15-Feb-98	Mississippi River @ SW Pass	Mazur suffered a fire of unknown origin while carrying 123 metric tons of sodium cyanide, 11 metric tons of wet acid batteries etc	Ship was sealed, fire controlled and response team boarded in gear	Chemical
C/V Teval	14-Nov-97	Ambrose Light Anchorage New York Harbor	Crew member reported ill after walking by cargo of 23 cylinders of methyl bromide ship causing leaking concerns	Stopped at Ambrose light, inspected in suits, allowed to continue to Elizabeth, NJ where unloaded, checked, and reloaded	Chemical
C/V MSC Clorinda	18-Jul-97	3 days outside of Wilmington, NC	Leak of benzyl chloride from safety valve of chemical tank, vessel cleared to enter port by HAZMAT personnel	Vessel required to wait 2 days in port for appropriate tank pump to arrive in order for cargo to be transferred to new tank	Chemical
Formosa Six	11-Apr-97	Southwest Pass of Mississippi River	Vessel carrying 1,2-dichloroethane collided with freighter, trapping cargo in ballast tanks	Tanker kept offshore for over 30 days due to the unavailability of a lightering vessel to transfer hazardous material	Chemical
T/B TMI-11	11-Mar-96	33 miles east off Flagler Beach, FL	Barge carrying caustic soda solution sinks and is deemed not worthy of salvaging	Cargo declared inextractable, controlled discharge of caustic soda solution into sea performed	Chemical
M/V Sealand Innovation	19-Apr-95	Off the coast of Charleston, SC	Container leak of allyl caproate and caprylic acid within safety container while vessel at sea	Hazardous materials contractor hired to remove leaking containers from safety containers aboard vessel	Chemical
T/B Conuma River	6-Dec-94	Tacoma, WA	200 gallons of sodium hydroxide spilled during transfer into barge, efforts to purge lines caused tank vents to overflow	Vacuum truck used to recover material from deck of barge, sodium hydroxide neutralized and disposed of	Chemical

F/P All Alaskan	24-Jul-94	10 m. W of Cape Sarichef on Unimak Island, AK	Vessel carrying ammonia, chlorine, and acetylene caught fire out at sea, towed into even deeper water due to chemical hazards	Vessel kept out at sea until fire subsided and hazardous material could be secured	Chemical
Tokyo Senator	28-Apr-94	Thimble Shoals Channel, VA	Non-regulated cargo (thioureadioxide) spilled onto hold after fire, vessel remained outside of port for one day before being cleared	Already suppressed fire was fully extinguished, vessel decontaminated by IMS, a hazardous waste contractor	Chemical
Barge Liberty Trader	15-Apr-94	Port of Hampton Roads, VA	Fire within non-hazardous containers on barge carrying 1,1,1-trichloroethane, compressed nitrogen, and potassium hydroxide	Fire quelled on container at a time, crane used to remove containers, some containers removed directly from vessel by hand	Chemical
C/V Newark Bay	11-Aug-93	Charleston, SC	Chloroacetic acid leak from faulty tank valve and crack in outer insulation skin of container, acetaldehyde oxide also onboard	Decontamination at terminal using sodium ash followed by high-pressure fresh-water washing	Chemical
M/V Ellen Knutsen	31-Mar-93	Philadelphia, PA	16,000 gallon spill of cumene due to crack between starboard ballast tank and starboard cargo tank	Vessel was deemed safe for removal from port in order for cleaning crews to access hazardous material under piers	Chemical
Nuclear powered merchant ship Matsu	1-Sep-74	Sea of Japan	during test voyage leaks develop in reactor shielding system resulting in radiation release	after floating at sea for weeks bc of local protests ship is moved to Sasebo and repairs begin in 1980	Nuclear
Savannah nuclear powered cargo ship	24-Nov-67	off coast of New Jersey	nuclear powered cargo ship Savannah springs a leak in its reactor auxiliary cooling unit Atomic Energy Comm. and Maritime admin say no radioactive material escaped	ship returned to Hoboken NJ for repairs	Nuclear

Appendix F - Other Related Incidents

Incident Name	Date	Location	Incident Description	Incident Response	Incident Risk	Incident Relevance
Cruise Ship *Seabourn Spirit*	5-Nov-05	100 Miles off coast of Somalia	Pirates using machine guns and RPG's attempt to seize cruise ship with 312 passengers		biological weapon	FYI good to consider especially if a nuclear powered cargo ship or hazmat ship was hijacked a cleanup crew would be needed if/after the ship was retaken
Dirksen Senate Office Building	2-Feb-04	Washington, D.C.	Ricin found in senator's office mailroom	Containerized 80 drums of mail and clothing of 32 potentially effected individuals	biological weapon	sensitive area could provide good source of materials and info of government run decontamination efforts also recent
Ricin North Carolina	2003	Greenville, NC	Ricin in letter		biological weapon	
Houston Texas BioWatch	2003	Houston, TX	tularemia detected by BioWatch and confirmed		biological weapon	
USPS Brentwood facility	21-Oct-01	Washington, D.C.	letters containing Anthrax passed through this facility killing 2		biological weapon	
Hart Senate Office Building	9-Oct-01	Washington, D.C.	Letter containing Anthrax mailed from post office in NJ to Senator Daschle is discovered 31 Senate Staffers test positive for exposure to Anthrax		biological weapon	Capitol Complex cleanup involved sensitive government areas a warren of tight spaces, HVAC systems, and enclosed areas including the tunnels
USPS Trenton facility	1-Oct-01	Trenton, NJ	Letters containing Anthrax passed through this facility		biological weapon	
NBC Studios	12-Oct-01	New York City, NY	letter containing Anthrax is found in NBC mailroom, already opened. Only trace amounts of Anthrax found.		biological weapon	
American Media Incorporated	1-Oct-01	Boca Raton, FL	anthrax letter sent to tabloid magazine		biological weapon	

Japan Subway	20-Mar-95	Tokyo, Japan	Aum Shinrikyo cult members release Sarin nerve gas during morning commute on the Tokyo subway 12 are killed 500 hospitalized and 5300 are medically examined	Task force of the Japanese SDF (military) sprayed and washed down the subway using a bleach and water mixture Subway was back in use at end of day	biological weapon	tight enclosed spaces, high numbers of people some analogy to aircraft carriers and submarines also a fast decontamination and quickly back in service
Brazilian clinic	15-Sep-87	Goiania, Brazil	cesium found in abandoned radiotherapy clinic causing 20 people high dose exposure, 129 contaminated and thousands monitored		nuclear exposure	well documented and studied case involving the difficulties of tracking and treating large numbers of exposed persons…makes sea based options attractive
Chernobyl Nuclear Power Plant	26-Apr-86	Pripyat, Ukraine	reactor 4 suffered a catastrophic steam explosion that resulted in a fire, a series of additional explosions, and a nuclear meltdown.		nuclear exposure	large scale nuclear disaster one of the few good case studies available for such nuclear powered ships and submarines would have greatest relevance
Union Carbide Pesticide Plant	3-Dec-84	Bopal, India	methyl isocyanate gas (MIC) escaped when valve in plant's underground storage tank broke killing 3,000 at the time and 15,000 over the next several years		chemical exposure	industrial site cleanup mimics tight spaces, pipes, and uses of a naval vessel
Russian Anthrax Leak	2-Apr-79	Ekaterinaberg, Russia	Suspected Anthrax spores released by bioweapons lab in the city affecting at least 94 killing 64 of them		biological weapon	