INSTITUTE FOR DEFENSE ANALYSES

Defense Science Study Group (DSSG): Think Pieces of the 2014–2015 DSSG Class

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June 2016

IDA Document NS D-5828
Log: H 16-000679

INSTITUTE FOR DEFENSE ANALYSES
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

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About This Publication

This work was conducted by the Institute for Defense Analyses (IDA) under contract HQ0034-14-D-0001, Project DA-2-2895, "Defense Science Study Group (DSSG)," for the Defense Science Office (DSO) of the Defense Advanced Research Projects Agency (DARPA). The views, opinions, and findings should not be construed as representing the official position of either the Department of Defense or the sponsoring organization.

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Executive Summary

The Defense Science Study Group (DSSG) is a program of education and study that introduces outstanding science and engineering professors to the United States' security challenges and encourages them to apply their talents to these issues. The program, begun in 1986, is directed by the non-profit Institute for Defense Analyses (IDA) and is sponsored by the Defense Advanced Research Projects Agency (DARPA).

Technological advantage is fundamental to our nation's security. To achieve this advantage, amidst rapid change in technology opportunities and defense needs, it is crucial that strong links are developed between the national security community and emerging leaders in the fields of science and technology.

The DSSG seeks to convey to its members an understanding of these issues and an appreciation for the people involved in defending our nation. The program also solicits new insights from members and helps facilitate their continuing involvement with the complex technical challenges of safeguarding the United States.

Group members interact with top-level officials from the Department of Defense (DoD) and other government organizations, various intelligence agencies, the White House, and Congress. Visits to military bases throughout the United States provide members a unique perspective of operating forces and allow program members to meet with senior commanders responsible for our nation's defense. Tours of defense laboratories and industrial facilities provide further insight into the technical dimensions of national security.

Integral to the program are studies written by DSSG members, either individually or in small groups, on national security issues of their choice. These "Think Pieces" allow members to personalize the DSSG experience, to focus on a particular area of importance to DoD, to bring their knowledge from an academic environment to bear on issues of concern, and to interact with individuals in DoD with related interests.

Each group meets for 2 years for approximately 20 days per year, divided into 2 week-long sessions each summer and two 3-day sessions each academic year. During these eight sessions, members focus on defense policy, related research and development (R&D), and the systems, missions, and operations of the armed forces and the Intelligence Community (IC).

The first session, held at IDA's headquarters in Alexandria, Virginia, provides members an overview of the DSSG program. Prominent individuals from the defense and

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national security arenas, IDA researchers, DSSG mentors, and alumni introduce new members to the defense establishment, the current national security environment, and the role that science and technology plays in that environment. Members also visit the Pentagon's National Military Command Center, are briefed by such senior Pentagon officials as the Chairman of the Joint Chiefs of Staff, and meet with national security professionals within the Executive Office of the President.

The second session includes members' first foray into "the field." Members visit Army, Navy, Marine Corps, and Joint Command facilities on the East Coast. Previous classes have met with senior military officers from the Navy's Atlantic Fleet, Marine Forces Atlantic, and special operations teams. They have also toured aircraft carriers, AEGIS-equipped destroyers, and tactical submarines. In addition, the second session included visits to the II Marine Expeditionary Force at Camp Lejeune, North Carolina; the 82nd Airborne Division at Fort Bragg, North Carolina; and the U.S. Central Command and U.S. Special Operations Command at MacDill Air Force Base (AFB), Florida. It ended with a tour of a Trident submarine base in Kings Bay, Georgia.

The third session focuses on Army, Navy, Marine and Air Force installations and defense industry facility tours on the West Coast and in the Midwest. Members fly via military aircraft. Past trips have included visits to Boeing, Lockheed Martin, and Northrop Grumman facilities; Fort Lewis; Edwards, Peterson, Offutt, and Wright-Patterson AFBs; Fort Irwin National Training Center; Third Fleet, Naval Special Warfare Command, and Marine Corps Air Ground Combat Center at Twentynine Palms.

The fourth session includes visits to intelligence agencies in the Washington, DC, area. Prior classes visited the Office of the Director of National Intelligence (ODNI), Central Intelligence Agency (CIA), National Security Agency (NSA), National Counterterrorism Center (NCTC), and the National Geospatial-Intelligence Agency (NGA).

During the fifth session, also held in the Washington, DC, area, members discuss their initial ideas for research "Think Pieces" and meet with key members of the U.S. House of Representatives, the U.S. Senate, and with other senior Government officials involved in national security. They also spend a day hosted by DARPA being introduced to their technology programs.

In the sixth session, DSSG members tour national laboratories. In 2015, DSSG members visited the Air Force Research Laboratory (AFRL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory, and Los Alamos National Laboratory (LANL).

In the seventh session, members take advantage of the resources available to them at IDA and visit defense and Government offices in the Washington, DC, area to advance their research. They also visit additional defense-related laboratories such as the Naval

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Research Laboratory (NRL) and Massachusetts Institute of Technology (MIT) Lincoln Laboratory.

During the eighth and final session of the program, members present the results of their “Think Pieces.” They are also briefed by representatives of Government study boards, including the Defense Science Board (DSB), the Air Force Scientific Advisory Board (SAB), the Army Science Board (ASB), the Naval Studies Board (NSB), JASON, and the Information Science and Technology (ISAT) Panel. Representatives from these boards provide an overview of their group’s activities and future projects and explain how members can participate in the work done by these defense advisory organizations.

This report contains the Think Pieces of the 14th DSSG class, which met during 2014–2015. Each Think Piece is a brief, informal study of an area of specific interest to the participants and one that may be outside the participants’ areas of expertise. It may contain thought-provoking ideas that are far from the official positions of DoD or DARPA. The primary purpose is to enable the authors to determine defense community interest in the selected area, to begin to make contact with appropriate individuals in that community, and to present their thoughts on the subject. All of the Think Pieces are unclassified.

The Think Pieces were reviewed and organized by Dr. Robert E. Roberts, Director of the DSSG program, and facilitated by Ms. Katherine E. Gliwa, DSSG Administrator.

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Foreword

The Think Pieces in this document are the result of an informal, quick study on a problem of interest to the author. All findings, opinions, and recommendations are solely those of the author and are not necessarily the position of either DARPA or IDA.

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Think Piece 1

From Buildings to Bathrooms: Finding People in Urban Environments

by

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From Buildings to Bathrooms: Finding People in Urban Environments

Greg Fiete, Tadayoshi Kohno, Todd Murphey
Defense Science Study Group 2014-2015

Summary

This *Think Piece* is focused on finding and tracking (specific) people and devices in urban environments, with a particular emphasis on using a distributed collection of cheap, ubiquitous, low signal-to-noise (individually) sensors whose combined result is a significantly enhanced probability of detection. Our goal is to highlight how emerging technologies can qualitatively impact the success rate of finding and tracking a person/object on a variety of different distance and time scales in an urban environment. This project is inspired in part by conversations at NAVSOC, Fort Bragg, the NGA, the NSA, the CIA, and with our DSSG mentors.

Motivation and Background: Global Urbanization

Modern day Shanghai, 25+ million inhabitants

Global population growth models predict a significant increase in the fraction of the human population living in urban areas over the next few decades (reaching, perhaps, close to 60%). In addition, the number of megacities—those with a population of over 10 million people—will also increase dramatically, with especially large expansion expected in Africa and Asia. With their complex infrastructure and large civilian populations, these environments present significant security challenges and will likely be locations of future conflict and/or locations where significant preparations--such as production of weapons--for conflict occur. A central challenge in this environment is the locating and tracking of particular individuals (or hazardous objects) in real-time with a high spatial accuracy (such as a meter). In many cases, it may be desirable for the subject to be unaware that he or she is being tracked.

Compared to rural areas, urban areas offer challenges and opportunities for location and tracking. For example, overhead assets, such as satellites, which rely primarily on imagery and host of electromagnetic signals of varying wavelength, are natural for tracking the movement of large artillery and tanks across largely rural open spaces. However, they may have difficulty imaging narrow alleys between tall buildings, maintaining persistent surveillance, or picking up other weak signatures in the complex electromagnetic environment of a city with electrical power. On the other hand, the infrastructure of an urban environment offers opportunities to monitor electricity use, water use, and various forms of waste production (sewage and trash) that may contain signatures of interest, or could be modified with emerging technologies to have them. Moreover, if it is a person one is seeking or attempting to track, the likelihood of that person interacting with others (e.g., to buy food, to perform financial transactions) in urban environments may be exploited.

Objectives

In this *Think Piece*, we ask what low-signal-to-noise signatures one might exploit in the urban setting for location and tracking, and we suggest how one might deploy various networks of sensors to detect them. To fine-tune the strategies, we break the problem down into different length and time scales: What strategies might one use to localize/track on a 10,000 ft, 1000 ft, 100 ft, or 10 ft length scale? We ask the same question for periods of roughly days, hours, minutes, and seconds (down to the instantaneous knowledge of where an object is).

In developing a technical approach to this problem, one must consider a number of relevant questions: How accurately does one need to know the location of an object in time? How do the strategies differ for a person versus an inanimate object? Is the urban environment one where sensors can be deployed freely, or is it a denied access area? If it is a person one is seeking, what are the different approaches that can be used depending on whether or not the target knows it is being sought? Can we anticipate the first steps one might take to hide the signatures of either the person or object of interest so that one might work around these? Are there strategies that one might use to detect whether “spoofing” attempts are being made by the target?

First, we seek to provide a broad survey of challenges and opportunities for locating people and objects in urban environments, including our best estimate of the current state-of-art. We present this survey from a perspective that is informed by our experiences as DSSG members, but also from a perspective that is shaped by our experiences in academia and our research fields. We hope that this survey will either corroborate the perspectives taken within the DoD and IC, or contribute new insights to those perspectives.

Upon surveying the landscape, we identify two key directions for future innovation: **crowdsourcing** and **unconventional sensing modalities**. The major goals of this project are therefore to explore the advantages that crowdsourcing and the deployment of unconventional sensors (to be defined shortly) may bring. An unconventional sensor may be something that is intended for common civilian use but inadvertently acts as a sensor with proper exploitation, or may be an object that is explicitly designed to operate in two ways -- one of which the user believes is the sole function, and the other that may be used by the IC for sensing. We would like to expand our definition of crowdsourcing to include the situation where many cheap (perhaps expendable) sensors are deployed with the idea that only one or a small number of these may reach their target, or otherwise detect the signal of interest.

For concreteness, we will focus special attention on two specific sensing modalities that we believe could be useful in an urban environment: (i) A physical “virus”, whereby a small device containing some type of sensor might pass from person-to-person (perhaps on their clothing) in order to reach “deep” inside a denied access area or to finally land on the person of interest. (ii) “Misused sensors” in which some object (a water pipe, money, a cell phone) is used to detect a signal for which it was not intended/designed to be sensitive.

In both of these examples, we would expect there to be a small signal against a noisy background. Once such sensing modalities are in place, there remains the higher-level challenge of how best to fuse the results of all of the “new” sensors with more conventional ones. In addition, if some of the “sensors” are humans providing intelligence, one needs to incorporate their information as well into a full data fusion. Quantitative methods for fusing the data of different types is an active topic of research, both in academia and the department of defense. Rather than discuss those methods in detail, here we will emphasize one particular point: The more “orthogonal” different sensing modalities are, the higher the level of confidence in the detection. This basic idea informs our approach of using a variety of low-cost, low-signal to noise sensors (which may also be individually large in number, for a particular type--which also increases the probability and confidence of detection). By the same token, this challenge also intersects with the ubiquitous “big data” problem in which one has a vast amount of data, yet is looking to extract “simple” patterns or other useful information from it.

In order to help frame our discussion, we consider three example use cases that may be relevant to the DoD. One focuses on a situation where an action is to be taken, once the person or object is found, another on a situation where the goal is to monitor the person or object at some standoff distance, and a final one where the chief goal is the finding itself.

Use Cases / Scenarios

Scenario 1 (Action): Someone within the IC or DoD (e.g., CIA, special forces) wants to find someone (or something) in an urban environment (city) where he or she is known to be. Once found, the team may want to execute some quick, coordinated action upon that person, e.g., rescue or capture. How does one localize them sufficiently in space and time for such a coordinated action (especially, if they may be in the interior of a building on a high floor)? Assuming the sought individual does not want to be found, what are some strategies for working around their spoofs and false trails?

Scenario 2 (Monitoring): As with Scenario 1, we begin with the assumption that a DoD team wishes to find someone (or something) in an urban environment, such as a city. Unlike Scenario 1, after finding that person, the team will not (immediately) carry out a fast action but will instead institute continuous monitoring. That continuous monitoring might be to: track the individual over time, monitor what the person does or says, or monitor who that person meets with (and possibly start monitoring those people as well).

Scenario 3 (Finding): Finding hostages or abducted people, e.g., the abducted school girls in Nigeria, or people being trafficked within the U.S. What are the different signatures one might exploit for a group of people compared to a single individual?

"Contributions" of this Think Piece

- A fresh perspective on the "finding people and objects" problem, including our perspectives on the key axes and issues defining the problem space and possible solutions. We suspect that different parts of the DoD are already thinking about some of these issues, but some may be new.
- A discussion of crowdsourcing as a tool to facilitate finding people and objects in urban environments.
- A discussion of the use of weird/unconventional sensing technologies in the quest to find people and objects.

Axes and Issues

In considering this topic, we consider a number of different axes and issues. As noted above, we consider the enumeration of these axes and issues to be a contribution of this work.

- **Instrumentation.** We must consider different levels of instrumentation. For example, can one instrument the environment or leverage the existing infrastructure (e.g., by erecting cell towers with the ability to monitor communications or the movement of cell phones, or by modifying parts of a building)? Or must one avoid instrumenting the environment (and hence, for example, might be able to fly drones in the area but not erect any permanent structure)? Or must one be even more discreet and passively monitor information that is already (publicly) available (e.g., by monitoring Twitter or Instagram posts)?

- **Presentation.** What is the best way to integrate different sources of information? For example, is it possible to present a single dashboard that would allow one to quickly assimilate the data from multiple sources? Also, is it possible to update the presentation in real-time as the target moves? What are measures of cognitive load that are operationally relevant?

- **Continuous vs location-based.** Some monitoring methods may be able to continuously monitor a person's location within a specific geographic region (such as within a city or within a building). Other methods may be more location based, e.g., a system might trigger an alarm when it detects a target within a building or within a room.

- **Preparatory time.** Related to the instrumentation a question of how much time one has to set up for an operation. The amount of time available to set up may affect which technologies can be deployed. Thus, for each monitoring technology that we consider, we must also consider how long it would take to deploy that technology.

- **Discretion.** How discreet is the monitoring infrastructure? Flying a drone around a city may not be discreet. Placing some device in a buildings sewage line may be more discrete. System level obfuscation--automating the process of making intent unclear--could play a role here.

- **Evidence of monitoring.** Will the use of the monitoring technology leave any evidence of use? For example, modifying a building's HVAC system may leave permanent evidence of monitoring (unless the system is designed to somehow revert to a previous state or a DoD team subsequently removes the technology). Putting a modified Android app on the target's phone might also leave behind evidence. On the other hand, monitoring wireless signals to infer information about the building occupants may not leave behind any evidence of monitoring.

- **Hints to others.** If one leaves a device behind (see "evidence of monitoring" above), then a subsequent question is: will the existence of that device, if discovered, help others avoid tracking in the future or help others track U.S. agents (neither of which we consider desirable)?

- **Sensing in depth.** How feasible is it for a DoD team to integrate measurements from multiple sources / multiple measurements?

- **Usability and cognitive load.** When information is presented to the DoD team, can they quickly digest it? Is enough information presented? Is too much information presented? What information does the team actually want and need? Cognitive load should be the primary metric, but light infrastructure also matters (e.g., computation that fits on a phone is useful to special operations, whereas computation that requires supercomputing is not).

- **Geographic Precision.** What is the geographic precision of the tracking technology? For example, a cell tower or IMSI catcher might be able to track a person to a city block, but a building with an instrumented Bluetooth sensor might be able to locate a person within a smaller region. Note that geographic precision refers to not only x- and y-coordinates, but also z-coordinates (e.g., what floor of a building is a person on).

- **Accuracy.** Related to precision is accuracy. For example, what is the false-positive and false-negative rate? And what is the standard deviation of the measurement (e.g., if the system reports a person as being in one room, could that person actually be in a neighboring room)? In this regard, what are operationally relevant measures of "location" at this scale? Are they always GPS coordinates, or the location of a subject down to the room within a (mapped) building. (E.g., if GPS coordinates predict that a subject is on top of a wall, that could lead to operational indeterminacy, but the *history* of that person's movements would make it clear which room he or she is in.) On a related note, what happens with the local structure is urban but very nonorthogonal (e.g., an environment in which rooms are not necessarily cleanly separate, making representation to the operator ambiguous)?

- **Dynamic tasking.** How do we handle dynamic tasking, where the goal suddenly changes, and the entire sensing element needs to adapt immediately? For instance, when someone deposits an IED, a user of the information system may wish to stop tracking the person and start tracking the IED.

- **Activity recognition.** In addition to determining the location of an individual, the DoD team might also be interested in learning about what that individual (and nearby individuals) might be doing -- are they asleep, are they stressed, are they watching TV, are they in the restroom, are they about to do something?

- **Monitoring technology form-factor.** What is the form-factor of the monitoring technology? First, there is the technology that the DoD team might deploy in the environment (e.g., the drones or some device to put into houses). Then there is also the technology that the DoD team will use to integrate and view the results of this sensing. Could that technology be as simple as a phone? How much of processing for small teams can be deployed on a phone?

- **Object of tracking.** While we have mostly discussed determining the location of an individual, we can also consider determining the location of groups of individuals or devices or animals or any other physical artifact. In terms of groups of individuals, there may be substantially more abstract goals, like actively extracting the social network connected to an individual (see degrees of association, below).

- **Degrees of association.** When considering technologies to locate an individual, it may be hard to locate that specific individual (e.g., because that individual does not travel much). In such a case, the DoD team may instead monitor an associate of that individual.

- **Perturbing the environment.** Active interrogation by physical intervention--can you improve computationally intractable problems (e.g., decryption) by changing physical situations/actions? Example: Battle of Midway, where we seeded decoding a message by leaking a supposed water shortage. The goal would be to automate this process, so the operator does not--in some situations--have to think about implementation. There might be other ways to perturb the environment for tracking purposes as well. For example, shut off water to a house and, thereby, force the occupants to leave the house if they want to shower.

- **Open source vs collected vs someone else's collected intelligence.** There are different sources of data. Some data may be open source. Other data the IC or DoD may collect. And other data someone else may collect but the IC or DoD may be able to purchase or otherwise acquire.

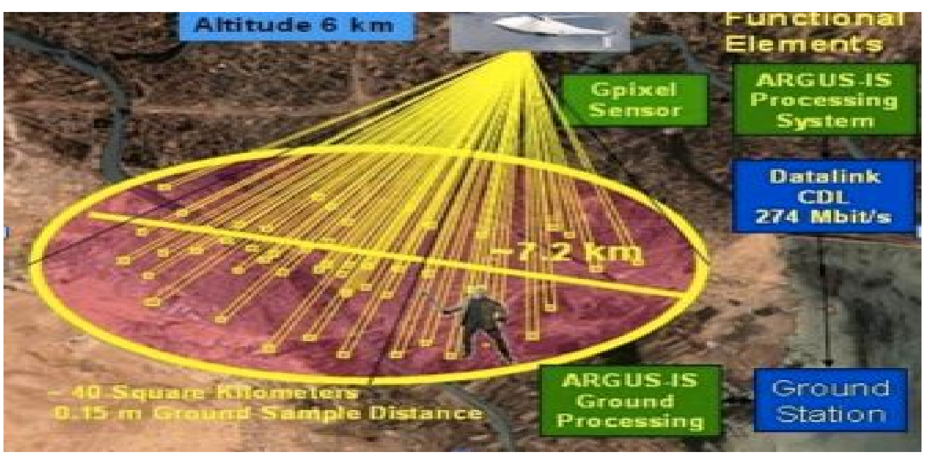
- **Location.** We consider both inside and outside of the U.S., though the approaches the U.S. government may choose to use may differ based on location.

Current state-of-the-art in urban location and tracking

Admittedly, we do not truly know the state-of-the-art in urban location and tracking within the IC and DoD, but here is what we are able to infer (in broad terms) from our non-classified DSSG sessions, mentors and various contacts within the government, and the Internet, particularly with regard to current trends in technologies.

We have seen that there is a demand and an attempt to move to a model of persistent surveillance whenever possible. We have seen that there are nearly continuous improvements in sensing across the electromagnetic spectrum with finer signature discriminating capabilities, and ever improving modeling of atmospheric effects of the signals. (By contrast, there does not appear to be the same level of sophistication with underwater sonar signals and the modeling of the oceanic effects on the signals, though we have the impression that the DoD recognizes this and is actively working to change that situation.) We have seen significant leveraging of computational resources to process signal data to render it in a visually appealing and meaningful way. We have seen increased exploitation of unmanned aerial vehicles for sensor deployment, and very recently there are efforts to go to expendable sensor platforms that may be produced cheaply and in large numbers. We have seen that many sectors of the DoD are grappling with ways to deal with "big data," much of which may come from "sensors" without clear signatures (e.g., social media postings).

To give one example that illustrates a few of these trends, the **Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System** (ARGUS-IS) is able to be deployed on an aircraft and provides continuous monitoring of an area of up to 36 square miles (wikipedia) with roughly meter-scale resolution. The technology is based on the fusion of images from a large number of cell phone cameras, and there are algorithms that have been developed to select and track specific classes of objects in time.



In addition to these technologies, which have often been specifically designed with surveillance applications in mind, we are aware of other relevant technological approaches that are likely to be used. For example, there are cameras set up at traffic lights, ostensibly for photographing traffic violators, but may also be used to photograph and identify any individual passing through an intersection. There are fake cell phone towers (IMSI catchers) that can be used to track phone motion, which may indicate movement of specific individuals.

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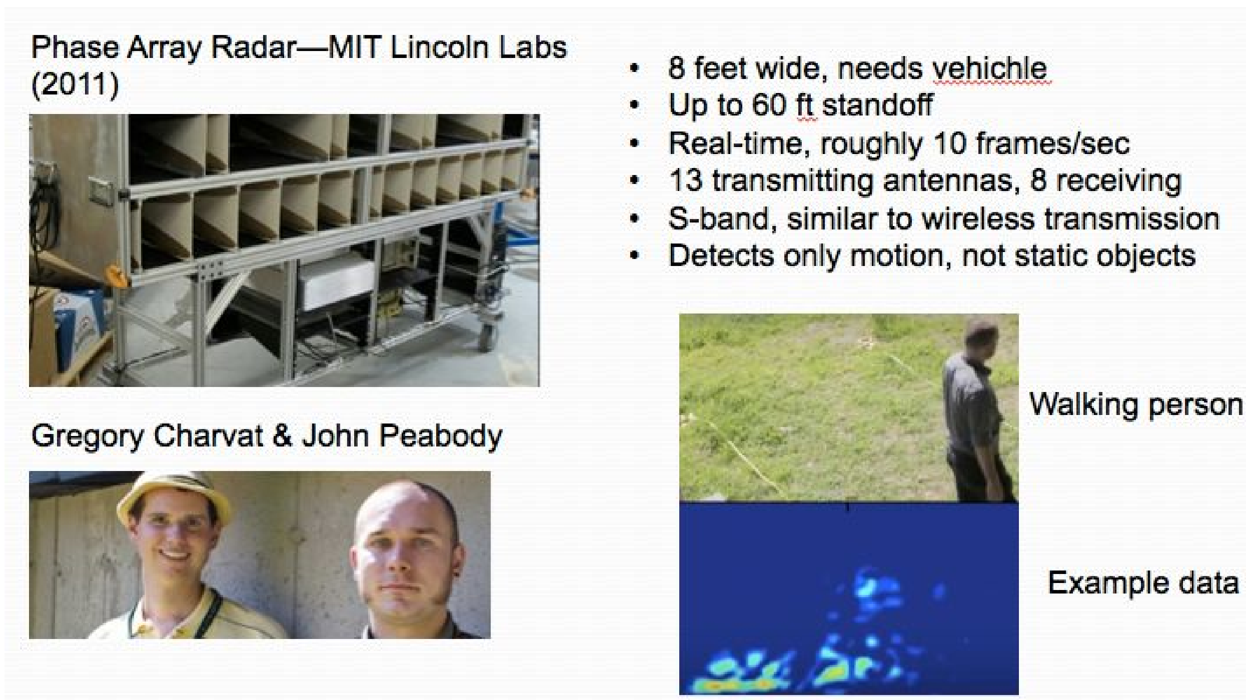
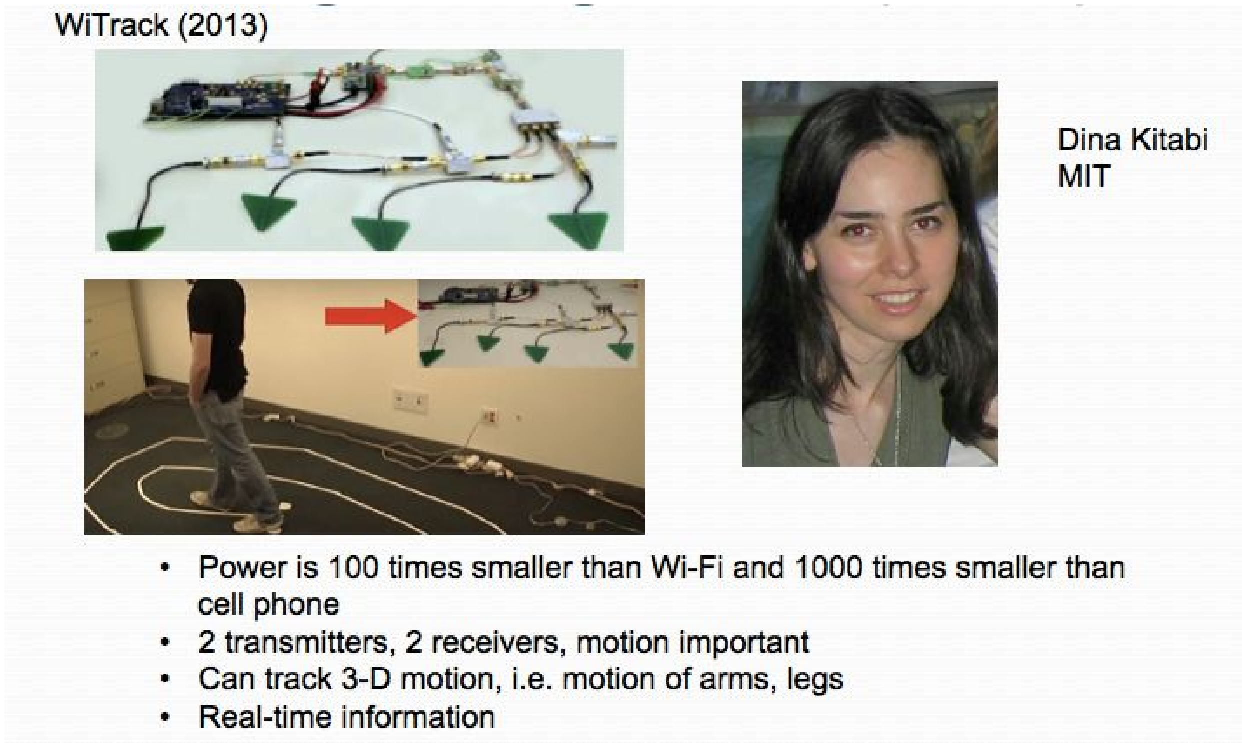
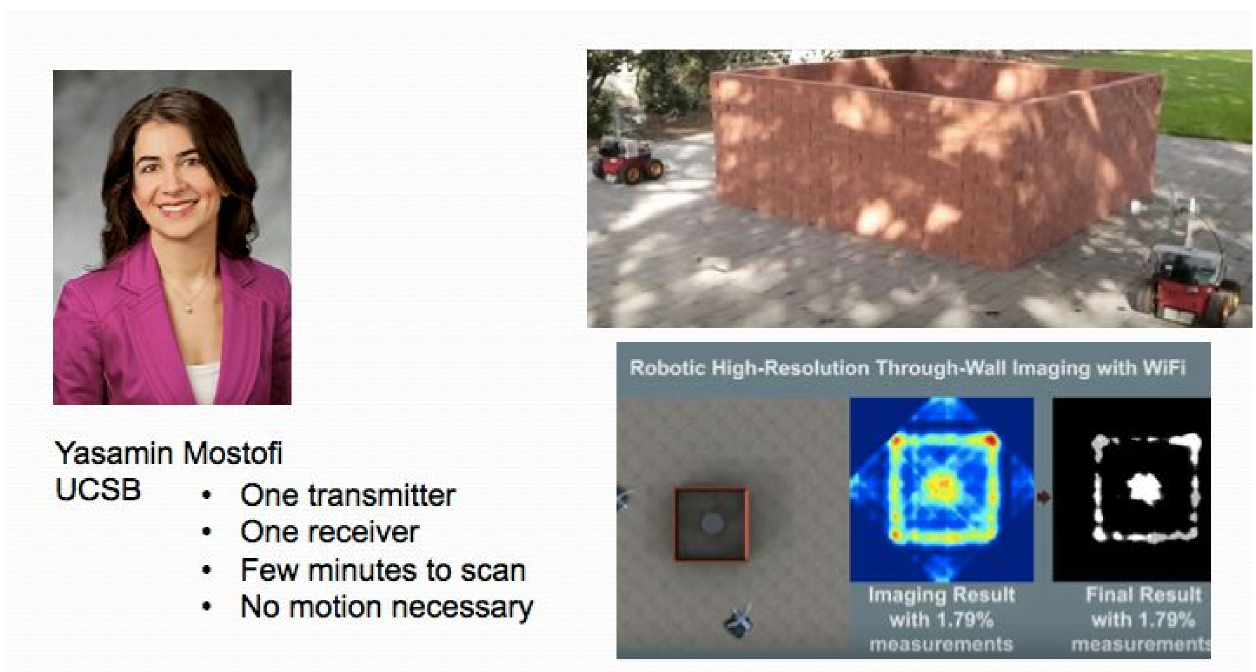
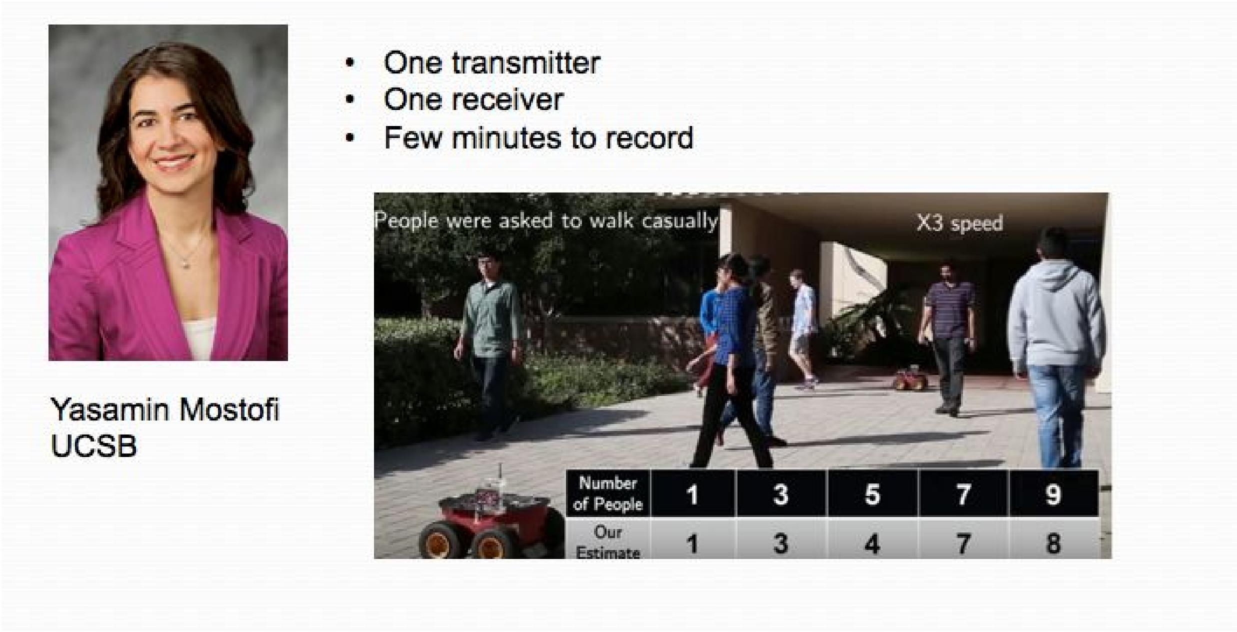
In the context of urban environments, it is especially important to be able to “look” inside buildings. MIT Lincoln labs developed a truck-portable device a few years ago that is highly sensitive to motion behind walls and has a reasonable stand-off distance. The other researchers below, Dina Kitabi of MIT and Yasamin Mostofi of UCSB have developed ways to use WiFi to image inside buildings and “see” through walls. A few highlights of their devices and their capabilities are shown below. There are other research groups operating in this space as well, e.g., the WiSee work of Shyam Gollakota and Shwetak Patel’s work at UW. (These works are also in collaborations with students and colleagues.)







In addition, WiFi can be used to "count" the number of people walking in an area, as shown below. More details of the research of these scientists can be found on their webpages.



Yasamin Mostofi videos:
Seeing people through walls with only wi-fi sensors
https://www.youtube.com/watch?v=iF1fY3bPAt0

Counting people with only wi-fi sensors
https://www.youtube.com/watch?v=B7o0qA4L4So

Crowdsourcing

One direction that we explore leveraging is crowdsourcing. We taxonomize the crowdsourcing space into several broad but related categories:

- **Crowdsourcing of people with knowledge.** Crowdsourcing people with knowledge is the conventional definition of crowdsourcing. For example, one can hire Mechanical Turk workers to perform tasks on their computers. In the physical world, one can hire Uber and Lyft drivers to take them places. In the physical world, one can also hire Task Rabbits to perform miscellaneous tasks, such as pick up groceries, move boxes, or deliver packages. One could also, of course, hire a Task Rabbit to take photos of a particular house or area of a city.

- **Crowdsourcing of people without knowledge.** People can also be crowdsourced against their knowledge. For example, it may be possible to surreptitiously place additional software on a person's phone that takes a picture every five seconds or five minutes. If placed on enough phones, those pictures could help visually canvas an area and could thus be useful for mapping a region and / or finding a target.

- **Crowdsourcing of people with unrelated goals.** Related to both the above categories, we also consider crowdsourcing whereby people are asked to perform one task (e.g., a Lyft driver being asked to go to a location to pick up a person) but the real objective is something else (e.g., to cause congestion in a particular region, thereby forcing a target that is being tracked to take a different route). Another related example is the Amber Alert system in the U.S. Whereas Amber Alerts are traditionally used to locate missing children, it would not be unreasonable to also use Amber Alerts as a mechanism to crowdsource people into helping find someone suspected of planting or planning to plant a bomb.

- **Crowdsourcing devices via people.** Further afield, but still in the space of crowdsourcing, we considering the crowdsourcing of mechanical objects. For example, the crowdsourcing of small, mechanical objects (which we call “mechanical viruses”) that can attach to people’s clothes, and -- via their human hosts -- propagate into new environments and sense information.

We now elaborate on several opportunities and directions for leveraging crowdsourcing capabilities.

One technical property that is changing about the world, and that might facilitate more “crowdsourcing of people without knowledge” and “crowdsourcing of people with unrelated goals” is the increasing ubiquity of wearable cameras. For example, future users of the Microsoft HoloLens or a Google Glass derivative may be wearing cameras on the heads. If accessible, those camera feeds could provide valuable intelligence to the IC or DoD. Similarly, modern cars are including cameras for self-driving or self-parking or similar capabilities. If accessible, those camera feeds could also provide valuable intelligence to the IC or DoD.

Another topic currently explored in academia is gamification. Through gaming, is it possible to encourage people to do some task (that they enjoy, hence the game) but that has some secondary motive (e.g., to help take photos that canvas an area suspected of housing the person being tracked). For example, the PhotoCity game (http://grail.cs.washington.edu/projects/photocity/) encouraged people to take photos of certain locations and thereby gain points by “capturing virtual flags” placed in those locations. The researchers used those photos to visually map a city. The recently announced augmented reality PokeMon game (https://www.youtube.com/watch?v=IKUwVYUKii4&feature=youtu.be) could similarly provide the maker of the game significant visual information about chosen regions of a city.

Separately, we encourage further investigation into mechanical viruses, or small devices that can (for example) attach to clothing, propagate with people, and / or float autonomously within an environment. We provide more information in the appendix to this document.

“Misusing” Existing Sensors to Create New Sensors

We encourage the exploration of novel ways of co-opting data already being collected by other sensors. We enumerate several possible directions below. We stress that these are simply illustrative examples; there may be many other opportunities to co-opt existing data, and there may already be advances in these spaces of which we are not yet aware.

- **Reflections.** Numerous photos and videos are being shared on the Internet, and countless more are available (but not shared) on cloud storage systems. A key question we must ask is: what information is available in an image about items not directly in the scene? There has been work on extracting information from reflections (M. Backes, T. Chen, M. Dürmuth, H.P.A. Lensch, and M. Welk, Tempest in a Teapot: Compromising Reflections Revisited. Proc. of IEEE Symposium on Security and Privacy. 2009. http://www.mia.uni-saarland.de/Publications/backes-sp09.pdf). We propose a deep dive into finding and recognizing people via reflections, e.g., by applying gate recognition to shadows or reflections in videos. Some reflections may not be visible to the naked eye, but may be visible to computer vision systems.

- **Interactions with Everyday Objects.** There has been extensive past work on using in-home sensing to monitor the use of appliances and other equipment in a home. For example, work on powerline sensing can inform the homeowner about the power consumption of different devices in a home, when those devices are used, and so on (S. Gupta, M.S. Reynolds, and S.N. Patel, ElectriSense: Single-point Sensing Using EMI for Electrical Event Detection and Classification in the Home. In Proc. of UbiComp. 2010. https://ubicomplab.cs.washington.edu/projects/ElectriSense). Additionally, waterline sensing can inform the homeowner about when individual faucets in a house are in use (J. Froehlich, E. Larson, T. Campbell, C. Haggerty, J. Fogarty, and S.N. Patel, HydroSense: Infrastructure-mediated Single-point Sensing of Whole-home Water Activity. In Proc. of UbiComp. 2009. https://ubicomplab.cs.washington.edu/projects/HydroSense). These cited works achieve their goals by (respectively) sensing the home electrical system and the home waterline from a single point within the home (e.g., a single power outlet or a single faucet).

  A question we ask is: if different people use the same objects in a home in different ways (e.g., if different people brush their teeth or wash their hands differently, or if different people turn on and off lights in different patterns), then could those people be fingerprinted by these already existing in-home sensing technologies? In this context, we refer to a fingerprint as a stable property measurable about an individual and that would allow the system to distinguish that individual from a (possibly small) set of other people (e.g., the other members of a family or group).

If it is possible to fingerprint people based off of home device (e.g., faucet or electrical device) usage, then it may be possible to remotely determine when an individual is in a specific room of a house -- e.g., among the four people known to be in the house, the system may output with high confidence that the target is currently known to be in the interior bathroom on the third floor.

- **Other Sensors.** We encourage the exploration of other sensors as well.

  For example, inspired by recent works on indoor person identification through vibrations (S. Pan, N. Wang, Y. Qian, I. Velibeyoglu, H.Y. Noh, and P. Zhang, Indoor Person Identification through Footstep Induced Structural Vibration. In Proc of HotMobile. 2015.) as well as gait detection via a mobile phone as a person is walking (C. Nickel, T. Wirtl, and C. Busch, Authentication of Smartphone Users Based on the Way they Walk Using k-NN Algorithm. In Proc. of Intelligent Information Hiding and Multimedia Signal Processing. 2012.), we ask whether existing systems in a home might collect sufficient accelerometer data to facilitate person identification. If any of those vibrations manifest into vibrations on windows, could those vibrations also be detected remotely (and hence enable remote person identification via vibrations).

  As another example, one of our past works found that it is possible to fingerprint (identify) drivers of a car (among a small set of possible drivers) with high probability simply by collecting and analyzing the data already communicated over the car's internal computer network (M. Enev, A. Takakuwa, K. Koscher, and T. Kohno, Automobile Driver Fingerprinting. In Privacy Enhancing Technologies Symposium. 2016. http://www.autosec.org/pubs/fingerprint.pdf).

  Additionally, HVAC systems could count the number of people in a room (http://www.energy-manager.ca/news/hvac-occupancy-sensors-count-occupants-and-adjust-air-accordingly-1842). Could the sensors on those systems also be modified or extended to identify people (from a possibly small set of candidate people)?

  The commercial sector is also creating many new technologies designed to track people, e.g., iBeacon (https://developer.apple.com/ibeacon/) and ShopKick (https://www.shopkick.com). Many of these systems purportedly have the goal of helping advertisers better target ads at individuals (e.g., because they know which aisles in a grocery store a person spends the most time). Obtaining access to that information could also help the IC or DoD locate a target, if that target has in his or her possession a device that supports these services (e.g., that supports iBeacon or ShopKick).

New Sensing

We similarly encourage the exploration of novel new sensing modalities. We enumerate several example below, though explicitly acknowledge that we do not consider the legal and ethical implications of these methods here.

- **Secure Human Identification through Toilets.** We postulate that in some cases it may be possible to track individuals through the sewage system. The signal to noise ratio in some cases may be too low. If a robot inserted into the sewage system could analyze DNA, it has the potential to snake up a sewage system and determine which appartment (and possibly which bathroom) an individual frequents. We postulate, for example, that this method might be useful in determining which bathroom an individual typically uses, among a possibly large set of bathrooms in a large apartment building, or even determining whether a person is in that large apartment building at all.

- **Modified Gut Bacteria (for Animals, if not People).** It may be possible to genetically modify food in a way that affects the consumer's gut bacteria. The modified gut bacteria could result in digestive output with detectable signatures (e.g., luminous under UV light). This approach could be applied to animals, e.g., to the horses traveling with a target. If the digestive output broadcasts information in the UV range, it could amplify its visibility to overhead aircraft.

- **Drones and Hummingbirds.** In dense urban environments, the use of drones (and similar technologies, like toy flying hummingbirds) may become more common. If they become common, then the IC or DoD use of such technologies of sensing would become less noticeable.

Discussion and Conclusion

Our Think Piece focused on finding and tracking people and objects in urban environments. Our contributions include a set of key axes and issues that define the problem space, a discussion of crowdsourcing as a tool to facilitate finding people and objects in urban environments, and a discussion of the use of weird/unconventional/new sensing technologies in the quest to find people and objects. We encourage further discussion and thought into the ideas described in this Think Piece. The directions proposed in this think piece are also dual-edged. If implemented, they could help the U.S. better find its targets, but could also help other entities better find people or objects that the U.S. would prefer to keep hidden. Thus, in addition to exploring methods for better finding people and objects, we must also consider methods to protect against the ideas discussed in this Think Piece.

Appendix

Basic elements of data fusion

A central theme in our think piece is the use of low-signal-to-noise sensors that might be combined in large numbers to supply useful information. Here we provide an appendix to illustrate how detection probability can be enhanced by the data fusion process--a process by which information from different sensors is combined to yield a "more than the sum of its parts" level of information.

A very common framework for the fusion of data is the use of Bayesian inference. In this method, one is interested in the probability that a particular hypothesis (e.g., the blip on the screen is an enemy fighter jet) is true given the signals that have been obtained in a collection of sensors. A schematic of one way this process can occur is shown in the figure below. In this example, each sensor individually classifies the observed object and makes a declaration of its type. These declarations (D^j for sensor number *j*) along with the probability that sensor j will declare the object to be type D^j given that is object *i*, $P(D^j|O_i)$, are then combined to give a fused (combined) probability the object is O_i given the intersection of the set of individual sensor declarations $D^1 \cap D^2 \cap D^3 \cap D^4 \cap \ldots\cap D^n$: $P(O_i|D^1 \cap D^2 \cap D^3 \cap D^4 \cap \ldots \cap D^n)$. This is done for each of *M* possible types of objects. The final step is to use decision logic to select the object i that gives the largest value of $P(O_i|D^1 \cap D^2 \cap D^3 \cap D^4 \cap \ldots \cap D^n)$. This results in a fused identity declaration.

It should noted that there are many different architectures that could be used for the data fusion process. However, they all aim to provide a more confident declaration of the object being sensed. Another architecture that might be used is to require that each sensor sends its information to a common processor that then fuses the raw data from the sensors to produce an identity declaration. We will consider a few examples below of this architecture to illustrate how fusion of multiple sensor can be used to identify objects.

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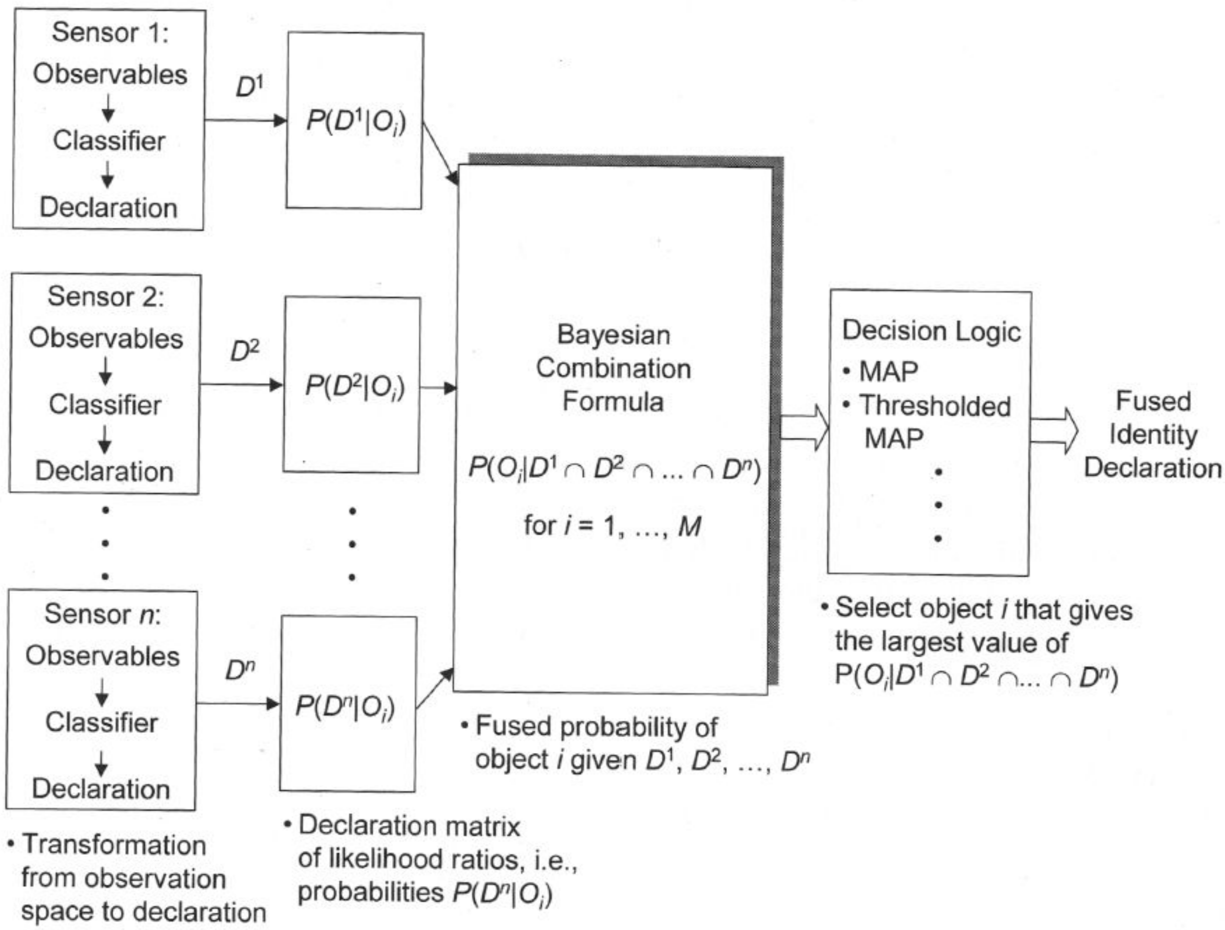

Figure adapted from E. Waltz and J. Llinas, *Multisensor Data Fusion*, Artech House, Norwood, MA [1990].

Bayesian inference is based on Baye's rule, which can be expressed mathematically as,

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} .$$

The expression above can be read as "The probability of outcome B, given A, is equal to the probability of outcome A, given B, time the prior probability of B divided by the probability of A.". P(B) is often referred to as the prior, and P(A|B) is often referred to as the likelihood function. P(A) is essentially a normalization factor so that when all possible outcomes B are considered, the probability of getting one of them is unity. P(B|A) is often called the posterior probability.

For data fusion problems, we are most often interested in situations where A=some type of data and B=object of interest, so we wish to find the probability that the data supports the presence of an object of interest. This is the final output shown in the figure above.

In the language of Bayesian inference, it is common to call the data “evidence” and the objects different “hypotheses”. For example, one can imagine a DoD relevant situation in which there are 4 hypotheses, $\mathbf{H} = \{H_1,H_2,H_3,H_4\}$, where

H_1 = enemy fighter, H_2 = enemy bomber aircraft,
H_3 = enemy missile, H_4 = no threat.

We can assume the evidence produced by sensor k (where k=1, 2, … ,N) can have one of several outputs in response to these cases,

E^k_1 = evidence from detected emission in spectral band 1,
E^k_2 = evidence from detected emission in spectral band 2,
E^k_3 = evidence from detected emission in spectral band 3.

The causal relationship between the hypotheses **H** and the evidence $\mathbf{E}^k$ is given by a q x r matrix $\mathbf{M}^k$, where q=4 is the number of hypotheses being considered, and r=3 is the number of output states of the sensor. This causal relationship is the matrix-valued likelihood function with $(i,j)^{th}$ component,

$$M^k_{ij} = P(E^k_j|H_i).$$

An example of such a matrix-valued likelihood function can be found in the table below.

	E_1^k : detection of emission in spectral band 1	E_2^k : detection of emission in spectral band 2	E_3^k : detection of emission in spectral band 3
H_1	0.35	0.40	0.10
H_2	0.26	0.50	0.44
H_3	0.35	0.10	0.40
H_4	0.70	0	0

Table above and much of the related discussion are adapted from *Sensor and Data Fusion*, by Lawrence A. Klein, SPIE, Bellingham, WA [2004].

The most important information contained in the table above is the relative weights of different likelihoods. An overall normalization can later be computed from the requirement that the probabilities of all hypothesis sum to unity. (This, of course, assumes that the list of hypotheses being considered is exhaustive--a weakness of the Bayesian inference approach, which can remedied with more sophisticated approaches, such as Dempster-Shafer theory that allows an incomplete probabilistic model, and has numerous extensions of its own.) For example, the overall probability that the i^{th} hypothesis is true (considering only one sensor, at the moment) is,

$$P(H_i|E_1,\ldots,E_r) = \alpha\ P(E_1,\ldots,E_r|H_i)P(H_i),$$

where α is a normalizing factor obtained by requiring that the sum over all i gives unity. In addition, when each hypothesis H_i is conditionally independent of the other hypotheses and the state of the sensor, the likelihood function simplifies to a prodect of individual likelihood functions for each of the sensor spectral bands (one may also think of each spectral band as a "different sensor" within a given physical device),

$$P(H_i|E_1,\ldots,E_r) = \alpha\ P(H_i)\ [\prod_{j=1}^{r} P(E_j|H_i)].$$

If there are several different sensors, the result above is modified by multiplying the likelihood functions for each spectral range together, spectral component by spectral component, for each sensor. This can be conveniently cast in a vector notation where the likelihood vector for sensor k can be written as

$$\lambda^k = (\lambda_1{}^k, \lambda_2{}^k, \ldots, \lambda_q{}^k) = P(E^k|H_i).$$

For example, suppose that we have two sensors. Referring to the table above, we might imagine that sensor 1 detects emission in spectral band 3, giving

$$\lambda^1 = (0.10, 0.44, 0.40, 0),$$

and sensor 2 detects emission in spectral band 1, giving

$$\lambda^2 = (0.35, 0.26, 0.35, 0.70),$$

which yields an overall likelihood vector of

$$\Lambda = \lambda^1\ \lambda^2 = (0.035, 0.1144, 0.140, 0),$$

where the 4 components refer to each of the 4 hypotheses H_i. In order to compute the posterior probability $P(H_i|E_1,E_2)$ we also need the prior probability for each hypothesis, we may also write as a vector,

$$P(H_i) = (p_1, p_2, p_3, 1\text{-}p_1\text{-}p_2\text{-}p_3),$$

which for illustrative purposes we might take as $P(H_i) = (0.42, 0.25, 0.28, 0.05)$. Therefore, the probability of each hypothesis being true, given the evidence from the two sensors is

$$P(H_i|E_1,E_2) = \alpha P(H_i)\ \Lambda_i = \alpha(0.42, 0.25, 0.28, 0.05)\ .(0.35, 0.1144, 0.140, 0)$$

$$= \alpha(0.0147, 0.0286, 0.0392, 0) = (0.178, 0.347, 0.475, 0),$$

where α is found by demanding a normalization of the probabilities. The result tells us that the probability of an enemy aircraft attack of some form, hypothesis H_1 or H_2, is 0.178 + 0.347 = 0.525 or 52.5 percent.

There are a number of interesting features worth emphasizing in this result. First, in the example above, it was implicit that the information from both sensors was fused "simultaneously". It is interesting to note that if the evidence is first collected from sensor 1, and then the prior probability updated before the evidence from sensor 2 arrives, the result is the same as the "simultaneous" fusion: After the data from sensor 1 arrives, the new prior becomes

$$P(H_i|E_1) = \alpha(0.42, 0.25, 0.28, 0.05) . (0.10, 0.44, 0.40, 0) = (0.1591, 0.4167, 0.4242, 0),$$

where α=3.7879 for proper normalization. This new prior can then be used to compute the posterior probability for $P(H_i|E_1,E_2)$ as,

$$P(H_i|E_1,E_2) = \alpha' P(H_i|E_1)\ \lambda^2_i = \alpha'(0.1591, 0.4167, 0.4242, 0) . (0.35, 0.26, 0.35, 0.70)$$
$$= \alpha'(0.0557, 0.1083, 0.145, 0) = (0.178, 0.347, 0.475, 0),$$

where α'= 3.2003, and the final posterior probability is the same as the "simultaneous" fusion. Notice that the additional information from sensor 2 lowers the probability of an enemy aircraft attack slightly from about 57.5 percent to 52.5 percent, but increases the probability of an enemy missile attack by the same amount, from about 42.5 to 47.5 percent.

This numerical example serves to illustrate some of the effects of data fusion on the final object declaration, but it is worthwhile to focus for a moment on some general features of multiple sensors combined using Bayesian inference. For example, in the example above we were "given" the matrix of the likelihood function, with the values listed in the table. How would one determine these in practice? There several ways that they might be obtained. The most straightforward route is to perform experiments in which a particular hypothesis is known to be true with certainty (have an enemy bomber fly in range of the sensor) and then measure the "evidence" on the sensor. Doing this multiple times for each possible hypothesis would allow one to determine the various likelihood functions.

If such an experiment is not available, or possible to perform, then one might be able to model (in most cases numerically) the situation using principles from physics and chemistry. If the physical model is realistic, this would yield a good approximation to the likelihood functions. Using techniques from machine learning, for example, it may also be possible to "train" a system, which would also yield some approximation to the likelihood functions.

However, what is perhaps less clear is how to assign the prior probabilities, $P(H_i)$. In general, one may not know how to determine these probabilities, so various recursive formulations of Bayesian inference have been developed in which initial guesses may be iterated upon (most often appropriate when there is a dynamic features involved, such as the tracking of an object in real time). In these formulations, the prior probabilities are updated sequentially in time, most often with a Markov assumption that only the evidence at the previous time influences the probabilities at the next time. In recent years, there has been significant work (and a number of textbooks written) on this subject. (See, *Bayesian Signal Processing* by J. V. Candy, Wiley, Hoboken, NJ [2009] , for example.)

Here, we will consider the situation in which the priors have somehow been previously determined, and ask how the number of sensors with given (arbitrary) likelihood functions will influence the posterior probability. We assume a general prior probability vector,

$$P(H_i) = (p_1, p_2, p_3, 1\text{-}p_1\text{-}p_2\text{-}p_3),$$

and also general likelihood vectors,

$$\lambda^1 = (a_1, a_2, a_3, a_4),$$

for a sensor of type 1 and

$$\lambda^2 = (b_1, b_2, b_3, b_4),$$

for sensor of type 2 (noting that in the previous examples, different frequency bands may effectively be treated as different sensors. If we have j identical sensors of type 1 and k identical sensors of type 2, the posterior probability becomes,

$$P(H_i|E^1{}_1,E^2{}_1, ..E^j{}_1; E^1{}_2, E^2{}_2, ...E^k{}_2)= \alpha\,(p_1\, a_1{}^j b_1{}^k,\ p_2\, a_2{}^j b_2{}^k, p_3\, a_3{}^j b_3{}^k,\ (1\text{-}p_1\ \text{-}p_2\ \text{-}p_3)a_4{}^j b_4{}^k),$$

where α is again the constant the leads to overall normalization of the posterior probabilities. The relation above clearly shows how the final posterior probabilities are related to the prior probabilities and the likelihood functions, under the assumption of a non-dynamic system (that is, one that does not evolve in time). Evidently, the prior and the likelihood functions of each sensor carry equal weight, hypothesis by hypothesis. As a result, the most likely scenario is the one in which the product is the largest.

To make the role of multiple sensors more transparent, it is useful to consider the case of a "uniform prior":

$$P(H_i) = (1/4,\ 1/4,\ 1/4, 1/4),$$

in which case,

$$P(H_i|E^1{}_1,E^2{}_1, ..E^j{}_1; E^1{}_2, E^2{}_2, ...E^k{}_2)= \tfrac{\alpha}{4} (a_1{}^j b_1{}^k,\ a_2{}^j b_2{}^k, a_3{}^j b_3{}^k, a_4{}^j b_4{}^k),$$

which shows how the likelihood functions of two different types of sensors are combined to yield a greater confidence in the result. For example, if both sensors of type 1 and sensors of type 2 have likelihood functions that indicated hypothesis 3, for example, is most probable, then $a_3{}^j b_3{}^k$ will clearly be larger than any of $a_1{}^j b_1{}^k$, $a_2{}^j b_2{}^k$, $a_4{}^j b_4{}^k$. If sensors of type 1 and sensors of type 2 do not agree on the most probable hypothesis, the final declaration of the most likely hypothesis will depend on the relative likelihood functions of the two different types of sensors.

Finally, suppose we have only j copies of one type of sensor, so that

$$P(H_i|E^1{}_1,E^2{}_1, ..E^j{}_1)= \tfrac{\alpha}{4} (a_1{}^j,\ a_2{}^j, a_3{}^j, a_4{}^j).$$

In this case, it is clear the the largest of the likelihood functions becomes ever more dominant as j increases in value, as the ratio of the largest to the second largest increases when raised to the power of j.

In summary, in this appendix we have used the framework of Bayesian inference to illustrate the central elements of the mathematics of data fusion in a simple way, and how it may be applied to the type of sensors used in DoD applications. We have also seen how increasing the number of sensors, and using different types of sensors can increase the value of the posterior probability for the most likely hypothesis.

Towards a quantum theory of inference--pushing the ultimate limits of signal detection in a distributed network of sensors

Our discussion above on Bayesian inference is based in real-value probabilities. In more complex problems, one often deals with recursive estimation and is forced to make various approximations, apply “filtering schemes”, etc. There is an entire industry built around finding computationally efficient methods of solving such problems, and they have an exceedingly wide range of applications in both defense and civilian problems.

On the other hand, if one views the Bayesian inference approach as a way to address measurement challenges (in physics, for example) then one realizes that in the quantum theory it is not probabilities that play a central role, but **amplitudes** for various process that are most important. Generally, in a quantum system, one first sums amplitudes (which can be complex valued) and then computes the modulus squared (a probability of an event) of these to determine quantities that are of experimental relevance. The procedure of first summing amplitudes, then computing the modulus squared opens the door for important quantum interference effects. Thus, it is clear that a measurement inference theory based on probabilities alone cannot capture one crucial aspect of quantum systems.

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In addition, multi-particle quantum systems exhibit a property called “entanglement”, which is the most distinguishing feature of a quantum system. (Interference effects, of course, occur for classical wave systems.) If one were to develop a quantum theory of measurement inference based on a network of quantum sensors, significant revisions of Bayesian inference would need to be made. Most importantly, assumptions about the likelihood functions would need to be revisited. For example, if quantum entanglement is present, it would not generally be possible to write the likelihood functions for different sensors as independent, as they would no longer be. In addition, one would need to account for partial measurements, in which some uncertainty of a quantum state is removed by a particular sensor, but the full quantum state is not determined by that sensor.

Automation of Tasking

Actively searching for a physical commodity, either a person or an object, involves tasking multiple sensing assets, collecting data from them, and fusing that information to improve situational awareness, as discussed in the previous section. However, tasking is a largely manual task, overseen and driven by human experts. Tasking *anticipates* data fusion, but the tasking process and the data fusion process are in many respects separate operations. Moreover, data fusion assumes that all environmental information is knowable, in principle, whereas there are situations where there are simply no mechanisms for obtaining information.

How can, or should, tasking be automated in the face of these considerations and what opportunities arise with doing so? What are the technical challenges associated with automating tasking, and where does the human operator play a role (both in terms oversight and in terms of directing the automation toward some target)? First, there are opportunities for developing techniques for automating tasking using the suite of current sensing capabilities at the nation’s command. Second, active interrogation—using collective sensor behavior to evoke information from substantial standoff distance—can be used to improve information when passive sensing is expected to provide poor quality results. Lastly, information acquisition systems could potentially use ambient environmental energy (e.g., thermal/radiant energy, human and vehicle locomotion, wind) to act, primitively, on the environment in a scalable and robust manner. These three opportunities are discussed here.

These recommendations, and the framing of automated tasking presented here, are motivated by the need for integrating information requirements organically across the TCPED (Tasking, Collecting, Processing, Exploitation, and Dissemination) enterprise in real time, without requiring supervision from human operators (though input from operators, treated as another information source, would naturally play an important role in an automated process). As in many control applications, when timeliness is essential, automation becomes inevitable. In additional to large-scale needs like those of the NSA, support for small teams in an information-acquisition architecture is critical to many activities in NAVSOC and SOCOM generally.

The outcomes possible that would result from innovations in tasking automation would include, at minimum, the ability to coordinate multiple sensing platforms in a task-oriented manner without human operators in the loop, permitting real-time execution of sensing strategies as time critical scenarios unfold. The most ambitious outcome of this work would be a systematic rethinking of the TCPED process, treating everything from space assets to human analysts as assignable agents towards some information acquisition goal. In general, operational settings can be assumed to always include unknown, and unknowable, considerations, and the examples discussed here explicitly take *unknown unknowns* into account. Moreover, sensing capabilities themselves often satisfy physical properties and have equations of motion that constrain their information acquisition capabilities, as indicated in the section on data fusion.

One of the key advantages of automating tasking is that doing so would result in a system that is agnostic with regard to the difference between using specialized sensors and trading off between sensors, so exploiting different sensors at different times is a natural product of automated tasking. Moreover, automated tasking would be similarly indifferent to whether a device is part of an available sensor suite (e.g., an unmanned aerial vehicle) or simply part of the ambient computing and sensing environment (e.g., mobile phones interconnected through a piconet in a moving crowd of people).

To motivate the discussion of automating tasking, consider the example of the release of chemical agent in an urban environment, where localization of the source is required, multiple sensors are available, and the fluid dynamics driving the diffusion process may be presumed largely unknown. The fluid dynamics are unknown for multiple reasons—the dynamics themselves are very complex and challenging to numerically simulate, they are influenced by global environmental factors likely to be unknown, and they are additionally influenced by local factors (population movement, vehicles, air circulation) similarly unlikely to be known. The question, from a tasking perspective, is whether one can show that coherent sensor tasking and active interrogation enable localization of the chemical source reliably without having complete knowledge of the fluid and without unattainable resources (e.g., ubiquitous chemical sensors). This hypothetical example does not only reflect challenges in biological or chemical warfare; locating a person in a crowded urban environment has many of the same challenges, because the actions of individuals and their interactions with each other are *a priori* unknown.

A Technical Approach to Automated Tasking

Looking at the prior section on data assimilation and fusion, what technical challenges need to be overcome to automate tasking processes? A critical issue can be seen in all the equations governing data association problems—a *prior distribution* is assumed known; that is, it is presumed that an information acquisition system already has a representation of the information it is attempting to find. What should a sensor suite do if there is no prior distribution? The Bayesian inference model, though still relevant to the fusion process, says little about where measurements should be taken and which sensors should take them. As a result, the *first*

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technical goal in tasking automation would be to determine how sensor tasking can be automated across multiple sensor types across multiple sensing environments, where there are substantial factors that are unknown (and potentially cannot be known). For example, how can sensing from wireless networks, surveillance cameras, unmanned aerial vehicles, low altitude vehicles, high altitude vehicles, space assets, and human assets be autonomously coordinated to achieve persistent situational awareness (e.g., about a person's location) from a substantial standoff distance? Answering this question requires more than sensor fusion because tasking involves coordinating the sensing modalities in response to evolving data, often without a prior distribution.

Automation of sensor actions (e.g., physical motion, emitting an electromagnetic signal, et cetera) is a well studied field. Generally, algorithms rely on some form of information maximization, either explicitly or implicitly, leading to sensors that are dependent on Bayesian priors, well-modeled environments, and well-characterized sensors. These algorithms sometimes perform well in laboratory settings, but rarely in the field. (This issue is the essence of what limits the data fusion techniques discussed previously.) The field of robotics has a long history in active sensing (e.g., D. Fox, W. Burgard, and S. Thrun, “Active Markov localization for mobile robots,” *Robotics and Autonomous Systems*, vol. 25, no. 3-4, pp. 195–207, 1998.), where various measures of information (e.g., Fisher information maximization, entropy maximization, ergodicity, and other information-oriented measures) are used to drive decision-making onboard robotic systems. These methods tend to assume a probabilistic view of the dynamics and measurements, similar to the previously described data fusion techniques. Active methods of collecting information organically drive an entire hierarchy of information acquiring capabilities to an information goal. For instance, ergodicity requires temporal statistics to match spatial statistics—and ergodicity can be used as a control goal/metric for an automation system. For instance, ergodic control on a robotic fish with nonlinear weakly electric sensing can be automated; the distribution describing an object's underwater location is shown in Fig. 1. Two inferences can be made from this work. First, ergodicity is a workable, actionable principle of motion. Second, ergodicity provides a systematic way to encode information needs in nonlinear, heterogeneous settings. However, other notions of information maximization (Fisher information, entropy) could be used to design principles of tasking.

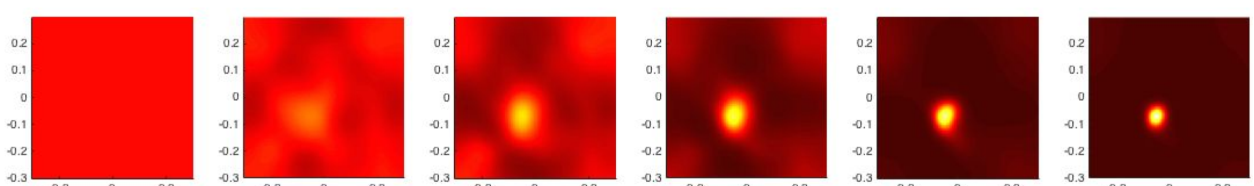

Fig. 1 Experimental evolution of a probability density function---starting from a uniform distribution and ending as a low variance distribution---describing the location in *(x,y)* coordinates of a conductive object in an underwater environment, using ergodic weakly electric near-field sensing. Here dark red indicates low probability and bright yellow indicates high

probability. (Figure taken from L. Miller, Y. Silverman, M. A. MacIver, and T. Murphey, “Ergodic exploration of distributed information,” *IEEE Transactions on Robotics*, 2016.)

A second technical goal—related to sensor tasking—would be concerned with how diverse sensor assets should act in an environment to actively stimulate/evoke information, and to what degree can this *active interrogation* be automated? For instance, again using the hypothetical example, a chemical source may be very hard to locate using only passive chemical trace in the atmosphere because of the rate of diffusion and fluid dynamics. But if each sensor can release its own unique (benign) chemical trace, finding a source becomes a matter of determining sensor strategies that have the most information content relative to the chemical source location. Active interrogation can dramatically change fundamental bounds---in simple robotic situations a change of three orders of magnitude in the information content available in a signal is possible.

A third technical goal would be to determine when a sensor can combine dynamic tasking and active interrogation to guarantee insensitivity to environmental effects. Examples of such effects might be unmodeled fluid dynamics, or a dynamically-evolving crowd of people, or unknown interpersonal interactions. How should sensors behave so that these obfuscating effects are irrelevant to overall sensing efficacy? For instance, can one create a sensing scheme in which agents release chemical trace so that the resulting algorithmic strategy is globally convex regardless of the underlying fluid flow and diffusion process? The answer appears to be yes—as suggested by the results in Fig. 2.

The top of Fig. 2 shows a sensor trajectory (obtained using by minimizing ergodicity) being used to track a collection of moving agents using a single sensor. The bottom of Fig. 2 illustrates multiple sensors being used to actively interrogate the location of a target by *both* ergodically moving and releasing chemical trace into the fluid flow. In both example cases, numerical experiments suggest that sensing reliability goes up dramatically as a result of these information-driven control approaches. Scaling these algorithms to hundreds or thousands of sensors may or may not be plausible, but scaling them to ten or twenty sensors, which may be relevant in many cases, appears certainly possible. Most importantly, using these techniques takes problems that would currently be impossible and makes them computationally tractable.

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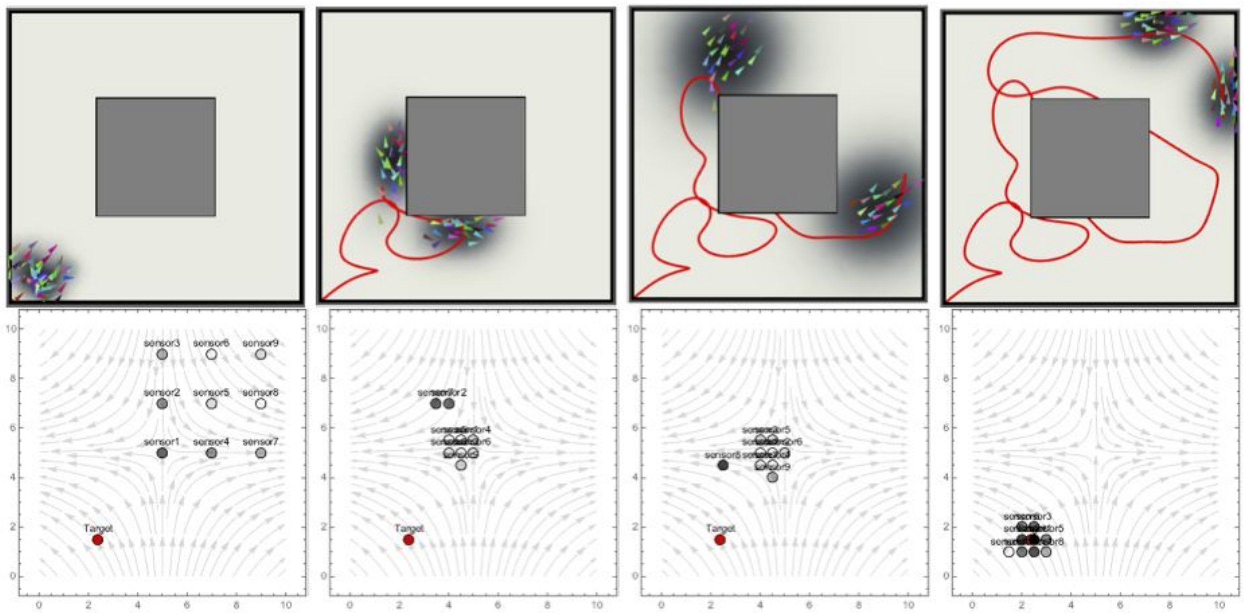

Fig. 2 *Top* Tracking a crowd with a single sensor is naturally an ergodic task. The population is a density function, and—if the goal is to make sure every agent is observed by the sensor (indicated by the red line)—the sensor must provide coverage as the density function evolves. By the end of the trajectory, the sensor has ergodically visited every agent. *Bottom* Here multiple sensors are searching for a chemical source diffusing in a nonlinear flow. The sensors reliably find the source only if they interrogate the source location by emitting chemical signatures while moving ergodically; that is, they localize the source regardless of the underlying flow of the fluid, because of the evolving topological characteristics of the sensors. (Source: L. Miller, "Optimal Ergodic Control for Active Search and Information Acquisition." Ph.D. Thesis, Northwestern University.)

The upshot is that one can enable information acquisition, across a wide variety of resources, to be automatically managed in a completely organic manner though software-enabled control.

However, consider a situation where existing sensors are incapable of acquiring relevant measurements. As a variation of the hypothetical example, consider a case where chemical samples from within a secure building are required. There may be situations where there exists no classical sensor activity capable of extracting information. Such a situation is discussed in the next section that discusses mechanical viruses.

Mechanical Viruses

The previous section discusses structural principles through which automated tasking could be used to coordinate multiple sensing elements in a coordinated, real-time manner without operator intervention. However, even with coordination, information may not be observable (e.g., about biological or chemical agents being processed in a building). The potential *ability* to coordinate large suites of sensors and the *need* to sense inaccessible areas suggests a new class of sensor types, which we here call *mechanical viruses*.

The principle idea is that if sensing modalities can be coordinated, very small devices designed to be compatible with the sensing requirement may have high utility whereas in more traditional, more myopic settings they may be essentially useless. Such devices would have limited actuation and sensing, but correspondingly low energy requirements and large-scale production possibilities. As an example, origami devices offer the possibility of small-scale, capable devices (e.g., S. Miyashita, S. Guitron, M. Ludersdorfer, C. Sung, and D. Rus. An Untethered Miniature Origami Robot that Self-folds, Walks, Swims, and Degrades. Proc. of International Conference on Robotics and Automation. 2015.). Such devices could collect samples, potentially many of them, with limited primitive control capabilities (e.g., adhesion, thermal threshold sensing, light intensity, et cetera). For instance, just with adhesion and thermal sensitivity, a device could adhere to its environment (e.g., people walking) and on long time horizons enter secure spaces (if it was small enough to be undetectable when it adheres to a person's clothing). Once a sample has been taken, the same process enables the device to exit a structure. Such devices would be small and would rely on miniaturization of electronics that are special purpose for each application (i.e., they would need to be smaller than the origami robots just mentioned). Programming them would be nontrivial, largely because they are structurally unlike most embedded systems. Nevertheless, the advantages of devices like these is that they could be mass produced, deployed in parallel, and only a few of them would need to succeed. That is, statistical guarantees across many sensing devices would replace traditional monolithic guarantees in individual sensing devices.

Think Piece 2

Medical Drone

by

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This report describes a solution to the challenge of deploying medical care to far-forward combat positions. It is widely recognized that combat medics have had an important impact on the health and survival of warfare fighters. However, combat medics carry a limited amount and variety of medical materials and their training is general and not specialized (e.g., for trauma); hard data supports the concept that complementing combat medics with the experience and knowledge of surgeons and medical professionals on-base can improve warfare survival. We propose a solution that fundamentally extends the reach of surgeons to improve medical care in warfare theatres using unmanned aerial vehicles (UAVs, or ‘drones’) to deliver supplies, equipment, and coms and reduce the possibility of casualties by removing pilots from the calculus.

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The fundamental problem we are solving is how to create a medical supply chain extending beyond the base in forward-operating environments. The US military has built and deployed an extensive supply chain to transport medical supplies to bases; it currently relies on combat medics and lightly equipped forward surgical teams to be the mechanism of deployment into the warfare theatre. The number of combat medics, their supplies, training, and tools are limited, and this poses a challenge for sustaining the 'golden hour' rule in combat medicine: in which the stabilization of trauma within the first hour after injury leads to a high survival rate. Medical supply chain logistics may not historically be connected to innovations in the development of cutting-edge technologies. However, UAVs represent an exciting opportunity to leverage several characteristics of this rapidly evolving technology for improving medical care.

Historically, wars have been lost and won based on the supply chain, making them one of the most important considerations in military planning. For example, the battles in Northern Africa in WWII were effectively distilled down to the battle for disrupting supply chains between General Patton of the Allied troops and General Rommel of the Axis troops. Supply chains continue to be important in battle planning and management as highlighted below.

The Battle of Magadishu is an illustrative example of the continuing importance of supply chain logistics. In October 1993, US forces supported by UNOSOM II fought with Somalia military aligned to Mohammed Farrah Aidid (the self-professed Somalian President who overthrew former President Mohammed Siad Barre during the civil war). A group of US Army Rangers joined a multi-disciplinary Special Forces operation that was sent to capture leaders of Habr Gidr, incluing Mohamed Farraf Aidid. During what was planned to be a rapid operation, Somali militia shot down two UH-60 Black Hawk helicopters, which led to an urban battle between the Somalis and the Black Hawk survivors. The operation to secure and extract the Black Hawk crews was complicated and delayed, and resulted in heavy casualties due to complications in logistics. It is widely recognized that the ability to provide care, water, ammunition, and night vision googles to the Special Forces operators could have dramatically reduced the rate of casualties and mortality associated with the operation.

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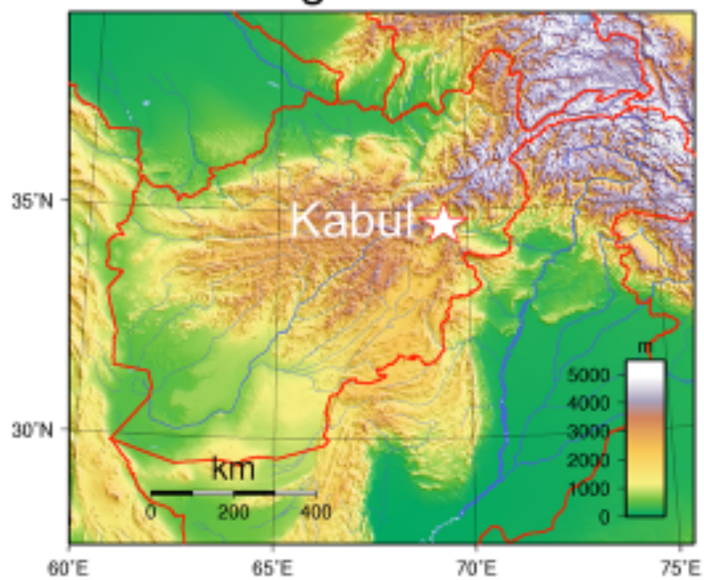
Supply chain logistics: still a challenge

Afghanistan



The road to Kabul…

Supply chain logistics continue to be a challenge in warfare theatres. In the Middle East, terrain is often difficult to access by means other than air. Consider Kabul, the capital of Afghanistan. Despite its population of 3.4M, the roads in/out of Kabul are rugged (see image above, right), limited, are often exposed through mountain passes, and in some places constricting to a single lane. Moving materials into these requires air transport, period.

Focus: forward deployed medical care

Figure 1. *Level III Combat Support Hospital. Image courtesy of the Borden Institute, Office of The Surgeon General, Washington, DC.*

Figure 2. *Level II FRSS-6/STP-7 in Southern Iraq in March, 2003.*

The focus of our think piece is on forward deployed medical facilities in austere environments. To provide context, a Level III Combat Support Hospital (left) is well equipped with trauma specialists, blood banks, multiple operating tables, and trauma surgeons. By comparison, a Level II Medical Treatment Facility (right) has more limited equipment and expertise and often is where casualties are first presented.

According to LTC Robert Mabry and COL Robert DeLorenzo in the US Tactical Combat Casualty Care manual:

"*Pre-hospital phase of care is the first link in the chain of survival for those injured in combat and represents the next frontier for making further significant improvements in battlefield trauma care.*"

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Key statistics

US fatalities 2001-2014:

Afghanistan: 2,372; Iraq: 4,493

The importance and scale of the problem has been highlighted in a number of reports. For example, Eastridge, Mabry, Seguin et al. performed a study of 4,596 battlefield mortalities from 2001 – 2011 and found the following data:

- 87% of all injury mortality occurred in pre-medical treatment facilities;
- 24% of these were classified as potentially survivable;
- 91% of those potentially survivable were associated to hemorrhage.
- Most battlefield casualties died of their injuries before reaching a surgeon.

ABC's of trauma care:

Airway management

Circulatory access

Bleeding control

"Establishing and securing the airway, ventilation and fluid resuscitations represent pillars of trauma care in the field" --Williamson, Ramesh, and Grabinsky.

The ABC's of trauma care present a set of operating rules to improve pre-hospital outcomes: Airway, Breathing, Circulation (Williamson, Ramesh, and Grabinsky).

- **Airway management:** the lack of airway management is a common cause of death and requires rapid stabilization, however it is difficult to ensure in-field;
- **Circulatory access:** required for fluids/medication;
- **Bleeding control:** control of hemorrhaging is the top challenge in battlefield trauma management. Tourniquets, advanced hemostatic dressings (e.g., Hemcon bandages, QuicClot ACS+), and granular agents (e.g., Celox, Wound Stat) are technologies that can facilitate control of warfare fighter bleeding

Key statistics

98% survival rate when transported to a combat hospital

Most battlefield fatalities occur *before* reaching a surgeon

A striking trauma care statistic is that wounded warfare fighters have a high-probability of survival if they are transported or arrive at a combat hospital alive (Level III trauma center or higher). This data further motivates our goal to improve battlefield stabilization and care of warfare fighters.

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Medical care structure: from theatre to hospital

Level 1	Level 2	Level 3	Level 4	Level 5
Self-aid, buddy-aid, Medic battalion aid	Forward surgical team	Combat Support hospital	Landstuhl, Germany	CONUS facility

There are 5 levels in the combat medical care structure. First responders are typically other soldiers, the injured soldier, or ideally a medic. Challenges in the current standard for medical care are that medics have limited training, rely on visual and physical examinations in making diagnoses for treatment, have limited equipment, and may be under fire or in dangerous/unstable surroundings when treating to the injured. The role of combat medics is to stabilize the patient for evacuation (by air or ground) to a forward surgical team (Level II). Forward surgical teams are small, mobile units capable of performing a limited number of lifesaving surgeries; their goal is stabilization for transport to higher-level care facilities. As mentioned previously, if the injured soldier arrives at higher-level care facilities, they have an excellent prognosis of survival. We target the first two levels of the medical care structure for improving survival rates of battlefield injuries.

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Current challenges of medical structure

Supply access

Time

Environment (unstable)

Medic limitations

Data/communication

As noted above, there are several fundamental challenges to the current medical structure. The "Golden Hour" and the "Platinum Ten Minutes" of trauma response depend largely on timeliness and capabilities of first responders and the forward surgical team – the time-to-providing critical medical care is based on both location and the tactical situation. Remote combat operations may not enable a patient to be transported to a Combat Support Hospital in time to receive required support.

Three key steps can improve medical care in the battlefield:

1. Augment current medical structure to reduce battlefield fatalities;
2. Extend the reach of surgeons into the battlefield;
3. Enable continuous real-time review of combat fatalities so that adjustments can be made.

Simple technologies can have a large impact

Tourniquets: 87% survival rate when tourniquet used to control hemorrhage

It is important to remember that often the simple solutions may have the largest impact! Tourniquets were not widely used at the start of the wars in Afghanistan and Iraq, however they are now widespread; tourniquets are now built into tactical gear packs and all soldiers receive training on their use (Kragh et al.).

The current approaches to field medical supply consists of carrying items by walking, driving, dropping, and flying. Each mechanism has different strengths and weaknesses. Soldiers are able to traverse a wide variety of terrain, however they have speed and weight restrictions; fatigue and supply of food and water is also an issue. Transporting supplies by car/truck improves speed and weight constraints, however it is more restrictive in the pathways that can be taken, has fuel limitations, and is more detectable (e.g., smell, sound). Airdrops can deliver large amounts of supplies, but have limited accuracy and are dependent on weather conditions; drops are also one of the most expensive approaches to transport. Flying in supplies is dependent on having clear and stable landing zones, and suffers from several of the limitations noted above (e.g., detectability).

Clearly there are important gaps that need to be filled, specifically the rapid delivery of relatively small, relatively lightweight (<10 lb) and potentially life saving supplies to soldiers in difficult to reach, dangerous, and/or unstable environments. Unmanned systems—including legged and aerial drones—provide opportunities to fill these needs.

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MD: medical drone transport of supplies and information into battle

The goal of MD is to augment human performance with aerial drones to carry out the "dull, dirty, and dangerous" tasks in the warfare environment. There are many advantages that this system could provide, including:

- Reducing soldier weight;
- Rapid delivery of life-saving supplies and care;
- Augmentation of communication between the battlefield and the pre-medical treatment facilities;
- Providing needed equipment/instrumentation to stabilize the wounded;
- Using onboard sensors to collect health data;
- The technology could also provide an asymmetric advantage by providing care and supplies to residents in difficult-to-reach areas, which can earn their trust and compassion, and assist in missions.

This approach represent an unconventional warfare mechanism to reduce lives at risk.

Current drone capabilities

To assess the feasibility of MD, we consider the capabilities of several current classes of drone systems (summarized below), loosely categorized as follows: fixed wing, rotary wing, and hybrid systems. We provide comparisons of these UAVs in terms of their range, endurance, payload, and cost.

Of the systems we surveyed, the hybrid configurations – that can transition between fixed and rotary wing operation – provide a reasonable compromise between the fixed and rotary wing systems. They provide good range and endurance, and the flexibility of hover and vertical take-off and landing (VTOL). Current systems in development are also relatively cost effective for small payloads.

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Fixed wing UAVs

RQ-11 Raven

Range: 6 miles
Endurance: 60-90 min
Payload: < 1lb
Cost: $35K

RQ-Shadow

Range: 68 miles
Endurance: 6-9 h
Payload: 50 lbs
Cost: $750K

MQ-1C Gray Eagle

Range: 250 miles
Endurance: 30 h
Payload: 800 lbs
Cost: $5M

Advantage: Adequate Range / Endurance / Payload
Disadvantage: Landing / Cost

These images depict three fixed-wing UAVs currently in use by the military, but not currently used for medical delivery.

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Rotary wing UAVs

Lockheed-Martin Indigo

Range: 3 miles
Endurance: 40 min
Payload: .5 lb
Cost: $25K

Turboace Cinewing 6HL

Range: 1-2 miles
Endurance: 25 min
Payload: 10 lbs
Cost: $3.3K

ENERGYOR Multirotor

Range: NA
Endurance: 3.75 h
Payload: 2 lbs
Cost: NA

Advantage: Excellent Landing Flexibility / Good Cost
Disadvantage: Poor Payload / Range Capabilities

Rotary wing systems have excellent flexibility for landings and are relatively inexpensive, however they have poor capabilities in terms of payload and range. One interesting technology is the ENERGYOR Multirotor, which uses a hydrogen fuel cell to yield unprecedented endurance for a rotary wing system. However, the operational details of this system are pending at the time of writing this report. It is also important to note that rotary wing dynamics in forward flight inherently limits airspeed.

Hybrid UAVs

Krossblade Skyprowler	Latitude HQ-60	Bell Eagle Eye
		
Range: 39 miles	**Range:** NA	**Range:** 920 miles
Endurance: 40 min	**Endurance:** 12+ h	**Endurance:** 6 h
Payload: 1 lb	**Payload:** 8-12 lbs	**Payload:** 200 lbs
Cost: $2K	**Cost:** $30K	**Cost:** $8.3M

Compromise on advantages/disadvantages of each system

Hybrid systems are relatively new concepts in UAV technology and offer exciting potential capabilities in terms of balancing the ability of long range, endurance, and forward speed with the ability of hover and VTOL. These capabilities (and others) make hybrid UAVs optimal platforms for the MD concept.

Key mission parameters

Range from base: 7-30 miles

Response time-to-care: < 1 h

Time-in-field: Days to months

Number of personnel: >8 + locals

Number of medics: 1

Medic bag: 30 lbs

Medic bag: 18” x 24” x 6”

Our discussions, interviews, and analysis of literature, have led us to arrive at the key mission parameters summarized above for a MD system. In addition to combat gear and other accouterments, soldiers carry a 4-day supply of food. Medics also carry a medic bag that can care for 3 terribly wounded patients and 4 or 5 gunshot wounds.

M9 Aid Bag

Field Ready M9 Kit Contents			
1	Enduro Headlamp w/Battery & Blue Flip Lens	1	Emergency Bandage, 4"
1	Trauma Shears	10	Disposable Gloves, Pair
1	Straight Kelly Hemostat, 6.25"	1	Pocket Bag Valve Mask
4	Mosquito Hemostat, 3.5"	1	Permanent Felt-tip Marker, Blue
1	TACOPS Personal Rescue Knife	3	Adhesive Tape, 1"x10yds
3	Triangular/Cravat Bandages, 40"x 40"	5	Fingertip Adhesive Bandage
1	Disposable Suction Device	5	Knuckle Adhesive Bandage
8	Alcohol Prep Pads	2	QuikClot® Z-Fold Combat Gauze
8	Iodine Prep Pads	2	SAM® Splint, 36"
1	Chest Seal	1	Silverlon Burn Kit
2	Nasopharyngeal Airway, 30Fr	2	Compression Bandage
2	Nasopharyngeal Airway, 34Fr	1	Oral Airway, 80mm
5	Elastic Bandage, 4"x5yds	1	Oral Airway, 100mm
6	Adhesive Bandage, 7/8"x3"	1	Sterile Burn Dressing, 18"x18"
6	2"x2" Sterile Gauze Pads, 2pk	1	Fine Point Forceps, 4.5"
6	4"x4" Sterile Gauze Pads, 2pk	1	MyClyns Protective Spray
5	Compressed Gauze Packs	2	SOF Tactical Tourniquet
6	Surgical Lubricant Foil Packs	1	Tac Notes Book, 4"x 6"

The M9 combat medic bag consists of the supplies summarized above. Beyond adding weight to the soldier carrying the bag, the bag has a limited supply of fluids and no refrigeration capability, which limits some of the items that are included.

Short-term implementation

Provide medical supplies, rapidly

Carry antennas; augment comms

Considering the current state of UAVs, and hybrid systems in particular, we envision the following capabilities could be implemented through a relatively incremental development cycle:

- Rapid delivery of relatively low weight medical supplies;
- Operate as mobile antennas for improved battlefield communication;
- Incorporation of real-time viewing and recording equipment to augment communication and improve battlefield awareness at pre-medical treatment facilities.

Medium-term implementation

Autonomous operation
Collect data to improve care
Surveillance/sentinel mode
Multifunctional, single use drones

Looking forward, we envision the incorporation of autonomous operations into MD UAVs to carry out the above tasks. An added objective should be considered: collecting data for later combat casualty care review. Other more advanced features include voice-activated commands on UAVs to provide a sentinel mode that improve situational awareness of the battlefield care-giver during treatment, and the incorporation of multi-functional capabilities where medical equipment is integrated into the UAVs and extracted when needed on the battlefield.

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Long-term implementation

Troop cooling (Mr. Drone)

Sensing soldier vitals

Charge devices (defib)

Record data/tele/videomedicine

One way/two way drones

1  = 2 

There is a wide range of long-term capabilities that could be achieved within a reasonable development time scale. 1) Providing troop cooling. With improved power use, the turbulence created by the rotating fan blades could be used to cool troops; particularly if the UAV contained an on-board system for creating a fine mist of water or small droplets. 2) Introducing different imaging capabilities to the UAV would enable the UAV operating to measure vital signs (e.g., heat signatures; respiration; perspiration) that could be transmitted to the combat medic and medical professionals at a high-echelon level of care. 3) Medical equipment could easily be attached/introduced to the UAV, including paddles for defibrillation. 4) The UAV could include capabilities for transmitting voice, video, or other electronic data to/from the combat medic to combat or trauma surgeons. 5) UAVs could in principle be designed so that they are inexpensive enough to be used in a single-user format, in which the UAV flies to a location for material delivery, and the end-user can disassemble the UAV into parts that snap together into other instruments, such as a weapon, medical instrument, or other. Here, we note the cost of one Krossblade skyprowler is equivalent to two combat assault rifles.

Constraints

Range (<50 miles)
Payload (<10 lb)
Cost (<$50K)
Uncertainty (unknown)
Locates troops on ground
Vulnerability

We have identified the above constraints that need to be carefully addressed and considered before implementing a MD system. In addition, the success of MDs depends on how efficiently supplies can be packaged and stored on a UAV. Thus, the actual rapid delivery of medical supplies depends on both a delivery system and a supply chain infrastructure to successfully leverage the capability.

MD advantages

Improved, rapid care
Treat within golden hour
Improve safety
Reduce costs
Reduce soldier's load

Despite these constraints, there are several game-changing advantages that would significantly improve warfighters capabilities and survivability in the event of battlefield injuries. These include: 1) rapid care that potentially exceeds what is currently available; 2) treatment to extend the golden hour; 3) improved safety for medical care in far-forward operating environments; 4) reduction in medical costs; and 5) reduction in the weight carried by warfare fighters. The bottom line for MD is the protection of and enhancement to warfighters, the reduction in battle-field mortality rates, and the improvement in the treatment of medical emergencies and conditions.

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Medscape Medical News

Drones in Medicine Take Flight

Nancy A. Melville

January 09, 2015

Fast drones, faster decisions the future for combat injured

August 26, 2015

By **Ramin A. Khalili, USAMRMC Combat Casualty Care Research Program Knowledge Manager**

Humanitarian drones to deliver medical supplies to roadless areas

Greek entrepreneur Andreas Raptopoulos saw drones being used to deliver pizza and set about solving a real problem

Shane Hickey

Sunday 30 March 2014 10.12 EDT

MAYO CLINIC

For Medical Professionals

Clinical updates

Medical drones poised to take off

THE WALL STREET JOURNAL.

U.S.

Drone Delivers Medicine to Rural Virginia Clinic

Government-approved demonstration also shows that hurdles remain

Since we first proposed this concept in Fall 2014, the first evidence of its possibilities have emerged in the popular press.

MD development and implementation

Customer: combat medics and surgeons
Implementers: logistics community
Enablers: engineers build tech

Bring stakeholders together to identify R&D opportunities and medical solutions

After a thorough review of the current needs, capabilities, and associated challenges it is clear that MD is not a research and development problem; rather it is a pure developmental problem. All of the pieces are available to develop and implement the MD concept. The key aspect is successfully bringing the above stakeholders together to work through the constraints and needed technology developments.

Acknowledgements & References

Tim Ruffing, Ret. Green Beret (2010-2012, Afghanistan), Combat Medic

Dr. Eric Spero, Aerospace Engineer, Vehicle Technology Directorate, Army Research Lab

LTC Jennifer Kishimori, Military Deputy to the Science Director, USAMRIID

Kelly Morris, Chief, Logistics Research & Development, Defense Logistics Agency

Combat Casualty Care: Lessons Learned from OEF and OIF, Office of the Surgeon General, Department of the Army, USA

Williamson, Ramesh, and Grabinsky (2011). Advances in prehospital trauma care. Int. J. of Critical Illness and Injury Science.

Eastridge, Mabry, Seguin et al. (2012). Death on the Battlefield (2001-2011): Implications for the future of combat casualty care. J. Trauma Acute Care Surg.

Mabry and DeLorenzo (2014). Challenges to Improving Combat Casualty Survival on the Battlefield

Kragh et al. (2009). Survival w/ emergency tourniquet use to stop bleeding in major limb trauma.

Think Piece 3

Longitudinal Biometrics and Biomarkers for Optimizing Warfighter Performance

by

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Title: Longitudinal Biometrics and Biomarkers for Optimizing Warfighter Performance

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1. Background and Context

A key aspect of the dominance of the U.S. warfighter over its adversaries is the technological advantage that the U.S. military possesses. For years, research and development has worked to create advanced electronics, communications systems, weaponry, and delivery vehicles in order to provide the warfighter with greater lethality and effectiveness. The resulting state-of-the-art tools that the United States has at its disposal is a clear demonstration of the success that the United States has had in moving fundamental science and engineering breakthroughs into critical applications that impact national defense. Within the past several decades, the knowledgebase that helps us to better understand the actual soldier and not just the weaponry has developed at a rapid pace. The confluence of advanced sensor technology, data sciences, neurosciences, and the ability to accurately measure biometric and biomarkers through advanced chemistry and DNA sequencing has given us new information on factors that enhance or limit human performance. The concept of human performance enhancement is very intriguing as it can lead to improved cognitive and physical performance of individuals, improved health and endurance as well as faster recovery from activity, and the possibility of building more effective teams to perform tasks and missions. This will ultimately require the establishing both neurological and physiological markers and how they relate to traits and human performance (Figure 1).

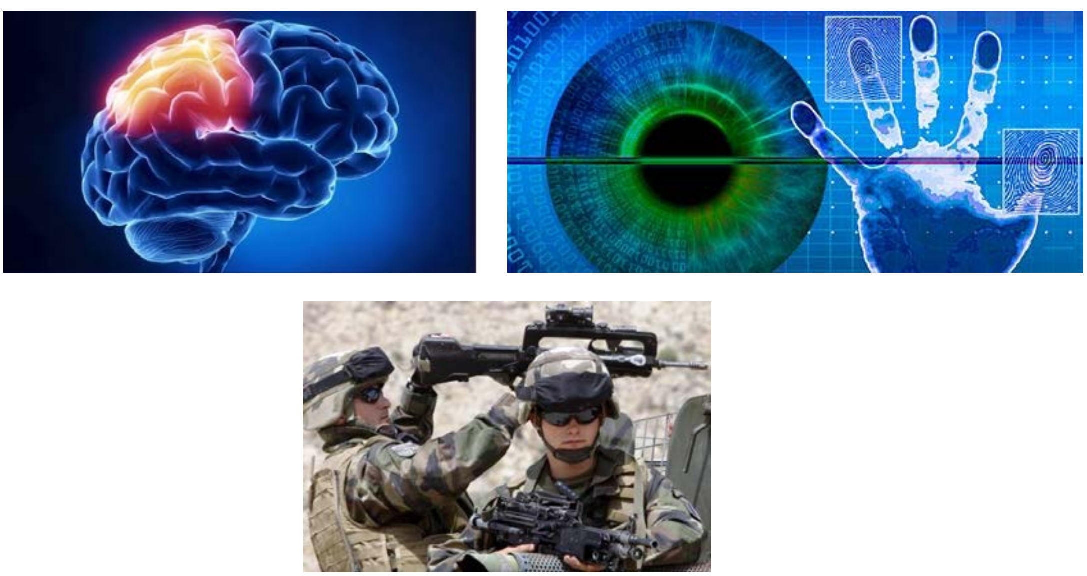

Figure 1. Images illustrating where neurological activity along with regions where physiological responses may be detected as soldiers perform tasks relevant to their military missions.

This is an exciting a new area of technology that is receiving attention both from the military and civilian sectors, but how to implement this technology effectively to enhance the warfighter remains an open question.

There are several areas where understanding limitations in human performance through advanced biometrics or biomarker analysis could improve the way soldiers are utilized in today's military. One could envision that if this technology were developed to the same level of proficiency as we have currently in understanding the aerodynamics of aircraft, the measurement of biomarkers could enhance the selection process and the placement of individuals into their military occupations specialties. For instance, if one could measure not only the health status of an individual, but also factors such as grit, determination, and aspects of their cognitive ability, would the military be more successful in choosing the fighter pilots and drone pilots? Members of Special Forces? Or members of submarine crews?

Currently, the selection process depends on well-established testing protocols including the Armed Services Vocational Aptitude Battery (ASVAB) as well as specialized tests for people wanting to go into aviation such as the Aviation Selection Test Battery (Navy) or the Air Force Officer Qualification Test and the Test of Basic Aviation Skill (Air Force). While such tests have served the U.S. military well, the question remains which skills are necessary to screen for individuals that operate unmanned systems that will be coming in the future? Can the use of biometrics and biomarkers help to delineate between individuals better suited for manned flight platforms versus remotely operated systems?

Another area of potential for the use of biometrics and biomarkers is in the training of military personnel. As recently as October 2015, the Army Capabilities and Integration Center developed 20 primary Warfighter Challenges. Included in the top 10 were Enhanced Realistic Training; Improved Solder, Leader, and Team Performance; and the Development of Agile and Adaptive Leaders. Virtual environments for flight training (flight simulators) have been used for several decades to help train pilots. Such concepts are now being adopted for the training of soldiers in other fighting missions (Figure 2). The Army's Training and Doctrine Command has specifically stated that blended live, virtual, constructive, and gaming training environments replicate complex operating environments and improve leader and team competence and confidence. Thus, we should expect them to become a critical part of the future training of warfighters. The use of these virtual gaming/training environments, where the actions of soldiers are tracked, extended from small-scale indoor shooting ranges through the National Training Facility at Fort Irwin. However, the firing of a weapon in a virtual indoor facility at Fort Bragg is much different that firing the same weapon in a hot, outdoor environment at Fort Irwin. Furthermore, these advanced training environments still lack critical elements that soldiers will face when engaged in combat.

The question becomes, how do we measure the realistic nature of the training in these environments? Are there neurological and biometric differences between these training environments and real combat that need to be replicated or addressed or is the virtual

Figure 2. Top Left: Image showing soldier in a virtual test range. Top Right: Image showing pilot being trained in a flight simulator. Bottom Left: Image showing an urban training center and the National Training Facility at Ft. Irwin. Bottom Right: Image showing soldier out on a live fire training mission.

training aspects truly sufficient? What are the types of physiological and neurological biometrics and biomarkers that we can be measured before, during, and after such training exercises without being too invasive to the soldiers and without hampering their capability to perform the training mission? It can also be perceived that the tracking of such biometrics and biomarkers could lead to the formation of more effective fighting teams as well as enhance the health and readiness of the warfighter.

While current training environments give military commanders confidence that their soldiers will be able to perform a variety of missions, additional insight into the performance of individuals is still desired. For instance, the use of basic training and intense realistic training used to prepare soldiers to fight are used annually to maintain the readiness of the warfighter. However, recent interest in grit and resilience of soldiers has is something that is of major interest to those studying human factors and human performance. At present, traits such as endurance, resilience, and grit can be determined from training, but also through psychological testing (cf., the Duckworth Laboratory at the University of Pennsylvania). It is not clear how such testing corroborates with the performance of actual soldiers. In addition, there may be room for the use of additional biometric and biomarker analyses that leverage advanced measurement technologies and informatics to help understand, predict, and/or optimize these traits in individuals and warfighting units.

Finally, another important area where the use of biometric and biomarkers can be of great use in developing effective fighting teams is in the health and wellness of the warfighter. For instance, when submarine crews board a ship for a mission, any sickness brought onto the submarine can spread until the crew has developed a sufficient resistance to the strain of bacteria or virus that lead to the illness. When going to a foreign country, there may be individuals more prone to getting sick based on new pathogens found in the local environment. Or for artillery crews, there may be genetic traits that lead to faster hearing loss in some individuals versus others. Is it possible to measure the triggers to PTSD in individuals and take actions to limit the exposure of individuals to situations that may induce this disease? These are only a few examples, but the measurement of biomarkers can lead to more effectiveness in the way we deploy healthy and ready soldiers for combat missions.

As previously mentioned, the confluence of neurosciences, data sciences, and advanced sensor technology has led to the great potential for the measurement and tracking of biometrics and biomarkers in individuals. Great efforts in the area of neurosciences are being led by the Army Research Laboratory (Dr. Jean Vettel and Dr. Corde Lane, Figure 3). In addition, the Air Force Research Laboratory along with the NextFlex Alliance and Nano-Bio Manufacturing Consortium are fast developing wearable sensor technologies that can measure biomarkers for stress and fatigue through sweat, saliva, and the breath (Dr. Joshua Hagen, Figure 3). Moreover, the commercial market is pushing wearable technology with a projected market size of $45 million in 2017. Thus, as we continue to advance our measurement technologies, it will now require additional work to understand the meaning of these biometrics and biomarkers in relationship to normal expected duties of the warfighter and how they can be used to enhance human performance in a manner in which we have done with other technologies for decades.

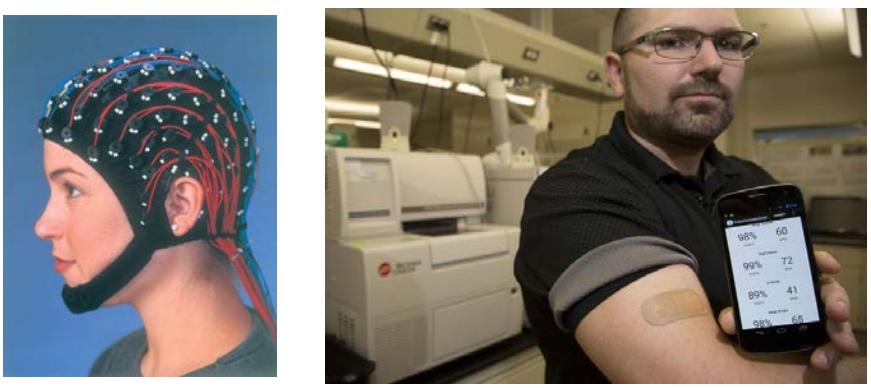

Figure 3. Image showing neurological sensors that can be worn during training developed by the Army Research Laboratory (Dr. Jean Vettel) as well as a sweat sensor developed by the Air Force Research Laboratory (Dr. Joshua Hagen).

The objectives of this think piece are to 1) Suggest the development of a pathway for the use of advanced biomarkers and biometrics that allow for an enhanced understanding of the state of the solider to improve training, mission readiness, and performance. 2) Determine opportunities neurological and physiological metrics that leverage today's technologies so that the Department of Defense (DoD) can rapidly incorporate new measurement approaches to quantitatively assess and optimize training and warfighter performance across a broad range of missions. Through the use of advanced biomarkers and biometrics, the DoD can continue to maintain an advantage over adversaries though human factor optimization and both the individual and unit level, and the present time is ripe for exploitation of current and emerging technologies and informatics approaches.

2. Biomarkers of Potential Relevance to Warfighter Performance

New technologies are paving the way for unprecedented levels of physiological monitoring, and data sciences are largely keeping up with the development of algorithms that allow for near real-time network analysis. This next section briefly discusses several classes of neurological imaging approaches, biomarkers, and biometrics that are poised to play a key role in providing quantitative measures to evaluate different approaches to training and operational deployment. They largely focus on establishing numerical baseline for individual warfighters that might be longitudinally-monitored to understand the progression of cognitive, instinctual, and physical capabilities and situational reactions. They also offer opportunities to shed light on complex, yet critically important stress-related disorders/diseases, including genetic and epigenetic modifications that may play may be diagnostic signatures for or therapeutic targets related to Post Traumatic Stress Disorder (PTSD). A final brief section also discusses an opportunity for optimizing warfighter performance through engineering the microbiome, potentially providing an approach that targets the gut-brain axis for improving soldier performance—particularly in forward operating theaters that are emerging as geographic areas in which DoD has identified as requiring strategic advantage.

Key to establishing links between cognitive and physical training and warfighter performance is the establishment of biochemical and biophysical biomarkers that can be used in the quantitative evaluation and comparison of training experiences. Of course, these markers would not replace, but be used in concert with more classical performance metrics (i.e. time to completion, etc.) as well as subjective measures of soldier performance.

a. Neuroelectrical Signatures of Cognitive Function

Measures of electrical impulses involved in brain function during training or in post-training testing can reveal insights into cognitive function. An interesting study by Matzen et al.[1] investigated the utility of event-related potentials as a measure of memory and word learning. Event-related potentials (ERPs) are measured through electroencephalgraphy, where brain activity is measured using sensors placed on the scalp. Brain activity measured during learning and recall from memory can be related to explicit processing functions, such as memory retrieval. Importantly, emerging tools such as the sensor array shown in Figure 4 might allow for real-time acquisition of ERPs.

[1] Laura Matzen, et al., *Using Recordings of Brain Activity to Predict and Improve Human Performance*, Sandia Report SAND2012-8305 (Albuquerque, NM and Livermore, CA: September 2012), http://prod.sandia.gov/techlib/access-control.cgi/2012/128305.pdf.

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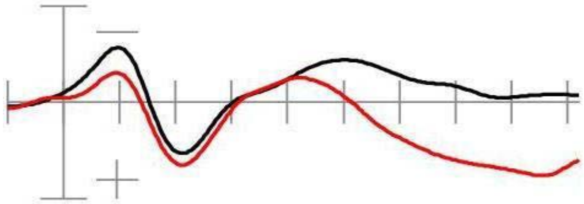
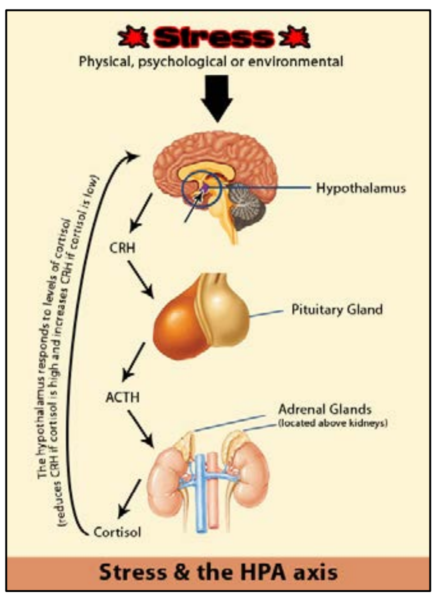


Figure 4. Representative event-related potentials measured during a study of cognition might distinguish cognitive performance, such as items from training that are subsequently remembered (black trace) or forgotten (red trace).

b. Dynamic Biomarkers and Biometrics of Stress

Response to stress is, in part, regulated by a complex biochemical feedback loop known as the hypothalamic–pituitary–adrenal (HPA) axis (Figure 5). Stress is transmitted from the brain to the hypothalamus, which secretes corticotrophin releasing hormone (CRH). CRH then signals the pituitary gland to secrete adrenocorticotropic hormone (ACTH), which stimulates the adrenal glands to secrete cortisol. The hypothalamus detects systemic cortisol levels and establishes feedback control over the HPA axis and overall stress response.



Source: 50 Symptoms Gone, "The Stress Response …and How It Relates to the HPA Axis," http://www.50symptomsgone.com/?p=4772.

Figure 5. The HPA axis links the cognitive observation of stress to compensatory biochemical mechanisms. This axis also provides biomarkers to probe acute and chronic stress exposure.

Importantly, many of these, and other secreted signals can be detected in body fluids and correlated as biomarkers of acute and/or chronic exposure to stress. Although many of these biomarkers are found in blood, many can also be measured in saliva, offering the potential for minimally-invasive monitoring that might be accessible during warfighter

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training or even deployment, as collection could be non-perturbative. Candidate biomarkers include cortisol, ACTH, copeptin, and alpha amylase.

In addition to molecular biomarkers, other physical biometrics that might be extracted using minimally perturbative, emerging wearable technologies can also be correlated with stress exposure and response. For example, systolic and diastolic blood pressure in combination with heart rate variability (HRV) can XXX.[2] Another recent report demonstrates the potential for measuring galvanic skin response (GSR), which is a measure of a change in the voltage across a skin electrode due to increased sweating.[3] Importantly, methods exist at present that would allow for these measures to be measured in real-time during training exercises. Moreover, powerful new bandage-type wearable sensors and wireless network transmission make the collection of these biomarkers in the battlefield a near-term possibility. Therefore, efforts should be made in the near future to probe the potential of these biometrics to be considered for incorporation into predictive algorithms that not only are useful in evaluating training exercises, but also performance in real-world deployment.

c. Genomic and Epigenomic Factors in stress Response, Resiliency, and post-Traumatic Stress Disorder

The fact that physical and intellectual traits are inherited from parents demonstrates the importance of genetic control over not only genotype, but phenotype. Beyond our genetic blueprint, the expression of genes is controlled epigentically, through a highly regulated series of covalent modifications to both DNA and the histone proteins around which DNA is wrapped as part of chromatin structure. Importantly, epigenetic factors are inherited, but also can be reprogrammed through environmental factors, which include exposure to stress.

A number of recent studies have highlighted the influence of both genomic and epigenomic factors and suggest how alterations in these factors can influence important warfighter characteristics, including susceptibility to adverse stress response (e.g. fight or flight), resilience, and development of PTSD.[4] Moreover, in model systems, traumatic events have

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[2] Julian F. Thayer et al., “A Meta-Analysis of Heart Rate Variability and neuroimaging Studies: Implications for Heart Rate Variability as a Marker of Stress and Health. *Neuroscience and Biobehavior Reviews* 36, no. 2 (February 2012): 747–756. http://www.sciencedirect.com/science/article/pii/S0149763411002077.

[3] Maria Viqueira Villarejo, Begoña Garcia Zapirain, and Amaia Méndez Zorilla, “A Stress Sensor Based on Galvanic Skin Response (GSR) Controlled by ZigBee,” *Sensors* 12, no. 5 (2012): 6075–6101, http://www.mdpi.com/1424-8220/12/5/6075.

[4] Joohyung Lee and Vincent R. Harley, “The Male Fight-Flight Response: A Result of SRY Regulation of Catecholamines?,” *BioEssays* 34, no. 6 (June 2012): 454–457, http://onlinelibrary.wiley.com/doi/10.1002/bies.201100159/pdf; Adriana Feder, Eric J. Nestler, and Dennis S. Charney, “Pshchobiology and Molecular Genetics of Resilience,” *Nature Reviews Neuroscience* 10, no. 6 (June 2009): 446–457, http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2833107/; Levent Siphai et al., “Longitudinal Epigenetic Variation of DNA Methyltransferase Genes Associated with Vulnerability to Post-Traumatic Stress Disorder (PTSD),” *Psychological Medicine* 44, no. 15 (November 2014): 3165–3179, http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4530981/; Marilyn C. Cornelis et al., “Genetics of Post-Traumatic Stress Disorder: Review and Recommendations for

been shown to cause epigenomic changes that appear to predispose individuates for increased susceptibility to PTSD.[5]

Given the significant advanced in both genomic and epigenomic analyses for healthcare applications, it seems as though these signatures should be investigated for use for DoD objectives in optimizing warfighter performance. Moreover, a number of epigenome-modifying therapeutic agents are being introduced as anti-cancer therapies and therefore similar strategies might have utility as preventative or corrective approaches for managing individuals suffering from or at high risk of developing PTSD.

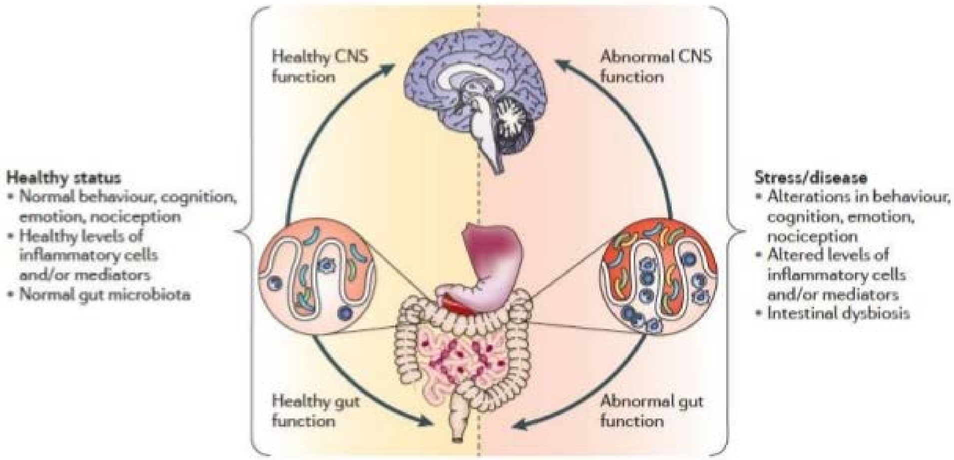
d. Opportunities for Engineering Microbiomes to Enhance Warfighter Performance

While not a biomarker or biometric, one other opportunity for optimizing warfighter performance that should be raised involves strategic engineering of the gut microbiome, which is not a new concept to DoD. The Office of Naval Research (ONR) has already invested ~$15 million over 7 years. Engineered microbiomes might be used to prepare soldiers lacking regionally specific gut microflora for operations in foreign environments where they are at risk to particular pathogens.

There is an also an increasing appreciation for the role the microbiome plays in the gut-brain axis (Figure 6). This axis plays a key role in modulating immune response, and also couples to stress response by interacting with the HPA axis. In general, can the microbiome be therapeutically treated or supplemented to reduce illness, optimize performance, or mitigate risk?

Genome-Wide Association Studies," *Current Psychiatry Reports* 12, no. 4 (August 2012) 313–326, http://link.springer.com/article/10.1007%2Fs11920-010-0126-6.

5 Florian Joachim Raabe and Dietmar Spengler, "Epigenetic Risk Factors in PTSD and Depression," *Frontiers in Psychiatry* 4 (August 2013): 80–128.



Source: John F. Cryan and Timothy G. Dinan, "Mind-Altering Microorganisms: The Impact of the Gut Microbiota on Brain and Behaviour," *Nature Reviews Neuroscience* 13 (October 2012): 709, http://www.nature.com/nrn/journal/v13/n10/full/nrn3346.html.

Figure 6. The Gut-Brain Axis Plays a Key Role in Modulating Immune Response and Reactions to Stress.

3. Potential Case Studies and Opportunities for Early Adoption of Biomarkers and Biometrics in Well-Defined Training and Deployment Environments

In this section, we discuss two exemplar scenarios that highlight the opportunities and benefits associated with the usage of longitudinal biometrics and biomarkers for optimizing warfighter performance.

a. UAV/Drone Pilots – Training and Performance

Although fighter pilots fly an average of 250 hours/year, front-line drone pilots fly an average of 900 hours/year and are taxed by the ever-growing need for more capabilities.[6] The Air Force and Army, which have the largest drone fleets, suffer from a chronic shortage of pilot training.[7] This limitation makes it difficult to keep current pilot's skills sharp and to train new pilots. Despite working in relatively safe conditions (i.e. not under direct enemy threat), studies have found that drone pilots report high levels of stress and fatigue, and suffer the same rate of PTSD as pilots flying downrange combat missions. A typical drone flying scenario involves shifts of up to 12 hours and missions that can go on for weeks or months. In such a scenario, maintaining concentration for pilots is a difficult task. This reduced need for interaction can result in a lack of sustained attention, leading to boredom, which can cut down on reaction times. Ironically, UAV pilots, who were groomed

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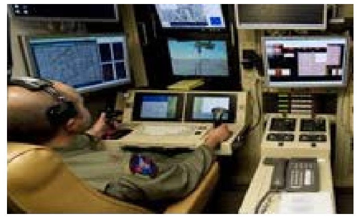
6 Stephen Losey, "Predator, Reaper Drones Pilots to Get up to $135K Re-Up Bonus," *Air Force Times*, July 15, 2015, http://www.airforcetimes.com/story/military/careers/air-force/2015/07/15/predator-reaper-drone-pilots-to-get-135k-re-up-bonus/30184499/.

7 Brian Fung, "The Army's Drone Pilots Aren't Being Trained Because They're Too Busy Moving Lawns," *The Washington Post*, May 15, 2015, https://www.washingtonpost.com/news/the-switch/wp/2015/05/15/the-armys-drone-pilots-dont-get-enough-training-because-theyre-too-busy-mowing-the-lawn/.

for their video-game joystick skills, and fighter-pilots-turned-UAV pilots, who relied on quick reactions and multi-tasking to succeed in combat, might not necessarily fit the bill when boredom is a factor.[8]





In such a scenario, a number of translational opportunities exist related to the use of biometrics and biomarkers in this domain. First of all, such a scenario provides a great opportunity to have military personnel wear sensing apparatus (such as a brain-computer interface (BCI) cap, eye-tracking sensor, or wearable sensors) and collect biospecimens without interfering with the pilot's performance capabilities. It is also the closest prospect available for extracting baseline performance metrics within a realistic combat situation, without hampering the pilot's performance. Translational biometrics and biomarkers opportunities include the following:

- Ability to identify and track environmental/combat conditions that result in stress and fatigue for the pilot;
- Through extraction of biometrics/biomarkers, develop the ability to identify realism of training scenarios which match to the realism of front-line drone pilot missions;
- Development of training opportunities that quantitatively maximize the quality of training scenarios to compensate for the reduction in the time available for training drone pilots;
- Ability to compare different training scenarios (e.g. virtual, field simulation, etc.) to maximize return-on-investment on current training opportunities and evaluate new, innovative, potentially disruptive training alternatives;
- Ability to evaluate grit and resiliency through real-world measurements extracted during training scenarios rather than paper-and-pen assessment methods;
- Through usage of biomarkers, develop the ability to predict real-world, in-combat, pilot performance based on a pilot's current training performance; and
- Establishment of long-term assessment processes that track pilot's performance from basic training to field training to combat.

b. Confined Spaces - Holistic Health and Fitness

When military personnel are sealed in tiny working spaces for long periods of time, it (1) increases the opportunity for the transmission of illnesses (such as viral respiratory infections, which is the most common category of medical events on submarines), and

[8] David Szondy, "MIT Investigating Ways to Combat Boredom in Drone Pilots, *gizmag*, November 18, 2012, http://www.gizmag.com/uav-pilot-boredom-mit/25014/.

(2) provides an opportunity to observe illnesses under unique conditions.[9,10] Currently, there is no protocol available to screen for illnesses. Another important aspect of these environments is the prolonged isolation. Studies have shown that imposed isolation can lead to several problems, such as fatigue, muscular tension, low motivation, disruption of circadian cycles, and minor emotional disturbances.



Exploiting information derived from biometrics and biomarkers provides a unique opportunity to address the needs of military personnel working in confined spaces, ranging from the U.S. Navy personnel who serve on submarines, Army Tank Crews, and Rangers deployed on long-duration missions. Since these military personnel work in a confined, pre-determined working space, a great opportunity is presented in which the environment itself can be to instrumented for data collection. In such a scenario, translational biometrics and biomarkers opportunities include the following:

- Developing the ability to identify pre-symptomatic illnesses (i.e. before any visible signs of sickness are detectable) through the usage of biomarkers;
- Developing the ability to monitor longitudinal biometric signatures before deployment in order to determine who might get sick in theater; and
- Augmenting personnel performance and providing therapeutic benefit through the introduction of microbiomes into the system.

Summary

These two exemplar scenarios optimize warfighter performance by 1) focusing on improving performance and effectiveness of the drone fighting unit through enhanced training and 2) focusing on improving health and, thus readiness, of military personnel operating in confined spaces. By using biometrics and biomarkers, human performance can be improved through the assessment of training processes, and using that information to iteratively feedback and enhance these training processes. By using biometrics and biomarkers, human health can be improved by reducing the opportunity for illnesses to materialize, especially while in theater. Through advancements in measurement science and data analytics, longitudinal biomarkers and biometrics are ideally situated to make a different in optimizing warfighter performance.

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[9] R. G. Burr and L. A. Palinkas, *Health Risks Among Submarine Personnel in the U.S. Navy, 1974–1979*, Report No. 87-5 (San Diego, CA: Naval Health Research Center, 1 December 1986), http://www.dtic.mil/dtic/tr/fulltext/u2/a185836.pdf.

[10] Terry L. Thomas et al., "Health of U.S. Navy Submarine Crew During Periods of Isolation," *Aviation, Space, and Environmental Medicine* 74, no. 3 (March 2003): 260–265, http://www.ncbi.nlm.nih.gov/pubmed/12650274.

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Think Piece 4

Human Endurance Advanced Technology Diving (HEATeD) Suit (a.k.a. the "Arctic Wetsuit")

by

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Title: Human Endurance Advanced Technology Diving (HEATeD) Suit (a.k.a. the "Arctic Wetsuit")

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Abstract

Drawing initial inspiration from animals that survive and thrive in frigid waters, we have explored several technology innovations that could be incorporated into an advanced diving suit system to keep cold-water divers and their equipment warmer for longer time, and help them swim more efficiently. Such innovations include:

- A modified neoprene material that increases the thermal resistance of standard neoprene by a factor of 3;
- Fur-like air-trapping coatings that provide some additional thermal insulation, and importantly reduce the viscous drag of a diver by as much as 90%, thus enabling more efficient swimming by the diver;
- Thermal resonators that can harvest energy from temperature fluctuations in the water and supply heat to the diver;
- Thermopower waves based on seawater-driven exothermic reactions that can safely deliver heat to the diver;
- Phase Change Material (PCM) pads that can mitigate the consequences of the diving suit failure as well as extend the lifetime of the batteries and electronics carried by the divers;
- Miniaturized temperature sensors that can monitor the core temperature of the diver.

While the above conclusions are based on rough, order-of-magnitude estimates, they provide sufficient motivation for a more systematic investigation of the ideas contained in this Think Piece.

Background

With significant spring melting of the ice cap occurring earlier every year, the race for control and exploitation of the Arctic hydrocarbon resources, fisheries and strategic navigation routes is on. Arctic nations, such as Canada, Norway and especially Russia, are aggressively positioning themselves to take advantage of these opportunities, in addition to newcomers such as China. The U.S. Navy's Arctic roadmap to 2030 [Ref. 1] envisions that U.S. armed forces will find themselves operating to a much greater extent in Arctic waters, above and below the surface, with increasing frequency as a result of the strategic national security interests in this area. More generally, cold-water diving is central to several aspects of the Department of Defense (DoD) and Navy mission, from special operations to undersea exploration and reconnaissance.



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Figure 1. Low-Temperature Dive Persistence Is Central to special Operations (Left) and Undersea Exploration and Reconnaissance (Right).

Divers in cold-water environment face major challenges including the following:

- Risk of hypothermia,
- Reduced swimming efficiency due to heavy protective gear,
- Reduced durability of power sources, since lithium ion battery lifetime is shorter at low temperature,
- Limited breathing air storage, and
- Degraded undersea navigation (i.e., proximity of the magnetic pole makes compasses relatively useless).

This Think Piece focuses on the first three challenges. Table 1 shows typical times to severe hypothermia and death for unprotected divers in water at various temperatures. Figure 2 shows the beneficial effect of a conventional protective wetsuit on reducing the time to hypothermia. We have consulted with DoD and National Science Foundation (NSF) cold-water divers, and confirmed that dive duration and range are severely limited in ice water: 15–30 minutes (somewhat longer with a drysuit), and under-ice maximum range of 200 m–300 m (shorter if the diver is tethered). Compare these figures to 1-km dive range (or up to 8 km with a swim aid) and 8-hour dive duration in warm waters.

Today's divers are not monitored during the dive and are expected to endure the cold temperatures as well as self-diagnose the point when there are significant risks from hypothermia. Thus, technologies that assist the diver in knowing dangerous drops in core body temperature would improve dive safety in cold-water missions.

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Table 1. Hypothermia and Survival Chart.

Water Temperature		Expected Time Before Exhaustion or Unconsciousness	Expected Time of Survival
(°F)	(°C)		
32.5°	0.3°	< 15 minutes	45 minutes
32.5–40°	0.3–4.4°	15 - 30 minutes	30 - 90 minutes
40–50°	3.3–10°	30 - 60 minutes	1 - 3 hours
50–60°	10–15.6°	1 - 2 hours	1 - 6 hours
60–70°	15.6–21.1°	2 - 7 hours	2 - 40 hours
70–80°	21.1–26.7°	3 - 12 hours	3 hours - indefinite
> 80°	> 26.7°	Indefinite	Indefinite

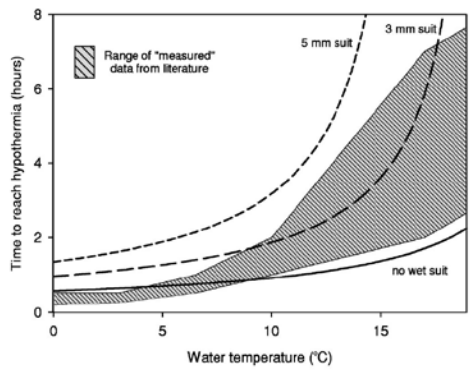

Figure 2. Calculated Time to Hypothermia with and without a Standard Wetsuit [Ref. 2].

There are four basic designs of diving suits:

- *Wetsuits* (Figure 3a) allow for a thin layer of water to be trapped in the gap between the diver skin and the suit. Flushing of water in and out of the gap greatly reduces thermal insulation. Regarding wetsuits, the U.S. Navy Dive Manual [Ref. 3] states that "in very cold water, the wet suit is only a marginally effective protective measure, and its use exposes the diver to hypothermia and restricts available bottom time".
- *Variable-Volume Drysuits* (Figure 3b) are constructed so the entry zipper and all seals are waterproof, keeping the interior dry. They are inflated with air, providing buoyancy and some thermal insulation; however, insulation comes primarily from the underwear worn by the diver. A parting seam or zipper can result in a dramatic loss of buoyancy control and thermal shock.
- *Hot-water Wetsuits* (Figure 3c) provide thermal protection by circulating a warm fluid which is typically fed by a surface supply. As such, this design severely limits dive range, and the diver is subject to thermal shock if the hot-water supply is disrupted.
- *Active Diver Thermal Protection Systems* are suits with a portable electric power unit and self-contained circulating hot fluid (e.g., Free Diver Heating System (FDHS) by Rini Technologies (Figure 3d)) but also battery-heated gloves, vest, and socks (e.g., SANTI, Golem Gear, Alcyon Dive Systems, DUI). Battery durability limits the bottom time, and the circulating fluid system is bulky.[1]

Additional challenges exist in terms of the operation of electrical equipment in cold environments. Such equipment may consist of dive computers, sensors, thermal protection systems for the diver, and communication equipment that operate on batteries. Due to the need for large energy densities, Li-ion batteries are often used for these systems. As with most battery chemistries, the internal resistance of the batteries increases with decreasing temperature which slows down the diffusion of Li ions between the cathode and anode. Thus, the battery capacity will decrease, resulting in shorter operational times for such electronic equipment. While the construction and exact chemistry of the battery will influence the temperature dependence of the overall capacity, all chemistries to date have capacity loss that may impact the diver's ability to perform tasks. Figure 4 shows an

[1] Among the active thermal suit concepts, it is worth mentioning that in the 1960s the U.S. Navy explored a 'nuclear wetsuit' design that would be based on heat generation from radioactive decay of Pu-238 [Ref. 4]

Figure 3. Examples of Current Diving Suit Designs.

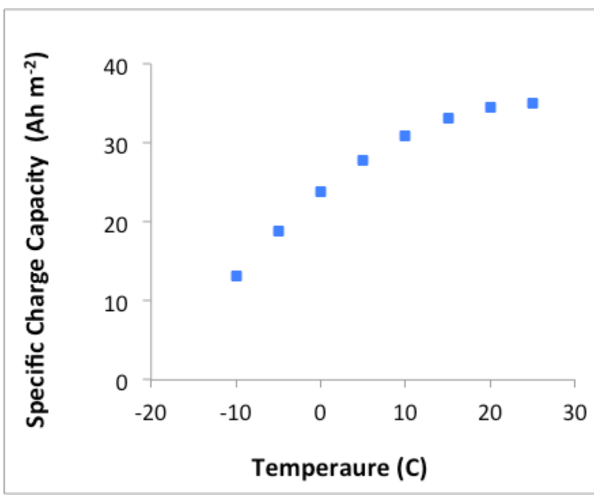

Figure 4. Estimates of the Specific Charge Capacity vs. Temperature for Li-ion Batteries Showing a Drop in Capacity of 25% between 30°C and 0°C.

Note for Figure 4: Estimates are based on correlations found in Ref. 5.

estimated loss of Li-ion battery capacity as a function of temperature, showing as high as 25% decrease when going from room temperature to 0°C. Thus, thermal management of the battery systems can help to maintain battery capacity and increase mission time.

This brief survey of the current diving suit technologies and power sources suggests that there is room for improvement and innovation. In this Think Piece, we explore the development of an innovative diving suit system that will allow for longer, more reliable and more effective dives in the Arctic. However, the technologies to be considered here may find broader applications also in the commercial domain, for example, recreational divers, triathletes and surfers, oceanographers, and shipyard workers.

Objectives and Approach

The overarching objective is to develop an innovative diving suit that will keep divers and their equipment warm, and help them swim efficiently during long dives in cold water. Top-tier requirements for the suit materials include ultra-low thermal conductivity, high strength, high bending flexibility, ease of fabrication, and low cost. To achieve these goals, we take initial inspiration from nature. Animals living in extremely cold water combat hypothermia through a small arsenal of evolution-designed features, as shown in Figure 5:

- Thick layers of insulating fat,
- Air-trapping fur or feathers, and
- High internal heat generation.

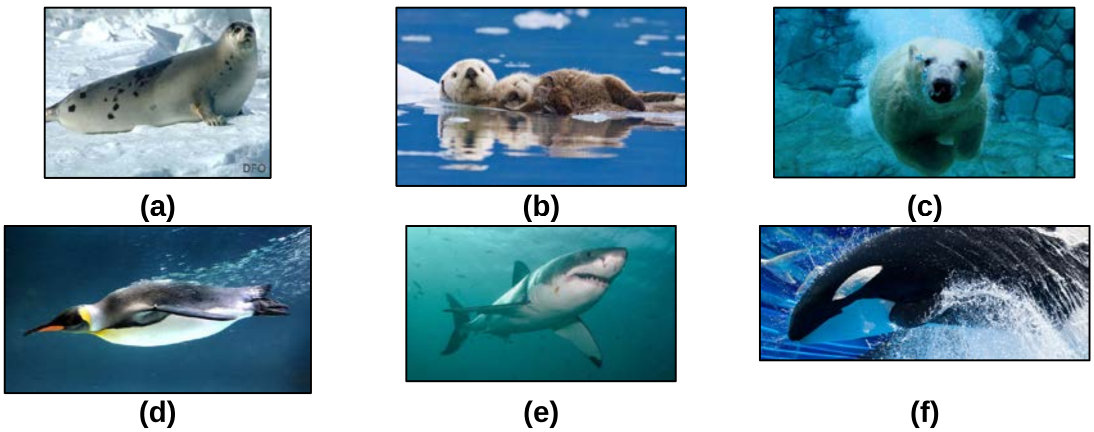

Figure 5. Animals Cope with Extremely Cold Waters Using Different Approaches.

Note for Figure 5: (a) seals have thick thermally insulating blubber; (b) otters use air-trapping fur; (c) polar bears combine under-skin fat layers with air-trapping fur; (d) penguins use air-trapping feathers for insulation and drag reduction; (e) and (f) great white sharks and killer whales are warm-blooded animals that maintain high core temperatures via high internal heat generation.

Our approaches align with and improve upon the aforementioned bio-features as follows:

- Synthetic 'blubber': an advanced suit material that provides superior thermal insulation;
- Synthetic 'fur': hydrophobic coatings that trap air on the surface of the suit, thus reducing heat losses and swim drag; and
- Advanced thermal management: energy harvesters, fuel cells, heat pumps, batteries, and thermal storage materials that provide additional means to warm the divers and their equipment.

The following sections discuss these three approaches in some detail.

1. Advanced Insulation

The process of heat transfer from the diver's body to seawater can be viewed as three thermal resistances in series: conduction through the dermis, conduction through the protective suit, and convection to the seawater (Figure 6). Using typical values for the dermis thermal resistance $R_{dermis} = 0.03$ K/W [Ref. 2], the surface area of the body (A_{body}=2 m^2), the thickness of the suit t_{suit} = 5–10 mm, the thermal conductivity of the suit ($k_{suit} \sim 0.045$ W/m-K), and the water heat transfer

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coefficient (h_{water} = 10–50 W/m^{2}K), we find that the thermal resistance of the suit accounts for about one-third of the total thermal resistance. Since it is not possible to manipulate the thermal resistance of the dermis and seawater, we focus here on increasing the thermal resistance of the suit.

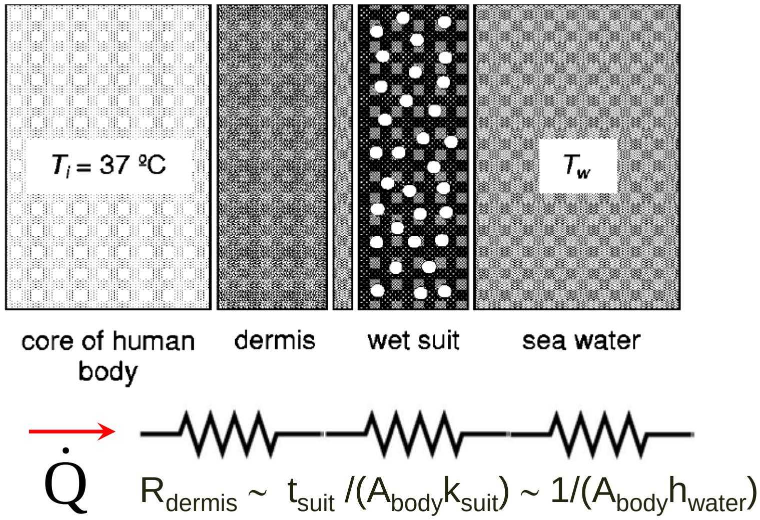

Figure 6: Thermal Resistances for Heat Transfer from the Diver's Body to Seawater.

1.1 Synthetic 'Blubber'

The current standard material for diving suits is neoprene, which is a rubber foam with a high density of large (~300 µm diameter) nitrogen pores (Figure 7). Uncompressed neoprene has an average porosity (i.e., volume fraction of the nitrogen pores) of ~75%. Since nitrogen is a poor thermal conductor, neoprene is a good thermal insulating material with a relatively low effective thermal conductivity, ~0.045 W/m-K. At typical dive depths of 10–20 m, hydrostatic compression of the pores leads to a significant increase in the effective thermal conductivity of neoprene.

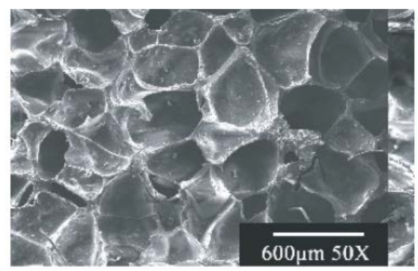

Figure 7. Microstructure of Neoprene Foam [Ref. 6].

Heat transfer within neoprene is a fairly complex process of heat percolation through the solid rubber matrix and heat diffusion through the gas filled pores. However, the homogeneous medium model [Refs. 7–8] has been shown to capture the thermal conductivity of neoprene foam, k, reasonably well [Ref. 6]:

$$\frac{k}{k_r} = \frac{k_g + 2\tilde{k}_r + 2(k_g - \tilde{k}_r)P}{k_g + 2\tilde{k}_r - (k_g - \tilde{k}_r)P} \text{ with } \tilde{k}_r \equiv k_r\left(1 + \frac{2R_b k_g}{d}\right), \tag{1}$$

where k_r is the rubber thermal conductivity, k_g is the fill gas thermal conductivity, P is the porosity, d is the pore diameter, and R_b is the Kapitza interfacial resistance. Equation (1) is plotted for standard neoprene with nitrogen-filled pores in Figure 8 (blue curve). If the porosity was increased to 85%, for example using poli-dispersed pores that fill the interstitial space between larger pores (Figure 9), the thermal conductivity could be reduced somewhat. However, if the fill gas is changed

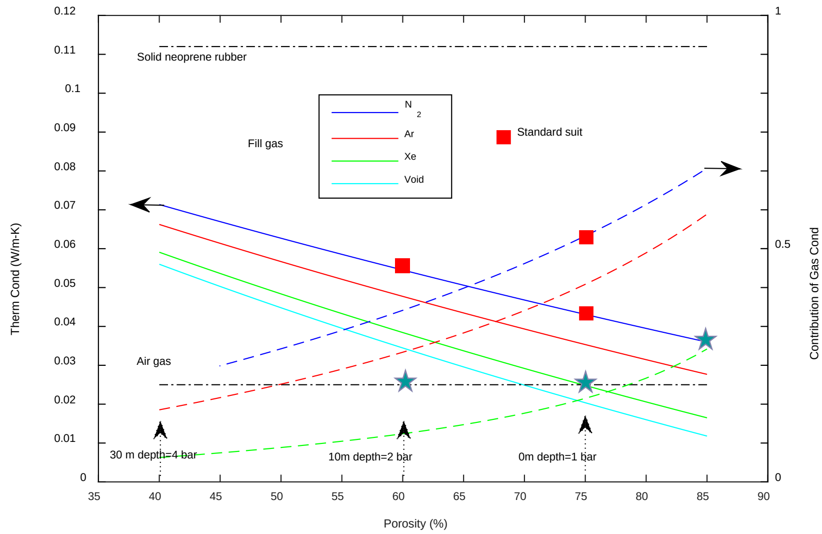

Figure 8. Thermal Conductivity (Left Axis) and Fraction of Heat Transfer through the Gas Pores (Right Axis) vs. Porosity for Neoprene Foam with Various Pore Fill Gases. (R_b=0, Spherical Bubbles).

from nitrogen to a more insulating gas such as xenon, the reduction in thermal conductivity is more dramatic (Figure 8, green curve). In fact, the resulting xenon-based neoprene foam would have a thermal conductivity as low as that of plain air gas (k~0.025 W/m-K)! Xenon is an expensive gas [Ref. 10], but the amount used in the suit would be so low that its impact on the overall production cost of the suit should be negligible.

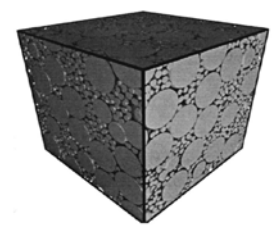

Figure 9. Packing of Poli-Dispersed Spheres [Ref. 9].

At typical dive depths of 10–20 m the suit porosity of a neoprene foam is reduced to 50%–60% (Figure 8), with a corresponding increase in thermal conductivity of 30%–40%. One way to prevent this unfavorable collapse is to reinforce the neoprene matrix with nanoscale inclusions. Nanoparticles such as graphene platelets, carbon nanotubes, or Ag nanowires can be added to a polymer matrix material such as neoprene to increase the mechanical modulus, creating a so called nano-composite. While such inclusions are often thermally conductive, they can reinforce a neoprene matrix at volume fractions far below their percolation limit. At low volume fraction, nanoparticles can mechanically stiffen the matrix to resist the collapse that will occur with increasing depth. The use of orientation and alignment can also ensure that such inclusions maximize mechanical reinforcement while minimizing thermal conduction.

Equation 1, as generalized by Nan et al. [Ref. 8], is used again in Figure 10 to show the effect of pore size, pore shape and interfacial resistance on neoprene thermal conductivity. Pore size reduction decreases thermal conductivity only if R_b is very high; R_b could be enhanced by nano-inclusions of graphene, carbon nanotubes (CNTs), nanoclay, nano cellulose fiber. However, use of non-spherical (oblate) pores would reduce thermal conductivity to a remarkably low value of ~0.017 W/m-K. Let us consider this figure a realistic lower limit for the thermal conductivity of our synthetic 'blubber'. It is worth noting that natural blubber (e.g., seal fat) has a thermal conductivity one order of magnitude higher, ~0.19 W/m-K.

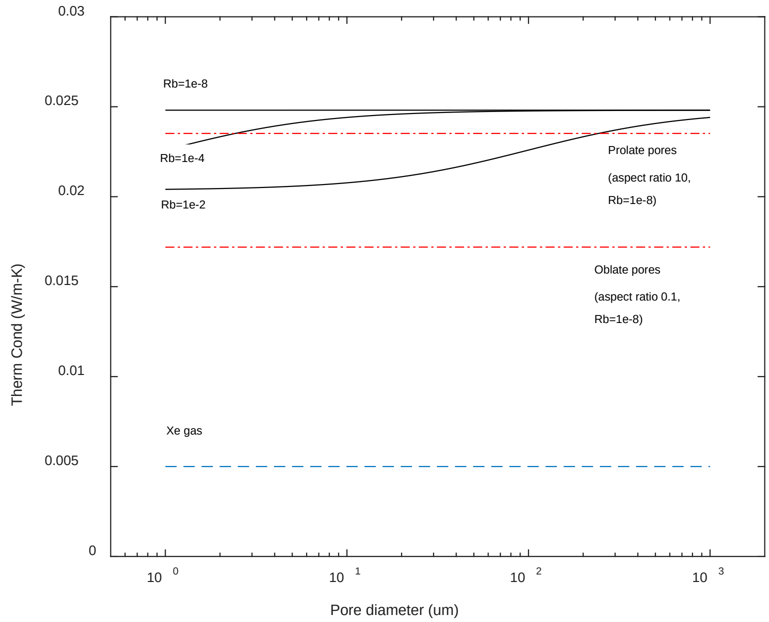

Figure 10. Thermal Conductivity of Neoprene Foam with Xenon-Filled Pores vs. Pore Diameter for Various Shapes and Interfacial Resistance.

Note for Figure 10: P=75%; R_b is in units of m^2K/W.

To quantify the benefit of a higher-insulation suit on the duration of a cold-water dive, we select time-to-hypothermia as the figure of merit and use a simple thermo-physiological model (recommended in Ref. 2) to calculate it. Let us start by writing the 1st law of thermodynamics for a diver:

$$(Mc)_{body}\frac{dT_{core}}{dt} = \dot{Q}_{gen} - \frac{T_{core} - T_{water}}{R}, \tag{2}$$

where T_{core} is the core temperature of the diver, $(Mc)_{body}$ is the thermal capacity of the diver, $\dot{Q}_{gen}$ is the diver's metabolic rate, T_{water} is the seawater temperature, and R is the total thermal resistance, which in accordance with Figure 5 can be calculated as $R = R_{dermis} + t_{suit}/(A_{body}k_{suit}) + 1/(A_{body}h_{water})$. Equation 2 is a first order ODE that can be solved analytically to give the temperature history of the diver, $T_{core}(t)$, from which the time-to-hypothermia is readily found to be:

$$\therefore t_h = R(Mc)_{body}\ln\left(\frac{T_0 - T_{water} - R\dot{Q}_{gen}}{T_h - T_{water} - R\dot{Q}_{gen}}\right), \tag{3}$$

where T_0 is the initial core temperature of the diver, and T_h is the core temperature at which hypothermia sets in. Figure 11 shows the time-to-hypothermia as a function of water temperature for various diving suit options, and for typical values of the input parameters: t_{suit} = 7 mm, h_{water} = 25 W/m²K, R_{dermis} = 0.03 K/W, A_{body} = 2 m², M_{body} = 75 kg, C_{body} = 3470 J/kg-K, T_0 = 37°C, T_h = 35°C, $\dot{Q}_{gen}$ = 120 W. The model suggests that in ice-water the use of our innovative suit material

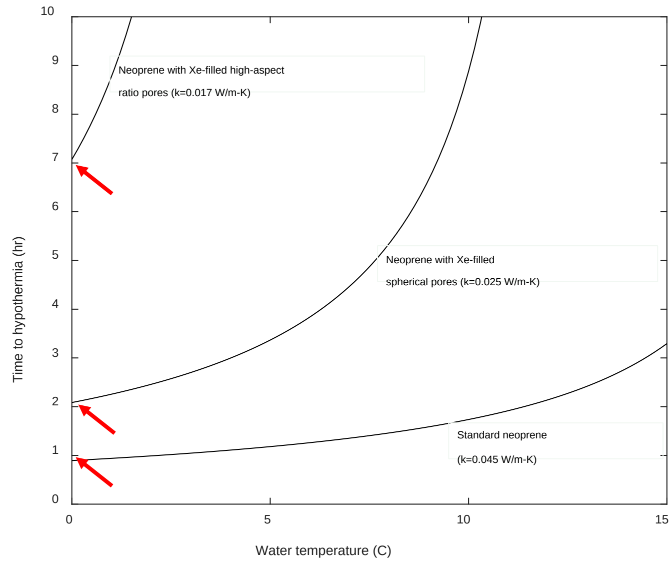

Figure 11. Calculated Time-to-Hypothermia vs. Water Temperature for Standard Neoprene as well as the Advanced Neoprene with Xenon-Filled Pores, both Spherical and Oblate.

can increase the time-to-hypothermia several folds. Note the non-linearity of the effect with respect to thermal conductivity, which comes from the logarithmic term in Eq. 3 (i.e., a small decrease in thermal conductivity can result in a large increase in the time-to-hypothermia as the asymptotic diver temperature ($T_{water} + R\dot{Q}_{gen}$) becomes closer and closer to the hypothermia temperature T_h). These results should be verified using more sophisticated thermo-physiological models (e.g., the model used by the U.S. Navy Experimental Diving Unit in Panama City).

1.2 Synthetic 'Fur'

As a complement to the aforementioned strategy of trapping gas within the interstitial pores of neoprene, it is also possible to maintain a stable air layer exterior to the diving suit by achieving a Cassie-state liquid-air interface within a "synthetic fur" coating. A similar approach is successfully implemented by sea otters which, like humans, are warm-blooded and face the challenge of thermal regulation in the absence of blubber. Sea otters achieve a stable air layer within their fur via a two-layer hair structure. The inner layer of densely packed hair serves as the primary means of producing a Cassie state. The air layer is protected by longer guard hairs, as illustrated in Figure 12. The regular surface features of the guard hairs allow them to interlock and trap the air during dives.

The advantage of this approach to thermal regulation is that it makes use of ambient air to provide thermal insulation. Measurements of native sea otter pelts indicate that thermal conductivities as low as 0.04 $Wm^{-1}K^{-1}$ can be achieved [Ref. 11]. The shortcoming of external air trapping is the limited depths to which air trapping has been demonstrated in animals. Over 80% of the insulating air is lost on dives below 20 m due to breakdown of the locking mechanism of the guard hairs. Although sea otters can replenish the air layer upon resurfacing, such interventions may not be feasible during human diver missions.

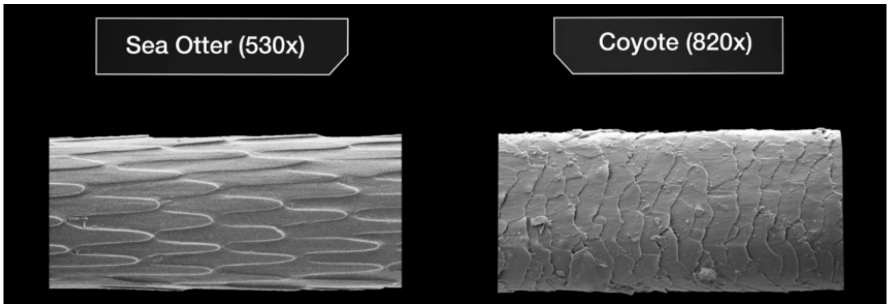

Figure 12. Comparison of Guard Hair Structure in a Sea Otter and Coyote.

Note for Figure 12: The regular surface texture of the sea otter hairs allows them to interlock under pressure, unlike the coyote hairs.

Potential solutions to this limitation can be found in mission design and in technology development. In terms of the former, it is worth noting that a large portion of an Artic dive mission would likely occur within the confines of the delivery vehicle, which would often operate at shallow water depths. Hence, the risk of air layer loss during this portion of the mission, which has been cited as critical for Arctic diver performance, is minimal. Nonetheless, an additional margin can be gained via technology development to surpass the performance of guard hairs found in nature. Specifically, the surface texture of the hairs can be designed specifically to enhance the interlocking that occurs under hydrostatic pressure. Manufacturing of synthetic nanostructured furs with functionalized surface chemistry can potentially lead to significant improvements over the air trapping observed in animal furs.

2. Drag Reduction

The external layer of trapped air described in the previous section can provide an additional, significant advantage in viscous drag reduction, as water will slip past the air layer with minimal resistance as compared to solid surfaces. This reduced friction can enable reduction in energy expenditure during long swims, as well as a reduced hydrodynamic signature of the diver in the water (e.g., the diver wake) due to the smaller number of swimming strokes required to move a given distance in the water.

Although the effect of viscous drag reduction is increased for larger trapped air pockets (i.e., a larger fraction of the diver surface covered in air vs. the solid diving suit), the larger pockets are also more susceptible to rupture by hydrodynamic forces. These tradeoffs can be quantified to generate a design space and performance envelope for drag reduction via external air trapping. The first constraint of relevance is the requirement that the air pocket dimensions l_a must exceed the size of the viscous sublayer at the surface of the diver. Under these conditions, the presence of the air layer will affect the flow past the diver, leading to drag reduction. This constraint can be quantified as

$$l_a > 5y^+, \tag{4}$$

where y^+ are dimensionless viscous wall units, or equivalently and

$$l_a > \frac{10\nu}{U}, \tag{5}$$

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where ν is the kinematic viscosity of the water and U is the swimming speed of the diver. The competing constraint on the air pocket dimension is that the dynamic pressure at the air-water-solid interface must be supported by the surface tension σ at that point, lest the pocket collapse or rupture. This constraint can be expressed as follows:

$$l_a < \frac{\sigma}{\rho U^2}, \tag{6}$$

where ρ is the water density. Combining Eqs. 5 and 6, Figure 13 plots the map of viscous drag reduction (taken as the fraction of surface area occupied by air) vs. swimming speed and air pocket size. At small feature size and low swimming speed, the air pockets are too small to affect the flow outside the viscous sublayer. At higher speeds and larger air pocket sizes, the air layers become susceptible to instability. However, there remains a large region of parameter space in which substantial drag reduction could be achieved by external air layer trapping.

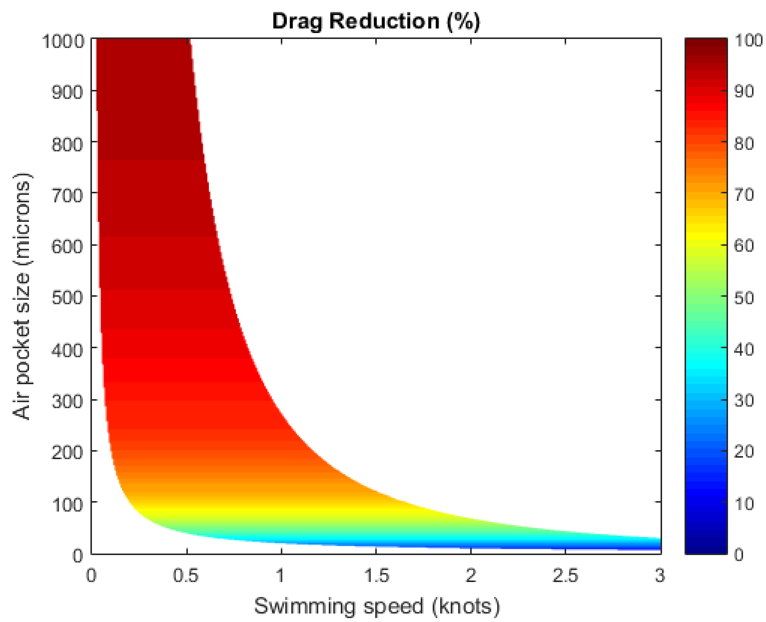


Figure 13. Drag Reduction for Combinations of Swimming Speed and Air Pocket Dimensions.
Note for Figure 13: Calculations assume minimum solid feature size of 50 microns.

It is important to note that hydrodynamic drag generally consists of a viscous component as well as form drag due to pressure imbalances on the fore and aft portions of the body. Given that the form drag is more difficult to affect, a companion strategy to air trapping must be a biasing of the hydrodynamic drag toward a regime dominated by viscous drag. This can be accomplished by streamlining the diver, either actively by affecting the swimming kinematics; or passively, via the use of a streamlined underwater diving shell. Both approaches are worthy of further investigation.

3. Advanced Thermal Management

3.1 Active Thermal Management

A next-generation suit could achieve dive persistence by employing active thermal management approaches to generate heat from stored fuel or from the environment to offset losses in the way that the hot-water wetsuit (Figure 3c), and active diver thermal protection systems (Figure 3d) accomplish, except untethered from a central energy source. There are two types of human-portable, active thermal management approaches considered in this Think Piece: (1) energy harvesting from the dive environment and (2) novel stored fuel or battery technologies for high power density thermal management.

3.1.1 Energy harvesting from thermal resonators

Energy harvesting from temperature fluctuations present in the arctic diving environment could provide a means for significantly reducing the net heat loss experienced by a diver, allowing for a drastically increased time frame before the onset of hypothermia. These temperature fluctuations may be due to the diver's movement throughout depths with different temperature distributions or they may be due to local temperature fluctuations caused by the mechanical work performed by the diver during swimming, for example near the diver's flippers. Such thermal resonators are conceptually new, and recently invented at MIT. Thermal resonators are devices capable of harvesting energy and generating electrical energy from broad band temperature fluctuations. They are based on highly nonlinear heat conducting elements – thermal diodes - that transform temperature fluctuations into single-polarity, persistent temperature gradients across a heat engine (e.g., a thermoelectric). An array of protruding thermal resonators on the outer surface of the diver's suit, or the backpack, the oxygen tank, and diver's flippers, such that the devices have minimized energy harvesting from the diver's body heat and a maximized exposure to the arctic environment, could accomplish the active thermal management required (Figure 14). The estimated maximum amplitude of temperature fluctuations that a diver may experience in an arctic environment is $\Delta T_{max} \approx 5$ ℃ [Ref. 12] (Figure 15). Engineering calculations can estimate the amount of heat per area that could be generated with this design in this environment. For a 1.5 cm x 1.5 cm bismuth telluride commercial thermoelectric, which has a Seebeck coefficient of approximately 8.5 mV/K and an internal electrical resistance of approximately 1 Ohm, the maximum expected power generation (heat generation) per area (p_{max}) can be found from a contour plot showing the solution of the transient heat balance. This solution can be plotted and used for optimal thermal resonator design, as shown in Figure 16.

$$V_{max} = (q\Delta T_{max})\left(8.5\frac{mV}{K}\right) = 34\ mV$$
$$P_{max} \cong \frac{V_{max}^2}{R} = 0.0012\ W$$
$$p_{max} = 5.1\ W/m^2$$

This value assumes that the area of the thermoelectric module (1.5 cm x 1.5 cm) is representative of the entire thermal resonator. The average rate of heat loss for a diver in a 5 mm thick wetsuit in 5 ℃ water is 32 W/m^2 [Refs. 2, 14–16] Therefore, as a rough calculation, this approach has the potential to compensate for close to 20% of the body's heat loss per area.

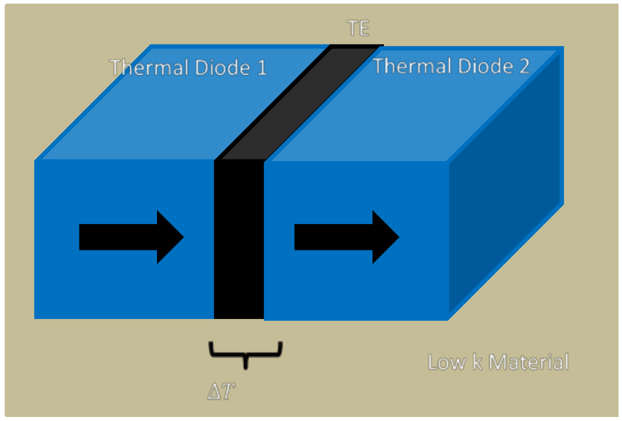


Figure 14. Illustration of the Incorporation of the Thermal Resonator onto the Surface of the Diving Suit as an Array of Fins.

Note for Figure 14: With this design, harvesting body heat (undesired) is minimized and exposure to the ambient environment is maximized.

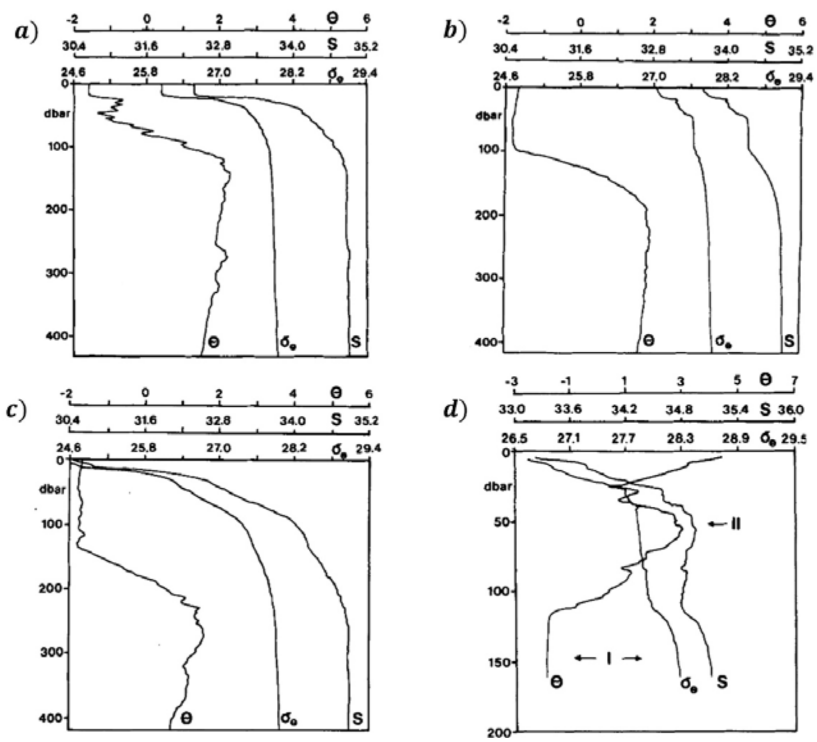


Figure 15. Potential Temperature (θ), Salinity, and Density Profiles for a) the Frontal Zone North of Svalbard b) the Sofia Deep North of Svalbard c) the Northern Fram Strait and d) Storfjorden. [Ref. 12].

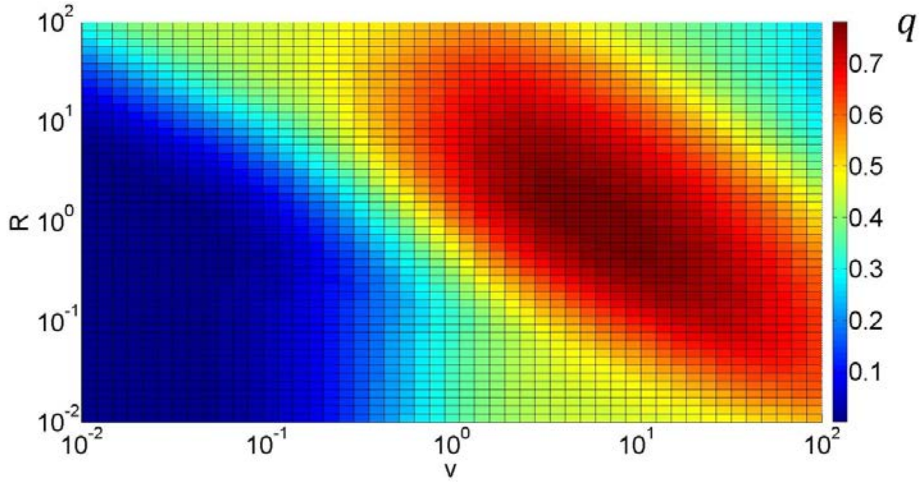


Figure 16. Contour Plot Guiding the Optimal Design of a Thermal Resonator Given the Ratio of thermal Diffusion Time Scales for Both Diodes (R) and the Dimensionless Temperature Oscillation Frequency (v). The Performance Factor (q) Is Defined as $q = \frac{|\Delta T|_{avg}}{\Delta T_{max}}$ [Ref. 13].

3.1.2 High power generation heat generation via seawater-driven thermopower waves

Thermopower waves are self-propagating reactivity waves along an electrically conductive nanoconduit, producing high power density pulses. The concept of using Al metal as an undersea fuel or electrode has been attractive because of its direct reactivity with seawater at low temperature: $2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2$ which produces a ΔH of -277 kJ/mol and ΔS of 26.2 J/K-mol. This reaction is inhibited by a coherent layer of Al_2O_3 which rapidly forms on reacting Al, thus reducing its surface area and power generation. The key to introducing and maintaining the reaction of aluminum with water is the continual removal and/or disruption of this coherent/adherent Al_2O_3 layer. The use of Mg/Al mixtures, hydroxide promoters [Refs. 17–18], oxide promoters and salt promoters has been explored to mitigate this problem. Since the 1970s, people have discovered that the reaction kinetics can be promoted via amalgamated aluminum surfaces [Ref. 19], and it has also been shown that Mg/Al mixtures have great reactivity in the presence of sea water [Ref. 20]. More recently, investigators have demonstrated the potentials of hydroxide promoters, where a much increased reaction rate was found when NaOH is present [Refs. 21–22], oxide promoters, where a mixture of Al and Al_2O_3 powders was shown to be reactive with water in the pH range of 4-9 at temperatures of 10°C–90°C [Ref. 23], as well as salt promoters, in which significant improvement of reactivity can be achieved when Al powder were ball-milled together with NaCl/KCl salts at slightly elevated temperatures [Ref. 24–25]. Furthermore, research has suggested a rapid heating and cooling thermal shock treatment of the aluminum leads to an improved reactivity with water [Ref. 17]. The concept of using reactivity waves, which transiently react the Al quickly before inhibition can proceed has high merit, and recent literature shows that rapid heating and cooling thermal shock treatment of the Al leads to an improved reactivity with water. It would be useful to explore seawater powered thermopower waves as a means of augmenting the power generation of the above resonator technology to further reduce thermal losses.

With all of these technological advances, an underwater heat jacket powered by electricity generated using thermopower wave [Ref. 18] is attractive. Carbon nanotube fibers, containing dispersed NaCl/Al powders directly exposed to sea water can generate high power density waves for thermal management. One form factor includes a carbon nanotube conduit that has a removable insulating cover that seals the sea water from a mixture of NaOH/Al/Mg powder coated onto the tip of the conduit. When desired, the diver can trigger the removal of the insulating layer at the tip and that sets off a reaction wave that will generate an average power of 2.15 W per cell, lasting around 5 seconds per cell. Considering the relative small form factor of the device (5 cm by 1 cm), such approaches can achieve high energy as well as power density (average 4.3 kW/m^2).

3.2 Phase Change Materials

Integrated thermal protection systems are ideal to augment the diving suit advanced neoprene insulation by providing heat to the diver. While tethered thermal diving suits have existed for years in the Navy, untethered thermal systems are also desirable in order to allow divers to move more independently during a mission. There are several technologies that can be used to provide heat to the diver which include electrical resistance heaters built into the suit, thermochemical systems that provide temporary heat through exothermic reactions (see Section 3.1.2), as well as heat pumps. While the thermochemical systems do not require a battery source, they are limited in terms of lifetime and must be discarded once they are exhausted. Electrical resistance heaters and heat pump systems operate on battery power and thus are limited by the energy storage of the batteries. While the operational time of the systems are limited by the batteries, the use of Li-ion batteries allows the power source to be recharged, and the system reused unlike the thermochemical heating systems. Therefore, both resistive heating and heat pump heated diving suits have a distinct advantage over thermochemical heating.

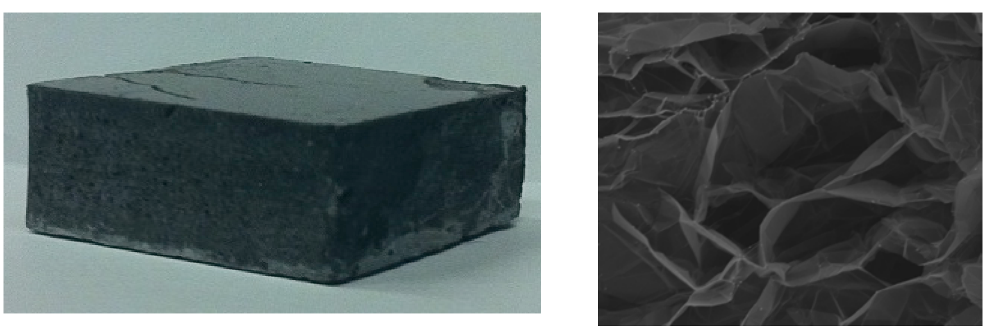
When comparing resistive heating to heat pump systems, the use of heat pumps provide a more efficient use of the electrical power. For a typical heat pump, a coefficient of performance close to 3 should be expected which means 100 W of electrical power will produce 300 W of heat. For an electrical resistance heating system, it would take 300 W of power to produce the same 300 W of heat. Thin-film electrical-resistance heaters have small form factors that fit easily into the diving suit and glove, and thus do not impede the movement of the diver due to their flexibility. The heat pump is much larger as it requires a heat exchanger to circulate warm fluid through the diving suit. Thus, tubes are placed inside of the diving suit in order to circulate fluid and their tube diameter is designed to minimizing the pressure drop. Overall, this approach seems quite promising. The development of a 400-W heat pump system for Navy divers by Rini Technologies has been supported by the Office of Naval Research (ONR) (Figure 17). The system is enabled by an efficient small form factor compressor that enables the miniaturization of the system to a size that can be easily carried by a diver. The system has a pump and heat exchanger in order to circulate warm fluid through the diving suit and the temperature (75°F–95°F or 24°C–35°C) can be selected by the diver. The compressor and pump are powered by a 14.8-V Li-ion battery pack that is rated to last greater than 3 hours. To last longer, a second battery pack can be attached and is hot swappable underwater.

While heated diving suits with compact thermal sources like those shown in Figure 17 are under development, a risk still exists if the unit were to fail. In this case, the diver would only depend on the thermal protection of the neoprene insulation of the suit which can be improved dramatically as discussed in Section 1.1. As a further precaution, it is possible to increase the thermal mass of the diving suit in order to increase its thermal time constant in response to the cold water, if power to the heating unit were to fail. In order to effectively increase thermal mass of the system, we propose using phase change thermal storage materials, especially in areas where hypothermia can impact the diver, namely around the head and limbs where the majority of heat is lost.

Figure 17. Components of the Heat Pump Thermal Diving Suit Made by Rini Technologies with Support of the ONR.

Note for Figure 17: From left to right: the compact heat pump system; the battery pack; the diving suit with tubes to carry fluid from the heat pump and heat exchanger; the entire unit assembled with air tank for diver.

Due to their large capacity to store thermal energy, phase change materials (PCMs) have been used to store waste heat as well as change the thermal mass of building materials used for homes in order to maintain a small temperature fluctuation inside regardless of the outside temperature and weather conditions. This is in effect what we seek to employ in emergency situations for the diver. Since the phase change process is nearly isothermal for PCMs (depending on the purity and type of phase change material), it is possible to reduce the rate of change of temperature in the diving suit although heat may be lost to the environment. By using organic materials, the phase change temperature can be selected based on the molecular weight (chain length) and side groups of the material. In addition, the thermal conductivity of the PCMs can be augmented through the creation of PCM-graphite nanocomposites where compressed expanded natural graphite is used as the filler material for the PCM. The materials can be molded into specific shapes and sealed in flexible containers to create “thermal pads” that can be inserted into the diving suit when needed. When used in nanocomposite form, the graphite holds the shape of the PCM even when the PCM has melted (Figure 18). Moreover, the material is machinable allowing maximum flexibility in creating complex shapes, if desired.



(a) **(b)**

Figure 18: (a) Image of a paraffin-compressed expanded graphite composite for thermal storage; (b) scanning electron microscope (SEM) image of the expanded graphite nanoplatelets.

For thermal storage, we will consider using a paraffin wax that has a phase change temperature near the body’s temperature (37°C) with only a small amount of compressed expanded natural graphite. The graphite is included to absorb microwave energy. Thus, the phase change materials can be quickly “charged” by using a simple microwave heating process and then placed inside of the diving suit in critical areas before entering the water (e.g., in gloves, along legs, around the head).

For analysis, we used finite element modeling to determine the impact of paraffin wax composite thermal pad underneath a neoprene shell on the temperature felt by the skin. For this system, the neoprene shell was assumed to be the conventional material used today without the advanced augmentation to reduce thermal conductivity as discussed earlier. Figure 19 shows the properties and boundary conditions modeled in the system.

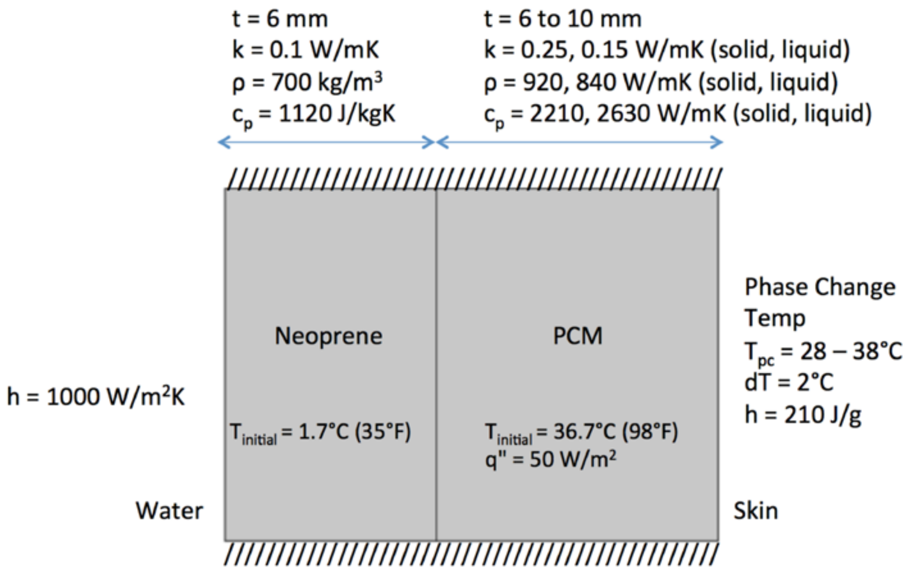


Figure 19: Properties, Boundary and initial Conditions Used to Model the Transient Temperature of the Neoprene/Paraffin Layered System.

Note for Figure 19: The water temperature of 1.7°C (which is also the initial surface temperature of the neoprene) is assumed while the PCM is initially at the body temperature of 36.7°C. The human body is supplying a heat flux of 50 W/m^2 to the backside of the PCM during the process.

Figure 20 shows a plot of the temperature next to the skin (back side of the paraffin) as function of time for an 8-mm thick paraffin wax layer with varying phase change temperatures. This is a conservative calculation as other layers and thermal resistances would exist in a real system which would enhance the performance. The data in Figure 20 assumes that the system will stay melted at the body temperature of 36.7°C and several PCMs with different melting temperatures are used. The thermal boundary condition outside of the suit is a water temperature of 1.7°C. What can be seen is that: (a) if no PCM material is used, the temperature next to the skin falls rapidly over the course of the first hour reaching a final temperature of approximately 5°C; (b) if a PCM with a melting temperature that is higher than the body temperature is used (38°C) the low thermal conductivity of the PCM provides very little thermal benefit as compared to the simply neoprene case; and (c) any phase change material with a melting temperature below 37°C provides thermal protection for the diver. Materials with a phase change temperature of 28°C–30°C maintain a temperature in the range of the phase change for more than an hour while PCMs with a phase change temperature greater than 34°C are also able to maintain an acceptable temperature next to the skin for an hour. However, their temperatures begin to rapidly drop after 1 hour due to the full solidification of the PCM at this point and loss of effective thermal mass.

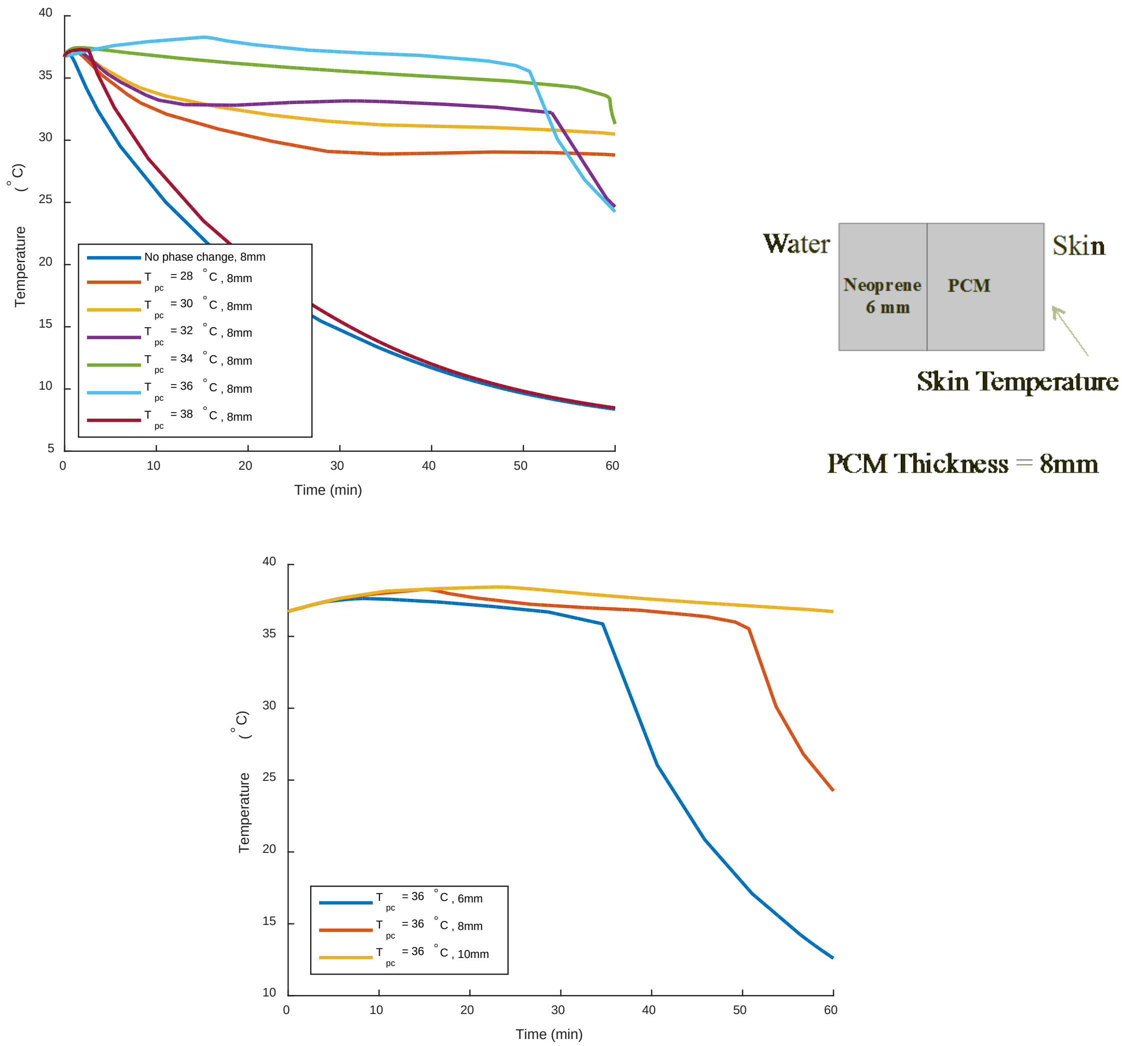
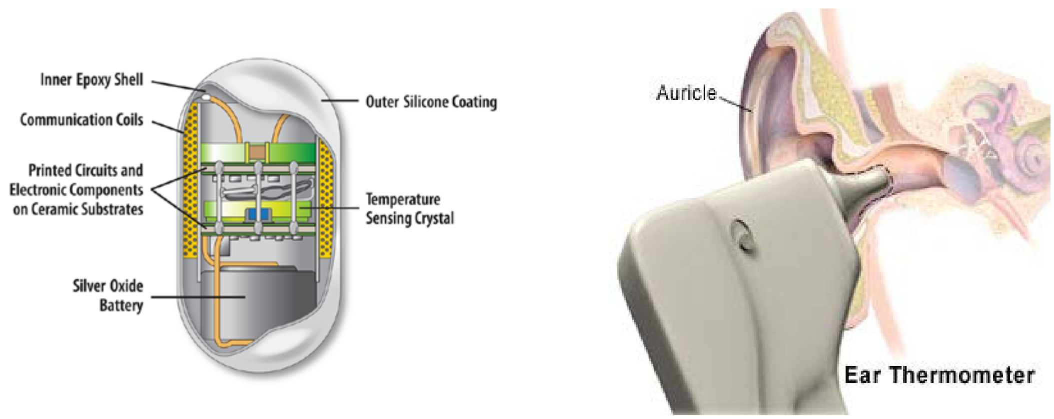


Figure 20. (Top) Plot Showing the Transient Temperature Next to the Skin as a Function of Phase Change Temperature (Fixed Thickness of 8 mm); (Bottom) for Variable Thickness (fixed Phase Change Temperature of 36°C).

Overall, the data show that it is possible to provide the diver with at least an hour of emergency protection if the heated suit fails due to the added thermal mass of the PCMs. In addition, the amount of emergency thermal protection scales with the thickness of the PCM. As shown in Figure 20, a 6 mm PCM will provide up to 40 min of protection if a “skin temperature” of 25°C is set as the limit. The 8-mm paraffin wax system provides 1 hour, while the 10-mm system is greater than 1 hour.

Measurement of core body temperature of the diver is also a concern, which has not been addressed in Navy systems. This is critical since a drop in core body temperature can result in loss of consciousness or even death in a diver. However, the most accurate methods of measure core body temperature (e.g., rectally) are not conducive to the activities of a diver. For medical purposes, it would be ideal to have measurements from both the core of the body and in the head to make the appropriate assessment of the state of the diver. To perform this task, we propose to use temperature probes that can be swallowed by the diver to measure the core body temperature and a tympanic membrane infrared (IR) thermometer to measure the temperature in the head. Today, there are commercially existing sensors that can be swallowed and provide body temperature through a radio frequency (RF) transmitter (Figure 21). Such a system could be augmented to fit Navy divers to provide temperature sensing capability that is read while underwater. The RF signal attenuation would be quite large underwater and thus leave the diver with low or null detection. To enhance this, we propose placing shielding inside of the diving suit in order to confine the RF signal and to provide the capability to turn off the device by the diver by sending an RF signal to the device. Once the device has been turned off, it cannot be turned on again. This will allow the diver to turn off the transmitter once reaching land, if such an option is necessary to help avoid detection.

The second thermometer will be built by placing a small fiber optic cable in headphones which are placed in the ear canal (Figure 21). The headphones will allow for any audible communications that the diver needs to have while providing for the ability to collect IR energy from the tympanic membrane. This will be fed back into a detector that can then provide temperature inside of the head during a dive. A drop in core body temperature would then be displayed as a simple warning light on a dive watch or inside of the goggles of the diver in order to allow them to take appropriate precautions before suffering severe hypothermia.



(a) (b)

Figure 21. Example of a small temperature sensor that can be swallowed and transmit core body temperature from BMedical, Inc.

Note for Figure 21: an example of an IR temperature sensor (a) using the tympanic membrane (b).

3.3 Battery-Life Extension

To maintain the power capacity of the Li-ion batteries during cold water operation, it is possible to insulate them with PCM materials as already discussed with the inserts for the diving suit. However, in this case, we need to be able to dissipate more thermal energy in order to help maintain the batteries in an operational range of 25°C–45°C, which is ideal for Li-ion systems. In order to prevent overheating of the batteries, we will utilize larger amounts of the compressed expanded natural graphite in order to make a material with a phase change of 35°C, but with a thermal conductivity in the range of 10–20 W/m-K. This paraffin can be molded around the batteries and placed inside of the normal water sealed plastic housings currently used today for batteries. Preliminary calculations show that it is possible to maintain the temperature of Li-ion 18650 cells in the 25°C–45°C temperature range, depending on the thickness of the PCM and temperature of the surrounding water. Another option is to utilize the heat pump heating system to provide a thermal source to keep the batteries warm. This however, adds some complications to the design, but is doable from an engineering point of view.

Conclusions

Drawing initial inspiration from animals that survive and thrive in frigid waters, we have explored several technology innovations that could be incorporated into an advanced diving suit system to keep cold-water divers and their equipment warmer for longer time, and help them swim more efficiently. Such innovations include:

- A modified neoprene material that increases the thermal resistance of standard neoprene by a factor of 3;
- Fur-like air-trapping coatings that provide some additional thermal insulation, and importantly reduce the viscous drag of a diver by as much as 90%, thus enabling more efficient swimming by the diver;
- Thermal resonators that can harvest energy from temperature fluctuations in the water and supply heat to the diver;
- Thermopower waves based on seawater-driven exothermic reactions that can safely deliver heat to the diver;
- Phase Change Material (PCM) pads that can mitigate the consequences of diving suit failure as well as extend the lifetime of the batteries and electronics carried by the divers;
- Miniaturized temperature sensors that can monitor the core temperature of the diver.

While the above findings are based on rough, order-of-magnitude estimates, they provide sufficient motivation for a more systematic investigation of the ideas contained in this Think Piece.

Acknowledgements

The following individuals are gratefully recognized for sharing their knowledge and suggestions with the authors:

- **Dr. Bill D'Angelo**, Undersea Medicine Program, Warfighter Protection and Application Division, ONR
- **Dr. Martin Jeffries**, Arctic and Global Prediction Program, ONR
- **Dr. Dennis Kowal**, Science and Technology Division, IDA
- **Dr. Maria Medeiros**, Sea Warfare and Weapons Department, Sea Platforms and Weapons Division, ONR
- **Dr. Jeremy Teichman**, Science and Technology Division, IDA
- **Dr. Matt Weingart**, Deputy Program Director, Defense, LLNL
- **Dr. Chuck Amsler**, Science Diver, University of Alabama at Birmingham
- **John Heine**, Diving Safety Officer, U.S. Antarctic Program, NSF
- **Roger Kuhn**, Science Advisor, ONR

References

[1] U.S. Navy. *The United States Navy Arctic Roadmap for 2014 – 2030*. Washington, DC: Department of the Navy, February 2014.

[2] Aguilella-Arzo, Marcel, Antonio Alcaraz, and Vicente M. Aguilella. "Heat Loss and Hypothermia in Free Diving: Estimation of survival Time under Water." *American Journal of Physics* 71, no. 4 (2003): 333–337.

[3] U.S. Navy. "Ice and Cold Water Diving Operations." In Chapter 11 *U.S. Navy Diving Manual*. Washington, DC: Commander, Naval Sea Systems Command, 15 April 2008.

[4] Grega, Michael G. Suit heater. U.S. Patent 3402708 A, filed June 27, 1967, and issued September 24, 1968.

[5] Yi, Jaeshin, Ui Seong Kim, Chee Burm Shin, Taeyoung Han, and Seongyong Park. “Modeling the Temperature Dependence of the Discharge Behavior of a Lithium-Ion Battery in Low Environmental Temperature.” *Journal of Power Sources* 244 (15 December 2013): 143–148.

[6] Bardy, Erik, Joseph Mollendorf, and David Pendergast. “Thermal Conductivity and Compressive Strain of Foam Neoprene Insulation under Hydrostatic Pressure.” *Journal of Physics D: Applied Physics* 38, no. 20 (2005): 3832–3840.

[7] Hamilton, R. L., and O. K. Crosser. “Thermal Conductivity of Heterogeneous Two-Component Systems.” *Industrial & Engineering Chemistry Fundamentals* 1, no. 3 (1962): 187–191.

[8] Nan, Ce-Wen, R. Birringer, David R. Clarke, and H. Gleiter. “Effective Thermal Conductivity of Particulate Composites with Interfacial Thermal Resistance.” *Journal of Applied Physics* 81, no. 10 (15 May 1997): 6692–6699.

[9] Anuraag R. Kansal, Salvatore Torquato, and Frank Stillinger, Computer Generation of Dense Polydisperse Sphere Packings.” *Journal of Chemical Physics* 117, no. 18 (2002): 8212–8218.

[10] Hwang, Shuen-Chen, Robert D. Lein, and Daniel A. Morgan. “Noble Gases” In *Kirk Othmer Encyclopedia of Chemical Technology*, 343–383. New York: John Wiley & Sons, 2001.

[11] Liwanag, H. E. M. “Fur vs. Blubber: A Comparative Look at Mammalian Insulation and Its Metabolic and Behavioral Consequences.” PhD diss., UC Santa Cruz, 2008.

[12] Rudels, Burt, Anne-Marie Larsson, and Per-Ingvar Sehlstedt. “Stratification and Water Mass Formation in the Arctic Ocean: Some Implications for the Nutrient Distribution.” *Polar Research* 10, no. 1 (December 1991): 19–31.

[13] A. Cottrill, S. Mahajan, A. T. Liu, and M. Strano. Manuscript submitted.

[14] Sarah Catherine Walpole, David Prieto-Merino, Phil Edwards, John Cleland, Gretchen Stevens, and Ian Roberts. “The Weight of Nations: An Estimation of Adult Human Biomass.” *BMC Public Health* 12 (June 18, 2012): 439–444.

[15] The Engineering ToolBox. “Human Body and Specific Heat.” http://www.engineeringtoolbox.com/human-body-specific-heat-d_393.html.

[16] MedicineNet.com. “Definition of Body Surface Area.” http://www.medicinenet.com/script/main/art.asp?articlekey=39851

[17] Watanabe, Maseo, Ximeng Jiang, Ryuichi Saito (Assignee: Dynax Corporation). Method for generating hydrogen gas utilizing activated aluminum fine particles. U.S. Patent 20060034756; filed August 4, 2005, and issued February 16, 2006.

[18] Choi, Wonjoon, Seunghyun Hong, Joel T. Abrahamson, Jae-Hee Han, Changsik Song, Nitish Nair, Seunghyun Baik, and Michael S. Strano. “Chemically Driven Carbon-Nanotube-Guided Thermopower Waves.” *Nature Materials*, 9, no. 5 (2010): 423–429.

[19] Smith, I. E. “Hydrogen Generation by Means of the Aluminum/Water Reaction.” *Journal of Hydronautics* 6, no. 2 (1972): 106–109.

[20] Gutbier, Heinrich, and Karl Hohne (Assignee: Siemens Aktiengesellschaft). Process for the generation of hydrogen. U.S. Patent 3,932,600, filed September 13, 1973, and issued January 13, 1976.

[21] Belitskus, David. "Reaction of Aluminum with Sodium Hydroxide Solution as a Source of Hydrogen." *Journal of the Electrochemical Society* 117, no. 8 (1970): 1097–1099.

[22] Stockburger, D., J. H. Stannard, B. M. L. Rao, W. Kobaz, and C. D. Tuck. "On-Line Hydrogen Generation from Aluminum in an Alkaline Solution." In P*rocedures of the Symposium on Hydrogen Storage, Electrochemical Society* 92 (1992): 1–44.

[23] Deng, Zhen-Yeng, José M. F. Ferreira, Yoshihisa Tanaka, and Jinhau Ye. "Physicochemical Mechanism for the Continuous Reaction of y-Al_2O_3-Modified Aluminum Powder with Water." *Journal of the American Ceramic Society* 90, no. 5 (May 2007): 1521–1526.

[24] Muñoz. A. G., and J. B. Bessone. "Pitting of Aluminum in Non-Aqueous Chloride Media." *Corrosion Science* 41, no. 7 (July 1999): 1447–1463.

[25] E. McCafferty. "Sequence of Steps in the Pitting of Aluminum by Chloride Ions." *Corrosion Science* 45, no. 7 (July 2003): 1421–1438.

Think Piece 5

A Call for a U.S. Biology Combatant Command (USBioCom): Exploiting Biotechnology Across All DoD Domains

by

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A Call for a U.S. Biology Combatant Command (USBioCom): Exploiting Biotechnology Across All DoD Domains

Manish J. Butte, Gregory S. Engel, Matthew DeLisa, Christina Smolke, Ryan Bailey

Executive Summary

The United States should have a Combatant Command, U.S. Biology Command (USBioCom), to engage the emerging threats and opportunities created by the explosion of biotechnology. "Bio-" must be viewed as "Cyber-" was viewed 25 years ago, and it can reasonably be expected to follow a similar trajectory. Bio- will quickly become a part of every military mission by improving human performance, confronting traditional biothreats, and detecting and attributing biothreats. Here, we examine the needs, requirements, mission, command challenges, and technical opportunities that will confront USBioCom. We focus on how USBioCom can improve Human Performance, Force Protection, Rapid Response to Biothreats, and Detection and Attribution of Biothreats.

Why U.S. Biology Combatant Command (USBioCom)? Why now?

The last century saw the dawn of the "Cyber-" age, and we are now facing the dawn of the "Bio" age. The U.S. Department of Defense (DoD) has traditionally viewed Bio- (construed broadly to contain biosecurity, bioweapons, and biodefense as well as biotechnology) as either Medicine or as weapons of mass destruction (WMD). The latter has been grouped with nuclear, chemical, and radiological threats. This view has to change. As a threat, **Bio- is far more similar to Cyber- than to Nuclear/Chemical/Radiological threats.** In particular, Bio- parallels Cyber- in the following specific ways:

- Bio- will inevitably become an integral part of every operation and will encompass not only operational security but also elements of enhanced human performance during the mission.
- Biological threats are typically discovered late and early detection ("left of bang") is critical to operational success.
- Bio- weapons can be employed by our adversaries in subtle ways to affect geopolitical power and economic power.
- Bio- threats can (quietly) self-replicate both in the theater of operations as well as on the home front.
- Attribution of biological agents is extraordinarily difficult.
- Bio- threats occur naturally as well as maliciously and thus an incident in the United States is NOT obviously an act of war.
- Containment of biological threats requires severe restrictions of motion that are impractical and may not have a basis in the law, especially with regards to people who have been exposed but not infected, those within an incubation period of the infection, and those who carry latent but minimally communicable infection.

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- Bio- faces similar (but legally distinct) policy challenges to cyber that limit our ability to make and test offensive technologies and therefore means that the U.S. lacks a trained bio-workforce focusing specifically on DoD problems.
- Response to a biothreat is not clear and proportional/symmetric response is not obvious. Therefore deterrence is not well-defined.

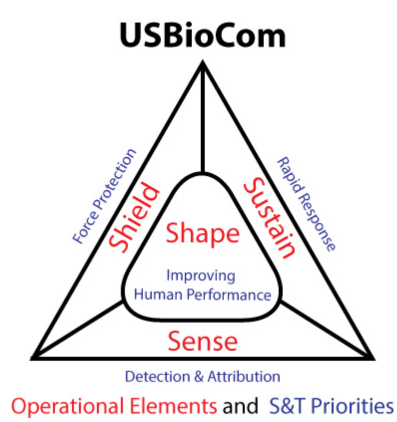
There is at present a lack of coordination of biology efforts in DoD. Currently, biodefense, biotechnology, and biowarfare efforts are housed in a series of small overlapping agencies (Defense Threat Reduction Agency (DTRA)/Defense Advanced Research Projects Agency (DARPA)), offices (Office of Naval Research (ONR)/Army Research Office (ARO)), and commands (U.S. Army Medical Research and Materiel Command USMRMC)), each of which contributes to narrow aspects of the mission space within DoD. Meanwhile, civilian National Security Laboratories have small efforts in bio-space, but there is no clear coordinating body, no clear mission, and no clear pathway to operationalizing biotechnology in the absence of an extant threat. This space very much resembles cyber- in the late 1980s through the 1990s, with individual units and commands recognizing the need for action, sourcing their own narrow solutions, and relying on self-trained workforces assembled for specific tasks.

Just as U.S. Strategic Command (USStratCom) incubated and stood up U.S. Cyber Command (USCyberCom), **it is now time to envision a U.S. Bio- Command (USBioCom)**. This combatant command would integrate biodefense, biomarkers, biometrics, and biotechnology into existing operations, define force-level science and technology priorities for biotechnology, and would provide an integrated global security view of emerging biothreats, forensics, and human performance.

Mission Objectives for USBioCom

USBioCom should plan, coordinate, integrate, and conduct activities to

- Direct the defense of DoD personnel and resources from biothreats;
- Direct the development and integration of biotechnology into DoD operating procedures to enhance human performance, readiness and resilience; and
- Prepare to, when directed, conduct proactive defensive military biological operations to enable actions in all domains, ensure U.S./Allied freedom of action and deny asymmetric advantage to our adversaries.



Science and Technology Priorities for USBioCom

Bio- presents a rapidly emerging and specialized field, and DoD will have to interface with it first and foremost through the development and deployment of new technologies. To anticipate USBioCom becoming operational, the following science and technology (S&T) challenges need to be addressed:

- Improving human performance;
- Modification, monitoring, and manipulation of Human Biology (neurobiology, micro-biome, endurance, clotting, wound healing, trauma response);
- Identification of soldiers at risk (e.g., subclinical heart conditions, maladaptive stress responses leading to susceptibility to infection);
- Bioenhancement of humans (e.g., sleep, oxygen, bio-enhancing drugs, visual acuity);
- Force protection and rapid response to biothreats;
- Battlefield medicine-on-demand using synthetic biology;
- Rapid vaccination potential (production, dissemination, monitoring);
- Identification of risk-factors within the force;
- Mitigation of cytokine storms during severe infections;
- Detection, attribution and counter-proliferation of biothreats within the United States and abroad;
- Improved bioinformatic filters for annotating sequence data in the context of biosecurity;
- Improved signatures for disease (i.e., pre-symptomatic and asymptomatic indicator of infection, trajectory of illness); and
- Improved metrics for contagion.

Command Structure of USBioCom

To ensure a consistent effort in protecting the homeland and the military, USBioCom should be dual-hatted with the Department of Health and Human Services (DHHS). For example, one logical connection might be with the Assistant Secretary for Preparedness and Response (ASPR) at the DHHS, a post currently held by a uniformed member of the Public Health Service. In particular, mission overlap will include public outreach and training of first-responders, coordination of acquisitions and research and development (R&D), defense of the homeland, non- and counter-proliferation efforts, and domestic and international monitoring.

Existing Policy and Authority Landscape regarding Biosecurity, Biothreats, Biodefense, and DIY Bio

The Biological Weapons Convention (BWC) forbids the development, deployment and use of biological weapons [1]. Existing national policy on biosecurity flows from Executive Order 13486 forming a working group to coordinate policy aspects of biosecurity and biodefense [2]. The report from this working group specifically focuses on use of the Select Agent program as the policy vehicle to improve biosecurity [3]. We are explicitly not recommending changes to the existing legal or policy landscape, but rather attempting to highlight the following points:

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- Separate but overlapping authorities amongst domestic entities has led to robust legal policy but does not currently serve DoD needs for integrated and responsive biotechnology/biodefense capabilities. The patchwork of domains can be illustrated clearly by examining the diversity of participants within the working group, such as DHHS, DoD, the Department of Commerce (DOC), the Department of Justice (DOJ), the U.S. Department of Agriculture (USDA), the Department of Homeland Security (DHS), the Department of Transportation (DOT), the Department of State (DOS), and the Department of Energy (DOE); the Director of National Intelligence (DNI), the Office of the President, the Environmental Protection Agency (EPA), and the National Science Foundation (NSF).
- Most of the regulatory policy regarding Select Agents focuses on legal process and proper procedure. Individual agencies have action plans for scenarios involving defense, quarantine, surveillance, delivery of critical services, etc.
- Forward-looking approaches to biotechnology and biosecurity exist in most agencies but no framework exists to mobilize technologies from these efforts.

Within DoD presently, operationalizing technologies from USMRMC, DARPA Biotechnologies Office (BTO), DTRA, and the National Nuclear Security Administration (NNSA) labs would likely fall to U.S. Northern Command (USNorthCom) or USStratCom [4]. These commands are hardly equipped to roll out new biotechnologies, very much analogous to the situation with Cyber in the late 1990s or early 2000s.

Emerging policy on research such as “Gain of function” research on which a temporary moratorium has been imposed [5] has clear consequences for DoD. Yet, these policies with significant impacts on competitiveness in national security arenas are largely being argued on the basis of civilian medical research. This particular area of research will be particularly important for DoD science for biodefense such as vaccine production [6] and for understanding evolution escape mutants under natural selection as compared to laboratory-based selection pressure or engineering. Gain of function research will also be useful for red-teaming exercises against emerging threats, both natural and man-made.

Selected Priorities and Opportunities for Science and Technology in USBioCom

Improving Warfighter Performance

Modification, monitoring, and manipulation of the commensal biome to identify soldiers at risk

Identifying sick soldiers before the onset of symptoms will dramatically improve reaction to illness, epidemic, and overall readiness. Commensal bacteria populations react and adapt to changing environs and to pathogenic invaders. Often, cues from the commensal biome trigger immune response that we associate with sickness. By engineering the biome to offer fluorescent markers such as green fluorescent protein (GFP) at the same time that it cues the immune system, we could enable simple, inexpensive surveillance to prevent the spread and severity of infection. For example, GFP in a solid waste stream could immediately portend abnormal health conditions and flag a soldier/unit for further evaluation.

Bioenhancement of humans

Improving the fitness and readiness of warfighters using reversible cues that emulate endogenous signals is likely to have better compliance than the use of stimulants. We envision that engineered organisms can provide a number of avenues of improving the condition of warfighters.

Mounting evidence suggests that the commensal biome may be linked to sleep both in the sense that the biome may provide a record of rest/readiness and that it may influence the need and cues for sleep. Understanding and manipulating these interactions may provide new avenues to improve human performance, reduce the impacts of shorter sleep cycles, and to select pilots/ soldiers based on empirical readiness.

Diarrheal illnesses or indigestion affects troops in the initial weeks after deployment overseas, which increases the risks of dehydration or general unreadiness. These illnesses occur because the gut biome has to change its populations to suit the local flora. Simple, effective fecal transplants using triple capsules can seed the gut with local flora ahead of time. These capsules could be given to troops deploying around the world, thereby preventing most of this morbidity. This already Food and Drug Administration (FDA)-approved technology would allow us to provide common, location-specific bacteria to units prior to deployment. For example, airborne units and submarine units that anticipate close personal contact during the coming weeks/months can avoid sickness that may affect unit readiness.

Manipulation of the lung bacteriome and virome to produce synthetic antibiotics in response to infection, to heal small air leaks after penetrating chest injury, and to produce surfactants after near-drowning incidents. The lung biome could be engineered to synthesize nitric oxide or beta-adrenergic agonists during periods of low oxygen These technologies have obvious dual-use benefits for asthma and pneumonias.

There is evidence that short-term stress is beneficial for a variety of performance measures, but long-term stress leads to dysfunction across a variety of systems including the immune system and endurance. Measuring long-term stress is currently difficult and rapid screening is all but impossible. We suggest that long-term stress impacts the biome through changes in the metabolic substrates they utilize and in the metabolic byproducts they produce. One might be able to use fast screening technologies such as polymerase chain reaction (PCR) or paper strip tests to screen warfighters for biomarkers of long-term stress. In the short-term, highly stressed warfighters would be excluded from combat and referred to psychological care. Long-term impacts could include reduction of PTSD and suicide.

Force Protection and Rapid Response to Biothreats

Synthetic biology is leading to new capabilities in engineering biology; in particular, the deployment of biology as an advanced manufacturing platform. Biological systems are being engineered to produce increasingly complex and valuable small molecules, macromolecules, and materials. Advanced biomanufacturing is fueled by advances in deoxyribonucleic acid (DNA) sequencing, DNA synthesis, and tools for functionally expressing large numbers of proteins in engineered host cells. These capabilities can be developed to enable rapid response to biothreats and force protection.

Battlefield medicine-on-demand

Rapid and immediate access to medicines is critical to our soldiers. Recent advances have been made in engineering biological organisms to make biologics and small molecule medicines. Opportunities exist for extending these advances to platforms that will support medicine-on-demand either in situ or on site. The following therapeutic activities are of particular interest: antibiotics, antivirals, anti-malarials, protein-based biologics, painkillers (opioids), epinephrine, clotting factors, and small molecules to protect against reperfusion injury. A number of platforms for production and delivery are envisioned such as engineering commensal flora communities for in situ and programmable production of medicines, phage-based programming of commensal microbial flora for drug production, or modification of human cells for on-demand medicine production. As one example, commensal bacteria in the lungs could be infected with phage designed explicitly to produce neuro-protective small molecules such as theanine (one enzymatic step from glutamate) [7]. Theanine can thus help to prevent reperfusion injury during transport of critically wounded and thereby extend the “golden hour” for these warfighters.

New materials from synthetic biology

Biomanufacturing platforms also provide new strategies to produce unique materials with valuable properties that cannot be achieved effectively through other synthesis platforms. Examples of materials of interest include adhesive materials that work when wet, novel wound healing materials, and high tensile-strength materials will be important in protecting our forces. Strategies may be based on engineering microbial hosts or microbial communities to convert simple feedstocks into building blocks for such materials or assemble such building blocks into these materials. In addition, strategies for the engineering of plant hosts for the efficient manufacturing of novel materials are envisioned.

Rapid capabilities for vaccines including production, dissemination, and delivery

Contagious viral vectors for distributing vaccines can help both military and foreign populations deal with endemic disease by making the cure as transmissible as the disease. Viruses that encode proteins including antigens (for vaccination) or antibodies (for passive immunity) would possibly require less refrigeration, making wider dissemination possible. There are many dual-use applications for these kinds of technologies.

Mitigation of cytokine storms

As healthy young soldiers, DoD personnel are particularly susceptible to diseases that kill by initiating a cytokine storm. Indeed, some of the most virulent epidemics in recent history (e.g., Spanish Influenza in 1918; smallpox during civil war) emerged from military field hospitals that enabled rapid transmissibility among injured adults with hyper-functioning immune systems. Inhibition of cytokine storms may be best accomplished “left of bang” by pre-infecting populations with phage or viral vectors that will produce immuno-suppressants in response to infection. For example, production of IL-1 receptor antagonist protein may reduce the impact of surging IL-1b levels during sepsis.

Detection, Attribution and Counter-Proliferation of Biothreats within the United States and Abroad

Improved bioinformatic filters for annotating sequence data in the context of biosecurity

Intelligence from all sources is critical for early identification of biological weapons being developed. Unlike intelligence related to nuclear weapons, where clear "choke points" exist, identification of bad actors preparing biological weapons is extraordinarily difficult to filter from the stream of commercial activities that would occur, for example, in a pharmaceutical research group.

Leveraging Information, Big Data, and Bioinformatics. USBioCom would be charged to develop new methods and approaches to effectively integrate diverse sources of information to more accurately identify potential threats. Integration with intelligence community is key here. Future threats include more than just identification of DNA sequences that could indicate the malicious intent to assemble genes that encode for anthrax toxin. Rather, sequences that bear synonymous mutations would not affect the protein sequence but would elude bioinformatics detection of these sequences, as well as PCR-based methods. The intelligence gathering systems need to be aware of the Genetic Code, the set of rules by which DNA is encoded into proteins, so that such synonymous mutations in malicious proteins can be identified.

The battlespace contains microbiological ecosystems, animals, and plants. Biomarkers embedded within these organisms can surveil and shape the battlespace. Traditionally, tasks of this nature have been done by brute force using defoliants, but new capabilities can be created to provide asymmetric advantage to U.S. warfighters. For example, the passage of vehicles through a region may have an impact on gene expression in nearby plants due to exposure to diesel exhaust particles and fuel.

Thermodynamics of escape mutants: Guiding principles to assign likelihood of intent

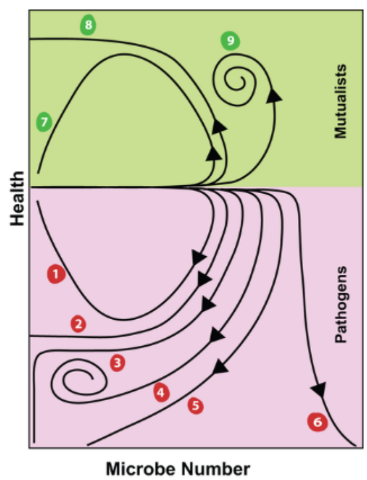
Intent will determine the appropriate military response to a biothreat whether it is encountered on the battlefield, in the agricultural economy, or in the homeland. We will require quantitative tools and metrics not only for attribution, but also to assess intent. Was the mutation willful or natural? Is this release part of a small-scale test? Was the pathogen created for nefarious purpose or simply for laboratory study? We need fast, quantitative tools to help us to assess intent. By exploiting phase-assisted continuous evolution (PACE), we can begin to build a thermodynamics and information theory of mutations. This work will help us to understand mutation patterns, natural evolution of pathogens in the field, escape mutants, and engineered mutations through CRISPR/Cas9 as well as traditional mutagenesis. We may even be able to predict evolutionary trajectories of pathogens in this fashion.

Identification of risk-factors within the force

Infections with incubation periods of a few days can have a serious impact on troops who are en route to the battlefield. Identifying the soldiers who are infected but pre-symptomatic is of particular interest. For example, soldiers from the 82nd Airborne who are infected and only become ill along the way of a 14-hour flight to battle can compromise everyone else on the plane and the mission. Sailors deploying on a submarine who develop an infectious diarrheal viral infection (e.g., norovirus) can compromise the health of the entire crew.

Improved signatures for disease (i.e., pre-symptomatic and asymptomatic indicator of infection, trajectory of illness)

Knowing which patients need escalation of care is an inherently reactive process at present, and results in states of unhealth that may be difficult or impossible to remedy. The grand challenge is to identify the trajectory of infections with sufficient accuracy as to correctly provide advanced care to those who require it *before* their condition worsens. What is the minimal number of measurable parameters, and at what point of the infection, that are needed to accurately gauge the trajectory of disease? There is a notion that the trajectory of disease can be at least partially gauged from measurable parameters [8].



There may be a large cost savings for society if we could correctly withhold expensive, advanced modalities when unnecessary. For example, 97% of middle ear infections will resolve without treatment, as seen in the pre-antibiotic era. Modern guidelines to avoid antibiotic treatment unless the subject is quite ill results in a savings of ~$4 billion.

For serious infections, early diagnosis and early provision of modern treatments are required for survival. Picking the right treatment necessitates knowing the cause of the infection so that one might choose a broad-spectrum antibiotic versus an antiviral. This dichotomy itself may be folly since we have known for decades that most sinopulmonary bacterial infections start as viral infections [9]. Nonetheless, the grand challenge for modern medicine is to identify the pathogen causing the subject's illness in a timely fashion. Our commensal bacteriomes and viomes live in dynamic equilibrium with invasive pathogens. They may share resources (carbon sources), other substrates for metabolic reactions, and even host cell tropism. The competition for these resources produces a signal that can be detected. By exploiting this signal we can detect the presence of viruses or bacteria. Resident viruses in the skin and GI tract include bacteriophage, polyomaviruses, and papillomaviruses. In the lung, these would include gammaproteobacteria, actinobacteria, and paramyxoviruses [10].

Early identification of contagious illnesses allows for quarantine, which spares unaffected troops from morbidity and mortality. Identifying an infection has occurred is typically reactive, waiting for symptoms to appear and become unambiguous before diagnosis or treatment is sought. This delay between infection and illness allows for the further spread of infections that are contagious prior to the onset of symptoms. We hypothesize that measuring the state of the infection through sampling of clinical parameters as well as the commensal microflora allows for prediction of the trajectory of infection. Microfauna may also be useful for this purpose. Infection with engineered parasites may permit temporary modification metabolism and introduction of novel biomarkers. Infection can be later cleared, and parasites do not multiply inside host—all human intestinal parasites require an outside organism to complete their lifecycle.

Improved metrics for contagion

For any infection, medical response depends first and foremost on containing the threat. The first question confronting every frontline physician is, “Is the patient contagious?” We know how to model contagiousness, but we do not know how to test for it prior to transmission. We do not understand the molecular basis for contagion or how to predict spread of infection “left of bang,” which represents a grand challenge for modern medicine. However, our immune systems have faced (and solved) this problem for millennia at the host level using commensal flora. Our commensal flora recognize infection and signal the immune system to respond. We must harness this same signaling to instruct our force-level medical personnel to respond in a similarly timely fashion.

For the purposes of maintaining public health and troop readiness, a major challenge in identifying the presence of an infection is to determine how infectious it is. Many viral infections are communicable by a single virion, whereas others in practice require a large inoculum to impart infection. In many bacterial and viral diseases, the pathogen continues to be shed long after the infection is clinically over, an evolutionary strategy that undoubtedly perpetuates the contagion, but also surprisingly can help the host maintain defenses. Detecting ongoing shedding presents a major challenge because it can cause new infections in troops, because it changes the requirements for contact, isolation, and transport of infected individuals, and because chronic infections lead to irreversible consequences of disfigurement, cancer, and autoimmunity.

Shedding has a major impact on human and agricultural infections: Over 95% of the infections by E. coli O157 of cattle were caused by ~10% of the most infectious animals [11]. Evidence from studies of shedding of Salmonella typhi, the causative agent of typhoid fever, after enteric infection show that 1%–2% of individuals will develop a long-term state of shedding and infection. Surprisingly, the host’s adaptive immune system does not play a major role in controlling the degree or duration of shedding after the infection is resolved [12]. Thus far, identifying the ongoing contagiousness of an ill individual has relied on detecting (and enumerating) the infectious particles emitted, e.g., determining the viral load of human immunodeficiency virus (HIV) in the blood; screening for respiratory viruses by PCR in the nasal secretions; measuring enteric pathogens in the stool.

Chronic shedding or permanent, latent infections may be beneficial to the host. By maintaining a heightened state of readiness in the innate immune system, chronic shedding can actually prevent subsequent infections from potentially more pathogenic organisms [13]. The feedback loops of interactions among the host innate and adaptive immune systems as well as the commensal flora create a delicate balance, and disturbances of this balance provide an opportunity to peer into the state of ongoing contagiousness.

We hypothesize that the signature of shedding or contagiousness is borne in the immune signatures and in the commensal flora of the host. The presence of certain molecules is evidence of ongoing disruption of the balance (e.g., RIG3g in the gastrointestinal (GI) tract, LL-37 in the skin). These molecules can be detected by synthetic bacteria or other sensors embedded into commensal bacteria. We believe that engineering a synthetic biology solution could identify such signals indicating disruption of the innate-commensal balance, and thus would indicate unambiguously the degree of ongoing contagiousness.

Prospective Benefits to DoD of Emerging Biotechnology

In times of war and in peace, the American warfighter is our most valuable military resource. Integration of biotechnology at all levels of the military will permit enhanced human performance, improved resilience of military units, and will improve likelihood of mission success while mitigating human costs. For example, engineering the human biome will allow us to surveil and improve human performance of the warfighter; biomanufacturing will permit scalable and rapid production of medicines and materials on demand in response to DoD needs; and developing new infectious biological agents to improve health of populations, an activity not prohibited under existing bioweapons treaties. We propose to form a new entity, USBioCom, to consider, fund, investigate, procure, and regulate these worthwhile biotechnologies for the benefit of both the U.S. warfighter and the populace.

References

1. Governments of the the United States pf America, the United Kingdom, and Russia. *Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on their Destruction*. New York: United Nations, 1972.
2. Bush, G.W. "Strengthening Laboratory Biosecurity in the United States.´ Executive Order No. 13486. January 9, 2009.
3. U.S. Department of Health and Human Services. *Report of the Working Group on Strengthening the Biosecurity of the United States*. Washington, DC: Office of the Assistant Secretary for Preparation and Response, 2009.
4. Department of Defense. *Joint Strategy for Biological Warfare Defense*. CJCSI 3112.01Washington, DC: Joint Chiefs of Staff. 22 May 2006.

5. "U.S. Government Gain-of-Function Deliberative Process and Research Funding Pause on Selected Gain-of-Function Research Involving Influenza, MERS, and SARS Viruses." Washiangton, DC: DHHS, October 17, 2014.

6. Ping Jihui, Tiago J. S. Lopes, Chairul A. Nidom, Elodie Ghedin, Catherine A. Macken, Adam Fitch, Masaki Imai, et al. "Development of High-Yield Influenza A Virus Vaccine Viruses." *Nature Communications* 6, no. 8418 (2015).

7. Deng, Wei-Wei, Shinjiro Ogita, and Hiroshi Ashihara. "Ethylamine Content and Theanine Biosynthesis in Different Organs of Camellia Sinensis Seedlings. *Zeitschrift für Naturforschung C* 64, nos. 5–6 (2009): 387–390.

8. Schneider, David S. "Tracing Personalized Health Curves during Infections." *PLoS Biology* 9, no. 9 (September 2011): e1001158.

9. Mills, Elaine L. "Viral Infections Predisposing to Bacterial Infections." *Annual Review of Medicine* 35 (1984): 469–479.

10. Lysholm Fredrik, Anna Wetterbom, Cecilia Lindau, HAnid Darban, Annelie Bjerkner, Kristina Fahlander, A. Michael Lindberg, et al. "Characterization of the Viral Microbiome in Patients with severe Lower Respiratory Tract Infections, Using Metagenomic Sequencing." *Plos One* 7, no. 2 (2012): e30875.

11. Chase-Topping, Margo, David Gally, Chris Low, Louise Matthews, and Mark Woolhouse. "Super-Shedding and the Link between Human Infection and Livestock Carriage of *Escherichia coli* O157." *Nature Reviews Microbiology* 6, no. 12 (December 2008): 904–912.

12. Gopinath Smita, Andrew Hotson, Jennifer Johns, GarryNolan, and Denise Monack. "The systemic Immune State of Super-Shedder Mice Is Characterized by a Unique Neutrophil-Dependent Blunting of T_H1 Responses." *PLoS Pathogens* 9, no. 6 (2013): e1003408.

13. Barton Erik S., Douglas W. White, Jason S. Cathelyn, Kelly A. Brett-McClellan, Michael Engle, Michael S. Diamond, Virginia L Miller, et al. "Herpesvirus Latency Confers Symbiotic Protection from Bacterial Infection." *Nature* 447 no. 7142 (2007): 326–329.

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Think Piece 6

Towards Ambient Armor: Can New Materials Change Longstanding Concepts of Projectile Protection?

by

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Title: Towards Ambient Armor: Can New Materials Change Longstanding Concepts of Projectile Protection?

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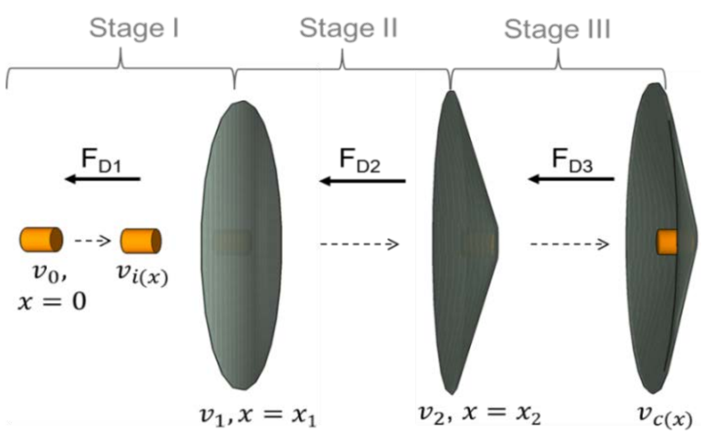
Executive Summary

Materials that protect against the high strain rate loading of a projectile have traditionally been constrained by their use on the target of protection. Here we explore the possibility of new materials, particularly carbon nanocomposites, for projectile protection removed off of the target, and placed along the trajectory at an intermediate location. In the case of light projectiles with low kinetic energy, a mathematical model of such Ambient Armor (AA) separates the impact, capture and energy dissipation of an incident projectile into each of three stages respectively. A distinct scaling of the projectile to composite area ratio, and areal density ratio is derived for a given requisite stopping distance. We consider the case where the projectile becomes embedded into the composite, and also the gyroscopic destabilization that proceeds when penetration occurs. As an example, the model in the former case predicts that a 1 g and 800 m/s projectile could be decelerated to 3 m/s within 6-9 m using a 2.34 × 10^4 layer monolayer graphene nanocomposite at 0.02 volume fraction. For heavier projectiles with higher kinetic energy, a tandem system using a second composite body with the specified area density is explored with the idea of making the projectile gyroscopically unstable for rapid deceleration and subsequent interception. Off target reinforcement or AA may in general allow for the exploration of a broader range of material properties for projectile protection.



Scheme 1. A schematic illustration of a simple three stage model of projectile interception with a free composite body. The projectile impacts the composite in stage I, traveling in the composite frame of reference in stage II, with F_{Di} as the drag force of the system in each stage and v_0 as the initial velocity of the projectile (x = 0). In stage III, the projectile is assumed to travel with the composite as a single mass experienced

increased drag. The trajectory along the gravitational direction is neglected. v_0, v_1, and v_2 are the velocity of the projectile at $x = x_1$, x_2, and x_3, respectively.

1. Introduction

Nanotechnology promises to enable new combination of material properties, leading to high strength to weight ratio nanomaterials with exotic structural performance and multiple functions to reinforce existing materials.[1, 2] There is significant interest in lighter and stronger materials, particular for protection against high strain rate loading of projectiles.[3, 4] The global ballistic protection market is $7.91 billion as of 2013 with 42% growth by 2020.[5] Personal protective armor systems alone are predicted to grow to $5.3 billion by 2024.[6] There is also significant interest in flexible, high strength systems that improve upon existing materials by decreasing weight requirements or increasing dexterity.[7, 8] Composite materials are emerging as contenders for these goals including models aiming for higher strength to weight ratio, penetration resistance, and flexibility.[4, 8, 9, 10] However, materials proposed and selected for this space are constrained by the traditional use of covering to being integrated with a target. For example, materials that undergo extensive elongation upon breaking are necessarily excluded due to unfavorable interaction with the target. Similarly, weight is a significant constraint for traditional protective materials associated with the target.[11-14] In this work, we explore an alternative protective strategy whereby the protective material exists as a free-body along the projectile trajectory distinct and a stand-off distance from the target, called *Ambient Armor*. We develop an approximate modeling framework highlighting new material opportunities that exist for protective systems in this space.

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Historic and existing reinforcement materials include glass-fiber reinforced polymer composites,[12] high stiffness fibers in the form of fabrics,[11, 13] and ceramics.[11, 14] Non-metallic armor made from glass-fiber reinforced polymer composites can adopt useful curvature and was widely employed prior to 1970.[12] High-stiffness polymer fibers and their fabrics including aramids like Kevlar and Twaron, the polyphenylene benzobizoxazole (PBO) Zylon, ultra-high molecular weight polyethylene (UHMWPE) Spectra, and polyhydroquinone-diimidazopyridine (PIPD) M5 have since been adopted due to superior ballistic protection and relatively low weight.[11] These fabrics are flexible and have high strength-to-weight ratio, e.g. PBO has a tensile strength of 5.2 Gpa, more than three times that of the strongest steel (piano wire) while its density is only 1/5 of the steel.[13] Such fabrics are able to significantly absorb projectile energy through elastic deformation. Meanwhile, the ceramic materials such Al_2O_3, SiC, B_4C and others have also been developed and applied for this purpose. Ceramics have superior hardness and toughness and relatively lower density (3~4g/cm^3) compared to steel. These materials also have an ability to blunt or fragment the tip of a projectile, augmenting ballistic protection.[11, 14] In spite of this progress, the net weight of such protective systems remains significant.[15]

New material concepts, such as those enabled by nanotechnology, offer new opportunities for addressing these problems. Nanocomposites promise new materials with superior stiffness (bulk and shear moduli),[2, 8, 10] greater strength, lighter density, and larger fracture resistance. Representative examples include natural fish armor and nacre,[16] synthetic polymer nanocomposites based on carbon nanotubes or inorganic fullerene-like nanoparticles (like WS_2 and MoS_2).[17] Over the past decade, efforts to create high-performance polymer nanocomposites yielded successful results.[18, 19]

Carbon nanotechnology, and graphene in particular,[19, 20] offers opportunities for nanocomposites because they can form the basis of high strength composite inclusions at low weight. Graphene is a one-atom thick (~ 0.335 nm), two-dimensional (2D) isotropic sheet comprising of sp^2-bonded carbon atoms in a hexagonal pattern.[21] An isotropic sheet or membrane has a critical penetration velocity approximately $\sqrt{2}$ times that of the traditional woven fabric with identical mass and tensile properties.[13, 22] Graphene is also known as one of the strongest material for mankind, the monolayer graphene has a density (ρ_G) of 2.2 g/cm^3, and a Young modulus (E_G) of 1 TPa, an intrinsic strength of 125 GPa at quasi-static testing conditions.[23] Its tensile wave speed ($\sim\sqrt{E_G / \rho_G}$) in plane is about 21.3 km/s, much higher than the 6.4 km/s of alumina and ever larger than 17.5 km/s of the diamond. Such a high wave speed is beneficial to the fast (in μs time scale) spread of the locally impact load and offer the best penetration resistance.[24] Recently, the dynamic mechanical behavior of multilayer graphene has been studied via supersonic projectile penetration, at extreme dynamic conditions, i.e. a high strain rate of $\sim 10^7$ s^{-1}, multilayer graphene with a thickness of 10 to 100 nanometers (30 to 300 graphene layers) has specific penetration energy ~10 times more than that of macroscopic steel sheets at 600 m/s.[25] Graphene also has a remarkable fracture strain (ε_{max}) of 0.25-0.30,[26] much higher than the ε_{max} values (< 0.04 typically) of the conventional armors consisting of polymer fibers, and thus graphene-based armor materials have higher resistance to perforation. Undoubtedly graphene may become one of the best nanoinclusions to fabricate high-performance nanocomposite materials for future light-weight armor.[22]

For body armor systems, even a projectile that is stopped without perforation, the rapid deformation of the armor plate upon high impact energy can still produce behind armor blunt trauma (BATT) to the thoracic and abdominal contents behind the plate.[27, 28] BATT is potentially life-threatening under high energy projectile impact.[27] Risk increases with decreasing armor weight and increased probability of deformation. How to dissipate the kinetic energy of the projectile and reduce or even avoid the BATT is therefore an important and emerging problem requiring innovative solutions in the design light-weight armor systems.[27]

In this paper, we demonstrate a new concept for projectile interception and protection which we tentatively call *ambient armor* (AA). Here, the concept is to use existing and new materials to defend against projectiles in a standoff capacity, using a variety of new mechanisms afforded by this arrangement. The approach is supposed to be differentiated from traditional armor concepts that focus on the target exclusively. AA is ideally removed from the target, at an intermediate location between it and the projectile source. Mechanistically, AA allows significant deformation and elongation at break, exceeding such limits for traditionally fixed armor and without causing any BATT. Hence, lightweight materials with large ε_{max}, for example, graphene, can be used optimally for this purpose.

One embodiment of the AA concept is interposing free composite bodies along the projectile trajectory and the target. Such composites could destabilize the projectile and/or capture/dissipate the kinetic energy of projectiles through different pathways,

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including increasing their drag coefficient in air. To explore this idea, we introduce physical models to estimate the velocity change and energy dissipation of the projectile/composite during and following the interception process and correlate them with the geometry and properties of the composites. We consider two cases depending on the size of the projectile: Case I uses a free composite body with required mechanical properties to intercept small projectiles and fragments with relatively low kinetic energy; Case II uses a common composite plate with more relaxed requirements on mechanical properties to gyroscopically destabilize larger and higher velocity projectiles with higher kinetic energy. For Case I, we propose two free composite body examples: a multi-ply fabric composite and multi-layer polymer/graphene nanocomposite to provide references to actual materials properties. For example, for the latter, the required graphene volume fraction and layer number can be estimated from the model, given current literature values for this system.[22, 26, 29, 30] Finally, AA system with a combination of the two types of composites from Case II and Case I, one destabilizes and one intercepts the projectile has been considered to defend large projectiles in a shorter distance.

2. Model Development

2.1. Case I

In this case, we consider using a free composite body armor off the target to directly intercept small projectiles with relatively low kinetic energy. We proposed a simplified model that segments the interception and energy dissipation into three stages. **Scheme 1** illustrates these stages, whereby a free composite body is assumed to intercept the projectile (stage I), and allow its embedment into the composite interior (stage II). The projectile is assumed to be a cylinder with a blunted nose and has a normal impact (attacking angle = 90˚). The deflection or the rebound of the projectile from the impacted surface (the so-called ricochet) is neglected explicitly. For the third stage, we first concern ourselves with the case where the projectile becomes lodged within the composite, with both moving as a single body, dissipating energy through an increased drag coefficient (stage III), because this is the case where energy dissipation can be greatest. Our model of this case is not designed to be a robust representation of how a projectile interacts with a wide range of free composite bodies, but merely to provide energetic bounds on possible energy dissipation with the goal of design.

Scheme 1

2.1.1. Stage I

The drag force (F_{D1}) that air exerts on a projectile in the direction of the flow velocity is given by Equation 1,[31]

$$F_{D1} = \frac{1}{2}\rho_{air} v_i^2 C_{d,p} A_p \tag{1}$$

with $\rho_{air} = 1.204$ kg/m^3 as the air density at 20 °C and 1 atm, v_i is the projectile velocity relative to air, $C_{d,p}$ is the drag coefficient of the projectile, depending on its Reynold's number Re and the Mach number Ma ($Ma = \frac{v_{object}}{v_{sound}}$). It is a constant at low Ma and Re when v_i is subsonic and increases at supersonic velocity, but remains less than 0.3 for

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common projectiles.[32] Hereby, we assumed $C_{d,p}$ = 0.295.[33] A_p is the projectile's cross-sectional area ($A_p = \frac{1}{4}\pi d_p^2$, d_p is the projectile diameter). The projectile velocity v_i is then:

$$a = \frac{\mathrm{dv_i}}{\mathrm{dt}} = -\frac{F_{\mathrm{D1}}}{\mathrm{M}_p} = -\frac{\frac{1}{2}\rho_{air} v_i^2 C_{d,p} A_p}{\mathrm{M}_p} \tag{2}$$

where M_P is the mass of the projectile, $M_p = \rho_p A_p h_p$, ρ_p and h_p is the density and height of the projectile, respectively. For convenience, the constant k_1 is:

$$\mathrm{k}_1 = \frac{\frac{1}{2} C_{d,p} \rho_{air} A_p}{\mathrm{M}_p} = \frac{\frac{1}{2} C_{d,p} \rho_{air}}{\rho_p h_p} \tag{3}$$

Then

$$\frac{dv_i}{dt} = \frac{dv_i}{dx} \cdot \frac{dx}{dt} = \frac{dv_i}{dx} \cdot v_i = -k_1 v_i^2 \tag{4}$$

$v_i = v_0$ at x = 0, therefore as expected for stage I,

$$v_{i(\mathrm{x})} = v_0 e^{-k_1 x} \tag{5}$$

2.1.2. Stage II

Momentum transfer and energy conservation: the projectile contacts the free composite body at $x = x_1$ ($v_{i(x_1)} = v_1$) at stage II and a rigid motion of the projectile and the composite with a same speed of v_2 at $x = x_2$ is assumed.[34] From momentum conservation,

$$M_p v_1 = M_p v_2 + m_c v_2 + \int_{t_1}^{t_2} F_{D2} t \tag{6}$$

where t_1 is the moment when the projectile travels to $x = x_1$, and t_2 is to $x = x_2$. The composite mass (m_c) should be comparable to M_p so that v_2 is not vanishing. To ensure a sufficient A_c for projectile interception and deceleration, the composite body is best to be a membrane/film with a relatively small thickness and we treated the composite body as a membrane in the following modeling process. It is useful to introduce two dimensionless design variables j and Γ_0, here, j is the cross-sectional area ratio of the composite to the projectile and Γ_0 is the areal density ratio of the composite to the projectile.[35]

$$j = \frac{A_c}{A_p} \tag{7}$$

$$\Gamma_0 = \frac{m_c'}{M_P} = \frac{\rho_c h_c A_P}{M_P} = \frac{\rho_c h_c}{M_p / A_P} = \frac{\rho_c h_c}{\rho_p h_p} \tag{8}$$

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where $m_c^{'}$ is the mass of the composite portion which has a same area of the projectile, h_c is the thickness of the composite, ρ_c is the density of the composite. To simplify, we neglected the contribution of air resistance in this stage:

$$v_2 = v_1 \times \frac{1}{1 + j\Gamma_0} \tag{9}$$

When the composite membrane impacted by a high-velocity projectile, only the portion that directly contacts the projectile first accelerates to the same velocity at $t = t_1$ due to instant momentum transfer.[13] Meanwhile, two waves form after the impact, one is the longitudinal (or tensile) wave and the other is the transverse wave. The longitudinal wave in 1D polymer fiber/yarn or 2D isotropic plane travels with a sound speed of

$$c = \sqrt{E / \rho} \tag{10}$$

where E is the Young's modulus and ρ is the density. The longitudinal wave velocity in the interwoven fabric is $\frac{\sqrt{2}}{2}c$, for example, due to the increased linear density of the yarns caused by crossovers.[36] This wave initiates the movement of the impacted portion in the fiber/yarn/membrane towards the projectile. The transverse wave, approximated as an inverted V, travels with a speed of U (in laboratory coordinates) or u (in a Lagrangian coordinate system) (I in **Scheme 2**). It drives the impacted portion to move in the same direction as the projectile. U is much smaller than c, the 1D fibers/yarns of a fabric composite under transverse impact, for example, is supposed to have U and u as shown in Equation 11 and 12, respectively.[37]

Scheme 2

$$U = c(\sqrt{\varepsilon(1+\varepsilon)} - \varepsilon) \tag{11}$$

$$u = c\sqrt{\varepsilon / (1+\varepsilon)} \tag{12}$$

where ε is the strain. If we treat the projectile impact ($v = v_1$) as a point impact, the initial strain ε_1 of a 1D fiber/yarn at t_1 (I of Scheme 2) is a constant as Equation 13 shows below.[37] The ε_1 of a 2D isotropic membrane can be also expressed with the same equation approximately.[13]

$$v_1 = c\sqrt{\varepsilon_1(2\sqrt{\varepsilon_1(1+\varepsilon_1)} - \varepsilon_1)} \tag{13}$$

If ε_1 is less than the ultimate tensile strain (ε_{max}) of the first fiber/yarn/layer of the composite body, the strain fast spreads to other parts of the yarn/layer with a tensile wave speed of c and a transverse speed of U, otherwise the layer breaks and the projectile travels forward, which may impact the next layer of the composite if the composite has a multi-layer configuration.

An ideal case for the free composite body is that it is totally free of any clamping but it is far more likely that the composite is clamped or held at the beginning but pulled out from the fixture after impact. When the longitudinal wave approaches or the clamp points or the boundary of the membrane (II of Scheme 2, t_a), the wave can reflect back leading to a superposition of reflected strain ($\varepsilon_{reflect}$) and the initial strain ε_1 in the transverse wave region.[38] The local strain in this annular region increases and the tension in the whole membrane increase continuously. If the clamp fails under this tension, i.e. the fracture strength of the mounting is much less than the composite membrane, the composite is ejected from the fixture and becomes a free body. Obviously, the tensile wave should have approached the boundary of the membrane before the projectile dissipating all its kinetic energy to the straining of the transverse wave region ($\varepsilon = \varepsilon_1$). Assuming the composite membrane is round with a diameter of D_c ($D_c = \sqrt{j}d_p$) and the projectile impacts its center, from the energy conservation, we have:

$$\pi\left(\frac{\sqrt{j}d_p}{2c}U\right)^2 h_c\int_0^{\varepsilon_1}\sigma_{(\varepsilon)}d\varepsilon \le \frac{1}{2}M_p v_1^2 \tag{14}$$

Combing Equation 8 and 14,

$$j\Gamma_0 \le \frac{\frac{1}{2}v_1^2\rho_c}{\left(\frac{U}{c}\right)^2\int_0^{\varepsilon_1}\sigma_{(\varepsilon)}d\varepsilon} \tag{15}$$

Equation 15 sets an upper limit value of $j\Gamma_0$ ($j\Gamma_{0max}$). Further assuming that all portions of the composite are accelerated to a uniform velocity of v_2 at t = t_2, we can write Equation 16 from the conservation of energy.

$$\frac{1}{2}M_p v_1^2 = \frac{1}{2}(M_p + m_c)v_2^2 + E_{internal} + \int_{x_1}^{x_2} F_{D_2}\,\mathrm{d}x + E_{LC} \qquad (16)$$

$E_{internal}$ is the internal energy of the composite membrane mainly arising from the longitudinal tensile straining of the reinforcement components (e.g. yarns).[39] F_{D2} is the air drag force in Stage II, and E_{LC} is the energy loss due to friction or thermal effects during the impact. $E_{internal}$ can be further represented as:

$$E_{internal} = V_y \int_0^{\varepsilon_2} \sigma_{(\varepsilon)}\, d\varepsilon \qquad (17)$$

where V_y is the volume of the reinforcing component of the composite, $\sigma_{(\varepsilon)}$ is the stress of the composite membrane at strain ε, ε_2 is the average strain of the membrane at t = t_2. Obviously, ε_2 should be less than the fracture strain (ε_{max}) of the composite membrane.

The other limiting case for the free composite body above is that the composite is doubly clamped and held steady during the interception. Analytical models for the clamped composite can be used to estimate the upper limit of the composite properties.

For the 2D composite membrane which is initially untensioned, quasi-isotropic, with linearly elastic properties in plane, an analytic model developed by Phoenix and Porwal can be used to correlate the composite properties with the ballistic limit ν_{50} of the membrane (the critical impact velocity of a ballistic armor at which the probability of perforation is 50% [11, 40]).[13] This model well fits the experimental results of various fibrous systems including Kevlar, PBO Zylon, and Spectra 1000. According to their work,[13] if the projectile is flat-nosed, ν_{50} of a multi-ply fabric membrane can be represented by the following equations with an introduction of two dimensionless variables Γ_0 and Π defined by Cunniff.[35]

$$v_{50} = \Pi \times \Phi^{1/3} \tag{18}$$

where $\Phi^{1/3}$ is a normalizing velocity and Φ can be expressed with the properties of the reinforcement component in the composite, i.e. fiber or yarn.[35]

$$\Phi = \frac{1}{2}(\sigma_{\max}\varepsilon_{\max} / \rho)c \tag{19}$$

$\sigma_{\max}$, ρ_y, and c_y are the ultimate axial tensile strength, density, and longitudinal wave speed of the fiber/yarn, respectively. The dimensionless parameter Π is a function of Γ_0 and $\varepsilon_{\max}$.

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$$\Pi = f(\Gamma_0, \varepsilon_{\max}) = 2^{1/3} \varepsilon_{\max}^{\frac{1}{12}} \frac{1+\theta^2 \Gamma_0}{K_{\max}^{\frac{3}{4}}} \tag{20}$$

$$K_{\max} \approx \exp\left\{ -\frac{4\Gamma_0}{3(1+\Gamma_0)} \left(\psi_{\max}^2 - 1\right) \right\} \psi_{\max}^{1/3} \left[\frac{\sqrt{\psi_{\max} / \varepsilon_{\max}} \left(\psi_{\max} - 1\right)}{\ln\left\{1 + \sqrt{\psi_{\max} / \varepsilon_{\max}} \left(\psi_{\max} - 1\right)\right\}} \right]^{2/3} \tag{21}$$

$$\psi_{\max} \approx \sqrt{\left(1+\theta^2 \Gamma_0\right) / \left(2\theta^2 \Gamma_0\right)} \tag{22}$$

where θ is a parameter typically somewhat greater than unity and $\theta = \frac{D_{p\theta}}{d_p}$ ($D_{p\theta}$ is an effective diameter of impact) , θ is about 1.3.[13] For an isotropic membrane with the same mechanical properties as the yarns above, its v_{50} is $\sqrt{2}$ times that of the cross-woven fabric membrane above.[22]

2.1.3. Stage III

In this simplified scheme, Stage III displays a scaling similar to Stage I, since we assume that the projectile remains lodged within the composite. Recall that our interest is in the pathway of maximum energy dissipation. The strain field in the composite does not reach the fracture strain. The velocity of the composite $v_{c(x)}$ ($x > x_x$) in stage III is then:

$$v_{c(x)} = v_2 e^{-k_3(x-x_2)} \left(x \geq x_2\right) \tag{23}$$

where for Stage III, k_3 is:

$$k_3 = \frac{\frac{1}{2} \times C_{d,c} \times \rho_{air} \times A_c}{\left(M_p + m_c\right)} \tag{24}$$

The drag coefficient of a flat composite body $C_{d,c}$ can be approximated as a constant of 1.28.[33] Assuming the deformation of the composite plane in Stage II changed the area of the composite A_c little, the velocity then scales as:

$$v_{c(x)} = v_1 \times \frac{1}{1 + j\Gamma_0} e^{-\frac{4.34k_1}{1/j+\Gamma_0}(x-x_2)} \quad (x > x_2) \tag{25}$$

2.2. Case II

Case I and the Phoenix-Porwal model are valid for fragments and small, but larger projectiles other failure mechanisms besides tensile failure are involved, i.e. failure by transverse compression. In practice, a hard ceramic striking plate is required to deform and capture such a large projectile. The assumption of Case I above that the projectile embeds with the free composite body and moves together will be no longer valid and new interception mechanisms for these large projectiles are required. However, an off target material designed for interception may still have advantages in this regime.

Generally, the ability of a projectile to maintain an accurate trajectory and carry

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momentum/energy to the target is highly dependent on the flight stability of the projectile. A gyroscopically stabilized projectile that becomes unstable will yaw dramatically, and decelerate rapidly, reducing its effectiveness for material penetration. Spin-stabilized projectiles when subjected to a small perturbation from stable flight exhibit an increasingly amplified perturbation as it continues to rotate and translate. A small transverse load input or more precisely an overturning moment impulse can introduce such a perturbation. A certain flight distance, however, is required to grow such instability. Obviously, traditional armor fixed on the target cannot satisfy the latter criterion. Off target armor (AA) may allow for the destabilizing of the projectile and growing such instability over a certain distance.

The spin-stabilized projectile should fulfill the conditions of gyroscopic stability, dynamic stability, and the tractability at the same time to guarantee a stable flight. Generally, only the gyroscopic stability has been considered in literature when it comes to stability considerations because it depends on only one aerodynamic coefficient (the overturning moment coefficient derivative C_{Ma}) and is much easier to determine than the other two. When a rotating projectile travels in air, a gyroscopic stability criterion for a symmetric projectile has been derived by Murphy in 1963.[41]

$$P^2 - 4M > 0 \tag{26}$$

where

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$$P = \frac{I_x}{I_y}\frac{pd_p}{v} \tag{27}$$

$$M = \frac{\rho_{air} A_p d_p^3}{2I_y} C_{M\alpha} \tag{28}$$

Here, I_x is the axial moment of inertia, I_y is the transverse moment of inertia, p is axial spin (or the angular velocity about the longitudinal axis of the projectile), d_p is the reference diameter of the projectile, *v* is the velocity of projectile at impact with the composite, $A_p = \pi d_p^2/4$ (the reference area), and C_{Ma} is the aerodynamic pitching moment coefficient. Typically, M > 0 for a spin-stabilized projectile and a gyroscopic stability factor S_g has been used by exterior ballisticians:[42]

$$S_g = \frac{P^2}{4M} = \frac{I_x^2}{I_y}\left(\frac{p}{v}\right)^2 \Big/ 2\rho_{air} A_p d_p C_{M\alpha} \tag{29}$$

According to Equation 26, $S_g > 1$ is required to achieve a gyroscopic stability for the rotating projectile. This is the classical stability criterion for the small mass projectiles. In the flight of a normal spin-stabilized projectile traveling in air, *v* decays due to air drag force is greater than p decay thus the projectile becomes more stable according Equation 29. But if the projectile is fired through an alternate medium besides air, i.e. the composite body of the AA system, the overturning moment contribution from the composite (M_{MC}) exerting on the projectile must be considered.[42]

$$M_{Mc} = \frac{\pi}{4}\rho_c d^2 h_c v^2 C_{Mac} \sin a_t \tag{30}$$

Where C_{Mac} is the overturning moment coefficient of the composite body, α_t is the total angle of attack, $a_t = (\alpha^2 + \beta^2)^{1/2}$, α is the angle of attack and β is the angle of side slip. A nondimensional overturning moment M_c can be defined on the basis of M_{Mc} and included into the M term of Equation 26.

$$M_c = \frac{\pi\rho_c d_p^4 h_c}{4I_y} C_{M_{ac}} \tag{31}$$

$$S_g = \frac{P^2}{4(\mathrm{M} + M_c)} \tag{32}$$

Recalling $\rho_c h_c = \Gamma_0 M_p / A_p = 4\Gamma_0 M_p / \pi d_p^2$ in Equation 8,

$$S_g = \left(\frac{I_x}{I_y}\frac{pd_p}{v}\right)^2 \Bigg/ \left(\frac{\rho_{air}\pi d_p^5}{2I_y} C_{Ma} + \frac{4\Gamma_0 M_p d_p^2}{I_y} C_{M_{ac}}\right) \tag{33}$$

Normally, d_p, M_p, ρ_{air}, I_x, and I_y are fixed and C_{Ma} only varies slightly for low angle, high velocity trajectories. For a projectile with given geometry and attacking angle, when it moves through a specific composite body, $C_{Ma,c}$ is a constant depending on Ma number

($Ma = \frac{v}{v_{sound}}$).[42] Hence S_g mainly depends on $\frac{p}{v}$ and the area density Γ_0 of the composite. The mechanical properties of the composite, the stiffness (i.e. the Young's modulus E) and the fracture strain (ε_{max}) for example, however, are not present in Equation 32. In this context, however, there is no particular strength requirement on this composite body and the kinetic energy dissipation of the projectile upon penetration of the composite can be generally neglected.

If Γ_0 of the composite body approaches a certain value, S_g can be less than 1 and the projectile will become gyroscopically unstable after penetration. The unstable projectile will tumble with increased yaw angles as shown in **Scheme 3**.[43] Its reference area (A_p) facing the air flow and correspondingly the drag coefficient $C_{d,p}$ will increase, resulting in a significantly increased air drag force.[43] The projectile should decelerate abruptly and stop within a specified range limit. The high air drag due to the tumbling of the projectile causes a fast deceleration of the projectile and *v* can be reduced faster than the angular velocity p, and S_g may become > 1 again so that the projectile is restabilized according to Equation 32. To potentially avoid this, an AA scheme might employ composite plates to continually destabilize the projectile along a trajectory. Below, we concern ourselves with the air drag force of the unstable projectile and its velocity change.

Scheme 3

Assume the projectile to be a cylinder with an inclination angle of γ during the tumbling process (Scheme 3) from position A (γ = 0) to position C (γ = π/2), the actual reference area of the projectile ($A_{p(\gamma)}$) projected into the plane orthogonal to the trajectory is:

$$A_{p(\sigma)} = \frac{1}{4}\pi d_p^2 \cos\gamma + h_p d_p \sin\gamma \quad (0 \le \gamma \le \frac{\pi}{2}\ ) \qquad (34)$$

The drag coefficient $C_{d,p}$ is then changed during the tumbling process with $C_{d,p}$ as 0.295 at $\gamma = 0$ as in Case I,[33] but at $\gamma = \pi/2$, the projectile becomes a cylinder with long axis facing the air flow and $C_{d,p}$ increases to 1.1.[44] Assuming a linear increase of $C_{d,p}$ with γ,

$$C_{d,p(\gamma)} = \frac{1.61\gamma}{\pi} + 0.295 \quad (0 \le \gamma \le \frac{\pi}{2}) \qquad (35)$$

Substituting Equation 33 and 34 into Equation 1, the drag force F_{Dt} in the tumbling stage is

$$F_{D,t} = \frac{1}{2}\rho_{air} v^2 \left(\frac{1.61\gamma}{\pi} + 0.295\right)\left(\frac{1}{4}\pi d_p^2 \cos\gamma + h d_p \sin\gamma\right) \qquad (36)$$

Assuming the period of one complete revolution from A ($\gamma = 0$) to F ($\gamma = 2\pi$) is T and the tumbling speed is uniform, γ at any instant of time can be represented as

$$\gamma = 2\pi t / T \qquad (37)$$

The total air drag impulse on the projectile in T is 4 times the impulse given in 1/4T (i.e from A to C) since $A_{p(\gamma)}$ varies in the same way in each of the four quadrants. The average drag force ($\overline{F_{D,t}}$) can thus be calculated from the impulse I given to the projectile in 1/4T,

$$I = \overline{F_{D,t}}\left(\frac{T}{4}\right) = \int_0^{T/4} F_{D,t}dt = \frac{1}{2}\rho_{air}v^2\left(0.257h_p + 0.147d_p\right)d_p\left(\frac{\mathrm{T}}{2}\right) \tag{38}$$

$$\overline{F_{D,t}} = \frac{1}{2}\rho_{air}v^2\left(0.514h_p + 0.294d_p\right)d_p \tag{39}$$

Combing Equation 39 and Equation 3, 4 and 5, the velocity ($v_{t(\mathrm{x})}$) of the tumbling projectile is

$$v_{t(\mathrm{x})} = v_1 \times \frac{1}{1 + j\Gamma_0} e^{-k_4 x} \tag{40}$$

$$k_4 = \frac{\frac{1}{2}\mathrm{C}_{d,p}\rho_{air}\mathrm{A}_p}{\mathrm{M}_p} = \frac{\left(0.514h_p + 0.294d_p\right)d_p\rho_{air}}{2\mathrm{M}_p} \tag{41}$$

v_1 is the impacting velocity of the projectile and in the penetration process, j is

$$j = \frac{\frac{1}{4}\pi D_{p\theta}^2}{\frac{1}{4}\pi d_p^2} = \theta^2 \tag{42}$$

where $D_{p\theta}$ is an effective diameter of impact and $\theta = \frac{D_{p\theta}}{d_p}$ can be assumed as a constant of 1.3 as mentioned in previous case.[13]

3. Further material considerations and the design of composite armor for Case I

As examples, we consider two composite systems in evaluating the stages in Case I above. The first system is a multi-ply fabric composite consisting of interwoven polymer yarns (fibers) such as Kevlar, Spectra, PBO Zylon and M5 Goal fibers. The second system is a hypothetical graphene/polymer multilayer membrane nanocomposite. The AA model can then provide estimates for the design these two composite systems.

3.1. Multi-ply fabric composite

The polymer fibers mentioned above usually have very high stiffness, very low strains to failure (<4%), and low density, for example,[11] 200 denier Kevlar™ 29 has the Young's modulus (E_y) = 91 GPa, ε_{max} = 2.95%, an ρ = 1440 kg/m^3, Spectra™ 1000 has E= 120 GPa, ε_{max} = 3.5%, and ρ = 970 kg/m^3. They are essentially elastic in tension and can assume as linearly elastic.[35] Therefore,

$$\int_0^{\varepsilon} \sigma_{(\varepsilon)} d\varepsilon = \frac{1}{2} E_f \varepsilon^2 = \frac{1}{4} V_y E_y \varepsilon^2 \tag{43}$$

Herein, E_f is effective modulus of the fabric, it is half of the fiber/yarn's modulus E_y due to that crossing yarns add cross-sectional area but not load carrying.[13] Combining Equation 15 and 43, we have:

$$j\Gamma_0 \leq \frac{2v_1^2 \rho_c}{\left(\frac{U}{c}\right)^2 E_y \varepsilon_1^2} \tag{44}$$

If we neglect the energy contribution from air drag force, friction and thermal effects in this stage for simplicity, a combination of Equation 9 and Equation 16 results

$$\frac{1}{2} M_p v_1^2 \left(\frac{j\Gamma_0}{1 + j\Gamma_0}\right) = \frac{1}{4} E_y \varepsilon_2^2 j\Gamma_0 \frac{M_p}{\rho_c} \varphi_y \tag{45}$$

where φ_y and ρ_y are the volume fraction and density of the fiber/yarn in the fabric composite, respectively. $\rho_c = \rho_m(1-\varphi_y) + \rho_y \varphi_y$ (ρ_m is the density of the resin binder), then,

$$\varepsilon_2 = \frac{v_1}{\sqrt{E_y \varphi_y / \rho_c}} \sqrt{\frac{2}{1 + j\Gamma_0}} \tag{46}$$

ε_2 should be smaller than ε_{max}, $j\Gamma_0$ (or the composite mass) therefore has a lower limit value at a given φ_y, as below.

$$j\Gamma_0 \geq \frac{2v_1^2}{\varepsilon_{max}^2 E_y \varphi_y / \rho_c} - 1 \tag{47}$$

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3.2. Graphene/polymer nanocomposite

Pristine graphene is elastically isotropic within the plane,[45] the elastic response of monolayer graphene of under uniaxial extension is nonlinear and follows Equation 48 below,[23, 26, 46]

$$\sigma = E_G \varepsilon + D_G \varepsilon^2 \quad (48)$$

where E_G = 340 ± 40 Nm^{-1} (≈ 1.0 Tpa in 3D value) and D_G = –690 ±120 Nm^{-1}. At very small deformation < 2.0%, the monolayer graphene is isotropic linear elastic with the Young's modulus ≈ 1 Tpa and intrinsic strength of 125 GPa. At a larger deformation before the fracture strain ($\varepsilon_{max} \approx$ 0.30),[26] however, a strain-softening behavior has been observed, that is, its effective modulus reduces with the increasing strain. This stress-strain curve can be also susceptible to temperature and strain-rate. The effect of temperature on Young's modulus is small at a given temperature range, i.e. < 10% between 300 and 2400 K. The strain rate has a positive effect on the graphene strength, both the fracture strength and the fracture strain increase slightly with the increasing strain rate.[47] It has been also demonstrated experimentally that the multi-layer graphene has a larger specific penetration energy (and therefore v_{50}) at a higher strain rate.[25]

The novel chemical vapor deposition (CVD) method reported by Ruoff group in 2009 allows the preparation of single-layer, high-quality, and large-area graphene with an aspect ratio (α) approaching infinite.[48] The elastic stiffness and strength of such polycrystalline graphene with larger grain boundaries are comparable to that of the pristine graphene (E ≈ 1.0 TPa, σ = 118 GaP) above.[23, 30] The CVD graphene grows on a copper foil substrate (catalyst) and can be easily transferred to arbitrary substrates like thin polymer (like poly(methyl methacrylate), poly(ethylene terephthalate) film via either a spin-coating/chemical etching or mechano-electro-thermal forces and its size can approach to hundreds of centimeters.[48, 49] These polymer-supported CVD graphene sheets can be further used as building blocks to construct multilayer nanocomposite via a convenient layer-by-layer hybridization approach. As **Scheme 4** shows, a multilayer polymer/graphene nanocomposite can be obtained via a simple stacking.

Scheme 4

In the calculation of the ballistic proof performance of the multilayer CVD graphene/polymer composite, the stress-strain curve of Equation 48 was used and the stain energy contribution from polymer part was neglected because its elastic modulus is much lower than graphene. Combining Equation 9, 16 and neglecting of the energy contribution from the air drag force in Stage II and the energy loss E_{LC}, we have:

$$\frac{1}{2}v_1^2\left(\frac{1}{1+j\Gamma_0}\right)=\left(\frac{1}{2}E_G\varepsilon_2^2+\frac{1}{3}D_G\varepsilon_2^3\right)\frac{\varphi_G}{\rho_c}=\left(\frac{1}{2}E_G\varepsilon_2^2+\frac{1}{3}D_G\varepsilon_2^3\right)\frac{\varphi_G}{\rho_m(1-\varphi_G)+\rho_G\varphi_G} \qquad (49)$$

φ_G is the volume fraction of graphene in the composite, ρ_G is the density of the graphene ($\rho_G \approx 2.22$ g/cm^3).[50] Obviously, $j\Gamma_0$ has the lower limit value ($j\Gamma_{0,min}$) at $\varepsilon_2 = \varepsilon_{\max}$ and this value depends on φ_G. The number (n) of graphene layers of the composite can be further calculated as Equation 50 shows.

$$n = \frac{h_c \varphi_G}{t_G} = \frac{\Gamma_0 \rho_p h_p \varphi_G}{\rho_c t_G} = \frac{\Gamma_0 \rho_p h_p \varphi_G}{[\rho_m (1-\varphi_G) + \rho_G \varphi_G] t_G} \tag{50}$$

where t_G is the thickness of a monolayer graphene, t_G is 0.335 nm.[51] n depends on Γ_0 when φ_G is fixed.

To calculate the ballistic proof performance of such a multilayer nanocomposite if it is doubly clamped, a linearization of the nonlinear stress-strain curve of graphene was conducted to meet the requirement for the 2D membrane model above (Equation 18-22). As **Figure 1** shows below, the new linear curve has the same strain energy and ε_{max} (0.30) as the true curve,[23] while a fixed elastic modulus (E) of 202 N/m. This treatment is reasonable since the 2D membrane model above mainly considers the elastic strain energy contribution of the composite and similar linearization treatment has been reported elsewhere.[13, 52] In addition, we assumed the modulus of the multiplayer graphene/polymer composite membrane $E_c = E_G \times \varphi_G$ without considering the contribution from the polymer. The required Γ_0 for the clamped graphene nanocomposite will be a functional of φ_G based on Equation18-22 above.

Figure 1

4. Discussion

4.1. Case I

Assuming a standardized 16 grain (M_p = 1 g) flat-nosed, cylindrical (RCC) steel projectile with D_p = 0.55 cm and h_p = 0.55 cm was used and v_0 is 800 m/s.[13, 35] Its deceleration curve in Stage I was plotted in **Figure S1** of support information. The projectile has a velocity > 640 m/s at a traveling distance x = 50 m.

4.1.1. AA based on the multi-ply fabric composite

We first calculated the performance of four polymer fibers including 200 den. Kevlar™ 29 (E = 91 GPa, ε_{max} = 2.95%), Spectra™ 1000 (120 GPa, 3.5%), PBO Zylon™ (180 GPa, 3.5%), and M5 Goal fibers (450 GPa, 2.5%) under a striking velocity v_1 = 800 m/s.[11] According to Equation 13, their initial strain ε_1 are 3.10%, 1.96%, 2.04%, and 1.17%, respectively. Kevlar™ 29 would break under the initial impact while the other three could survive. Specifically, we considered using the composite fabric membrane based on M5 Goal fiber, which has the highest ballistic performance ($\Phi^{1/3}$ = 1043 m/s [53]) among various polymer fibers. According to Cunniff et al. [53], M5 composite fabric can be made from fiber/resin tapes (ply areal density = 98 g/m^2) with a thermoplastic resin volume fraction of 12% approximately (φ_y = 0.88). Assuming the resin has a density of 1.0 g/m^3 and v_1 = 800 m/s, $j\Gamma_{0max}$ of the M5 Goal composite fabric is 1288.6 according to Equation 15. $j\Gamma_{0, min}$ is 7.35 based on Equation 47, which means that most of (> 98%) the kinetic energy of the projectile will be dissipated by the fabric membrane while not the air drag force. The upper limit value of Γ_0 ($\Gamma_{0, max}$) of the fabric membrane based on M5 Goal fiber alone is 0.031 according to Phoenix and Porwal's model (Equation18-22) [13]. Based on these results, M5 Goal fiber-based composite membrane with φ_y = 0.88, Γ_0 = 0.031/0.88 = 0.035, and 208.8 ≤ j ≤ 36608 (corresponding to 7.35 ≤ $j\Gamma_0$ ≤ 1288.6) can be used for the AA system and the composite/projectile can decelerate to a lower speed of 3 m/s in a distance < 2.6 m at j ≥ 208.8 after striking the membrane with v_1 = 800 m/s (**Figure 2**).

Figure 2

4.1.2. AA based on CVD graphene/polymer nanocomposite

We further investigated the example of using multilayer graphene/polymer nanocomposites for our AA. At v_1 = 800 m/s, the calculated ε_1 = 0.13% according to Equation 13. **Figure 3(a)** plots the lower limit value of $j\Gamma_0$ ($j\Gamma_{0,\ min}$) against φ_G based on Equation 49 (polyethylene terephthalate (PET, ρ = 1.38 g/cm^3) was used as polymer layer). $j\Gamma_{0,\ min}$ is almost 0 at φ_G = 0.015. A lightweight graphene/PET nanocomposite can thus be designed for the AA system. $\Gamma_{0,\ max}$ of the composite determined by Equation 18-22 was plotted against φ_G in **Figure 3(b)**. Higher $\Gamma_{0,\ max}$ values are required when φ_G < 0.01 and $\Gamma_{0,\ max}$ has little change at φ_G > 0.02. Multilayer CVG graphene/polymer nanocomposites with φ_G = 0.02 and $\Gamma_{0,\ max}$ = 0.013 (the number of graphene layer n = 23400 based on Equation 50) can thus be designed for the AA and **Figure 4** plots $v_{c(x)}$ against j and $x - x_2$ (the stopping distance) at Stage III. j has a fixed value if $x - x_2$ and the final $v_{c(x)}$ are known and 50 ≤ j ≤ 100 (0.65 ≤ $j\Gamma_0$ ≤ 1.3) is required to decelerate the projectile/composite to a lower speed of 3 m/s at $x - x_2$ = 9.0-5.9 m for example.

Figure 3

Figure 4

4.2. Case II

In the case of using AA to destabilize the larger projectile with higher kinetic energy, the projectile with the following physical properties and flight coefficient parameters have been used to calculate the Γ_0 of the free composite body for the AA: $M_{p,l}$ = 0.0112 *kg*, ρ_p = 7800 kg/m^3, $d_p = 7.82\times10^{-3}$ m (assuming the projectile is a cylinder, h_p = 30 mm), ρ_{air} = 1.20 kg/m^3, I_x = 0.72 g·cm^2, I_y = 6.86 g·cm^2.[42, 54, 55] Assuming the projectile is a cylinder, the calculated h_p = 30 mm. The ratio of the angular velocity p to projectile velocity v_1 can be assumed as a constant and written as, $\frac{pd_p}{v_1} = 0.18\, rad/\mathrm{cal}$.[55] For low angle, high velocity trajectories, C_{Ma} only varies slightly and herein we used C_{Ma} = 2.39 from literature.[55, 56] Substituting all these values into Equation 33, we have Equation 51.

$$S_g = \frac{0.55}{1.92\times10^{-4} + 3.99\Gamma_0 C_{Mac}} \tag{51}$$

If $S_g < 1$ is satisfied, then we have

$$\Gamma_0 > 0.138 / C_{M\alpha c} \tag{52}$$

For the projectile with given geometry and attacking angel, the overturning moment coefficient $C_{Ma,c}$ is a constant mainly depending on the composite material and Ma number ($Ma = \frac{v}{v_{sound}}$). For example, C_{Mac} = 3.8 has been reported for a projectile through yaw cards.[55] Because there is no special requirement on material properties (i.e. mechanical peformance) of the composite body to destabilize the projectile, we considered the AA to have similar C_{Mac} = 3.8 as the yaw cards, hence $\Gamma_0 > 0.036$ is required according to Equation 52. **Figure 5** plots the deceleration curve of the gyroscopically unstable ($S_g < 1$) projectile with an impacting velocity v_1 = 850 m/s (Ma = 2.5) based on Equation 39 and 40, the velocity change of the stable projectile ($S_g > 1$) in air is also included for comparison. The unstable projectile can decelerate to 3 m/s in a stopping distance ≈ 750 m, while ≈ 7400 m is required for the stable projectile.

Figure 5

4.3. A Combination of Case I and II

To further reduce the stopping distance of the unstable projectile, we can set a multilayer graphene/polymer composite of Case I at a specific point of the trajectory of the projectile. As **Scheme 5** shows, the graphene/polymer composite intercepts, embeds, and fast decelerates the unstable projectile. The set position of the multilayer composite depends on the kinetic energy of the unstable projectile. Particularly, where the kinetic energy of the larger, unstable projectile ($\frac{1}{2} M_{p,l} v_x^2$) reduces to the level that the multilayer composite can successfully dissipate, or:

$$\frac{1}{2}M_{p,l}v_x^2 = \frac{1}{2}M_{p,s}v_{50}^2 \tag{53}$$

$M_{p,s}$ is the mass of the projectile that the multilayer composite can intercept without perforation, v_{50} is the critical impact velocity of the composite body described in Equation 18-22. As a demonstration, if we use the multilayer graphene/polymer nanocomposite membrane (v_{50} = 800 m/s for the projectile with $M_{p,s}$ = 1 g) designed in Case I above, the set point is x = 162 m ($v_{t(x=\ 162)}$ = 239 m/s) for the above unstable projectile. Then the projectile will rapidly decelerate to 3 m/s in another 6-9 m.

Scheme 5

5. Limitations of the present model

As a simple physical illustration of the AA concept, the current analytical model has the following limitations: (1) Energy loss: we have neglected the energy contribution from friction in the model. In practice, the friction between the projectile and the composite membrane, between the basic elements of the composite, i.e. yarns of fabric, graphene and polymer layer in the nanocomposite, and the heat generated from friction are energy sinks during the impact. (2) We only considered the failure mode of the composite in tension, with failure caused by the transverse compression, shear stress, extension of the yarns, and others were neglected. (3) We assumed that the sectional area (A_C) of the composite has little change after impact, but the deformation of the membrane, the velocity difference between the impact center and the membrane edge may curve or bend the flat membrane to a conical shape, which can change A_c and its air drag coefficient.

However, as long as the composite size (A_c) is small and the thickness is not, the composite should be stiff enough to resist such a bending. (4) In the design and calculation of the graphene composite, we used an experimental stress-strain curve measured by Atomic Force Microscopy (AFM) for graphene, assumed to scale to macroscopic dimensions. This scalability remains an active area of investigation, and known to be limited by defects/cracks in the graphene inclusion, and poor interfacial bonding in some types of composites. (5) In the design of the AA to destabilize the projectile, the gyroscopically unstable projectile could be restabilized when decelerated to a lower velocity thus requiring an increasing number of composite plates to perpetuate instability. More analysis is required on this type of AA to address this concern.

6. Conclusions

We have introduced an analysis of off-target armor or ambient armor (AA) to intercept projectiles at some point along the trajectory as opposed to the conventional dissipation of energy on the target itself. For small projectiles with relatively low kinetic energy, multi-ply fabric membranes and hypothetical, multilayer semi-infinite graphene/polymer nanocomposites with designed mechanical properties can be used as free bodies in the AA system for projectile capture and energy dissipation via air drag without penetration. The nanocomposite-based AA can be on average 11 times lighter and dissipate 60% of the total kinetic energy of a projectile through air drag as opposed to 12% of the fabric-based one. For larger projectiles with higher energy, a regular free composite body with a specific area density can be used first to destabilize gyroscopically causing it to decelerate up to 10 times faster than a stable projectile. An AA system containing a regular composite in front of a multilayer graphene nanocomposite as an example is able to slow a larger projectile in a relatively shorter distance, of order 170 m. The analysis shows that when compared to conventional armor systems, AA may significantly lower the requisite composite size/material loading necessary and allow large deformations of materials currently prevented in on-target, conventional armor systems. These new options may open pathways for the exploration of here-to-fore unexplored materials for such applications.

Acknowledgements

We acknowledge helpful discussions with E Wetzel and S. Walsh, at Army Research Laboratories in Aberdeen, MD as well as Drs William Hong, Jenya Macheret, and Jeremy Teichman at the Institute for Defense Analysis

References

[1] (a) B. Bhushan, *Springer Handbook of Nanotechnology*, Springer Verlag GmbH, Heidelberg, Germany **2010**; (b) M. F. Ashby, P. J. Ferreira, D. L. Schodek, *Nanomaterials*, *Nanotechnologies and Design*, Butterworth-Heinemann, Boston, USA **2009**.

[2] P. M. Ajayan, L. S. Schadler, P. V. Braun, *Nanocomposite science and technology*, John Wiley & Sons, Weinheim, Germany **2003**.

[3] National Research Council, *Opportunities in Protection Materials Science and Technology for Future Army Applications*, The National Academies Press, Washington, D.C., USA **2011**.

[4] P. Qiao, M. Yang, F. Bobaru, *J. Aerosp. Eng.*, **2008**, 21, 235.

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Other requests for this document shall be referred to the Defense Advanced Research Projects Agency.

[5] MarketsandMarkets, Ballistic Protection Market by Type, sub-type, & by Application - Global Forecasts & Analysis to 2014-2020, http://www.researchandmarkets. com/reports/3024353/ballistic-protection-market-by-type-sub-type, accessed: Oct., **2014**.

[6] Strategic Defence Intelligence, The Global Body Armor and Personal Protection Market 2014-2024, http://www.researchandmarkets.com/research/jlk665/the_global_body, Dec., **2014**.

[7] D. J. Miller, *Design and Analysis of an Innovative Semi-Flexible Hybrid Personal-Body-Armor System*, University of South Florida, March, **2011**.

[8] N. V. David, X. L. Gao, J. Q. Zheng, *Appl. Mech. Rev.* **2009**, 62, 050802.

[9] (a) B. A. Cheeseman, T. A. Bogetti, *Compos. Struct.* **2003**, 61, 161; (b) A. Tabiei, G. Nilakantan, *Appl. Mech. Rev.* **2008**, 61, 010801; (c) G. Ben-Dor, A. Dubinsky, T. Elperin, *Appl. Mech. Rev.* **2005**, 58, 355.

[10] P. J. Hogg, *Science* **2006**, 314, 1100.

[11] R. Zaera, in *Impact Engineering of Composite Structures*, Vol. 526 (Ed: S. Abrate), Springer Vienna, New York, USA **2011**, Ch. 7.

[12] L. B. Tobin, M. J. Iremonger, *Modern body armour and helmets: an introduction*, Argos Press, Canberra, Australia **2006**.

[13] S. L. Phoenix, P. K. Porwal, *Int. J. Solids Struct.* **2003**, 40, 6723.

[14] R. Laible, *Ballistic materials and penetration mechanics*, Vol. 5, Elsevier, Amsterdam, the Netherlands **2012**.

[15] K. Horn, K. Biever, K. Burkman, P. DeLuca, L. Jamison, M. Kolb, A. Sheikh, *Lightening Body Armor*, RAND Corporation, Santa Monica, CA, USA **2012**.

[16] (a) B. J. F. Bruet, J. Song, M. C. Boyce, C. Ortiz, Nat. Mater. **2008**, 7, 748; (b) W. Yang, I. H. Chen, B. Gludovatz, E. A. Zimmermann, R. O. Ritchie, M. A. Meyers, Adv.

Mater. **2013**, 25, 31; (c) A. P. Jackson, J. F. V. Vincent, R. M. Turner, *Proc. R. Soc. Lond. B* **1988**, 234, 415.

[17] (a) K. Koziol, J. Vilatela, A. Moisala, M. Motta, P. Cunniff, M. Sennett, A. Windle, *Science* **2007**, 318, 1892; (b) K. Mylvaganam, L. C. Zhang, *Nanotechnology* **2007**, 18, 475701; (c) M. Moniruzzaman, K. I. Winey, *Macromolecules* **2006**, 39, 5194; (d) N. G. Sahoo, S. Rana, J. W. Cho, L. Li, S. H. Chan, *Prog. Polym. Sci.* **2010**, 35, 837; (e) J. N. Coleman, U. Khan, Y. K. Gun'ko, *Adv. Mater.* **2006**, 18, 689; (f) Y. Lin, B. Zhou, K. A. Shiral Fernando, P. Liu, L. F. Allard, Y.-P. Sun, *Macromolecules* **2003**, 36, 7199; (g) Z. Spitalsky, D. Tasis, K. Papagelis, C. Galiotis, *Prog. Polym. Sci.* **2010**, 35, 357; (h) M. Naffakh, A. M. Díez-Pascual, C. Marco, G. J. Ellis, M. A. Gómez-Fatou, *Prog. Polym. Sci.* **2013**, 38, 1163; (i) L. Rapoport, N. Fleischer, R. Tenne, *J. Mater. Chem.* **2005**, 15, 1782; (j) Y. Q. Zhu, T. Sekine, Y. H. Li, M. W. Fay, Y. M. Zhao, C. H. Patrick Poa, W. X. Wang, M. J. Roe, P. D. Brown, N. Fleischer, R. Tenne, *J. Am. Chem. Soc.* **2005**, 127, 16263.

[18] D. R. Paul, L. M. Robeson, *Polymer* **2008**, 49, 3187.

[19] H. Kim, A. A. Abdala, C. W. Macosko, *Macromolecules* **2010**, 43, 6515.

[20] (a) T. Ramanathan, A. A. Abdala, S. Stankovich, D. A. Dikin, M. H. Alonso, R. D. Piner, D. H. Adamson, H. C. Schniepp, X. Chen, R. S. Ruoff, S. T. Nguyen, I. A. Aksay, R. K. Prud'Homme, L. C. Brinson, *Nat. Nano.* **2008**, 3, 327; (b) S. Stankovich, D. A. Dikin, G. H. B. Dommett, K. M. Kohlhaas, E. J. Zimney, E. A. Stach, R. D. Piner, S. T. Nguyen, R. S. Ruoff, *Nature* **2006**, 442, 282.

[21] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, A. A. Firsov, *Science* **2004**, 306, 666.

[22] E. D. Wetzel, R. Balu, T. D. Beaudet, *J. Mech. Phys. Solids.* **2015**, 82, 23.

[23] C. Lee, X. Wei, J. W. Kysar, J. Hone, *Science* **2008**, 321, 385.

[24] J. E. Field, Q. Sun, in *19th Intl Congress on High-Speed Photography and Photonics*, Vol. 1358 (Eds: P. W. W. Fuller), SPIE, Cambridge, England **1991**; (b) Y. M.

Gupta, J. L. Ding, *Int. J. Impact. Eng.* **2002**, 27, 277; (c) J. R. Robbins, J. L. Ding, Y. M. Gupta, *Int. J. Impact. Eng.* **2004**, 30, 593.

[25] J.-H. Lee, P. E. Loya, J. Lou, E. L. Thomas, *Science* **2014**, 346, 1092.

[26] E. Cadelano, P. L. Palla, S. Giordano, L. Colombo, *Phys. Rev. Lett.* **2009**, 102, 235502.

[27] L. Cannon, *J. R. Army Med. Corps* **2001**, 147, 87.

[28] (a) D. Drobin, D. Gryth, J. K. E. Persson, D. Rocksén, U. P. Arborelius, L.-G. Olsson, J. Bursell, B. T. Kjellström, *J. Trauma Acute Care Surg.* **2007**, 63, 405; (b) D. Gryth, D. Rocksén, J. K. E. Persson, U. P. Arborelius, D. Drobin, J. Bursell, L.-G. Olsson, T. B. Kjellström, *Mil. Med.* **2007**, 172, 1110; (c) J. C. Roberts, E. E. Ward, A. C. Merkle, J. V. O'Connor, *J. Trauma Acute Care Surg.* **2007**, 62, 1127.

[29] C. Lee, X. Wei, Q. Li, R. Carpick, J. W. Kysar, J. Hone, *Phys. Status Solidi B* **2009**, 246, 2562.

[30] G.-H. Lee, R. C. Cooper, S. J. An, S. Lee, A. van der Zande, N. Petrone, A. G. Hammerberg, C. Lee, B. Crawford, W. Oliver, J. W. Kysar, J. Hone, *Science* **2013**, 340, 1073.

[31] A. J. Pejsa, *Modern practical ballistics*, Kenwood Pub., Minneapolis, MN, USA **1991**.

[32] (a) L. J. Clancy, *Aerodynamics*, Wiley, New York, USA **1975**; (b) W. King, *Drag Coefficients of Bullets, Arrows, and Spears*, https://sites.google.com/site/technicalarchery/technical-discussions-1/drag-coefficients-of-bullets-arrows-and-spears, accessed: Dec., **2011**.

[33] Glenn Research Center, Shape Effects on Drag, http://www.grc.nasa.gov/WWW/k-12/airplane/shaped.html, accessed: May, **2015**.

[34] M. E. Backman, W. Goldsmith, Int. J. Eng. Sci. **1978**, 16, 1.

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Other requests for this document shall be referred to the Defense Advanced Research Projects Agency.

[35] P. M. Cunniff, presented at *Proceedings of the 18th International and Symposium on Ballistics*, San Antonio, Texas, USA, November, **1999**.

[36] D. Roylance, S. S. Wang, in *Ballistic Materials and Penetration*, Vol 5 (Ed: R. C. Laible), Elsevier, Amsterdam, the Nertherlands **1980**, Ch 12.

[37] (a) J. C. Smith, F. L. McCrackin, H. F. Schiefer, *Text. Res. J.* **1958**, 28, 288; (b) J. C. Smith, J. M. Blandford, K. M. Towne, *Text. Res. J.* **1962**, 32, 67.

[38] B. Gu, *Compos. Part B: Eng.* **2003**, 34, 361.

[39] G. Nilakantan, S. Nutt, *Compos. Struct.* **2014**, 108, 137.

[40] P. M. Cunniff, *Text. Res. J.* **1992**, 62, 495.

[41] C. H. Murphy, *Free flight motion of symmetric missiles*, http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0442757, accessed, Jul, **1963**.

[42] R. L. McCoy, *The Effect of Yaw Cards on the Pitching and Yawing Motion of Symmetric Projectiles*, http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA250021, accessed: May, **1992**.

[43] M. A. Laviolette, J. R. Evans, B. Cheers (Her Majesty The Queen In Right Of Canada), *US 4827847 A*, **1989**.

[44] S. F. Hoerner, *Fluid-dynamic drag; practical information on aerodynamic drag and hydrodynamic resistance*, Midland Park, New Jersey, USA **1965**.

[45] V. M. Pereira, A. H. Castro Neto, N. M. R. Peres, *Phys. Rev. B* **2009**, 80, 045401.

[46] (a) Q. Lu, R. Huang, Int J Appl Mech 2009, 1, 443; K. H. Michel, B. Verberck, *Phys. Status Solidi B* **2008**, 245, 2177; (b) J. Zhou, R. Huang, *J. Mech. Phys. Solids* **2008**, 56, 1609; (c) G. Cao, *Polymers* **2014**, 6, 2404.

[47] H. Zhao, N. R. Aluru, *J. Appl. Phys.* **2010**, 108, 064321.

[48] X. Li, W. Cai, J. An, S. Kim, J. Nah, D. Yang, R. Piner, A. Velamakanni, I. Jung, E. Tutuc, S. K. Banerjee, L. Colombo, R. S. Ruoff, *Science* **2009**, 324, 1312.

[49] (a) J. Kang, D. Shin, S. Bae, B. H. Hong, *Nanoscale* **2012**, 4, 5527; (b) W. Regan, N. Alem, B. Alemán, B. Geng, Ç. Girit, L. Maserati, F. Wang, M. Crommie, A. Zettl, *Appl. Phys. Lett.* **2010**, 96, 113102; (c) W. Jung, D. Kim, M. Lee, S. Kim, J.-H. Kim, C.-S. Han, *Adv. Mater.* **2014**, 26, 6394; (d) S. Bae, H. Kim, Y. Lee, X. Xu, J.-S. Park, Y. Zheng, J. Balakrishnan, T. Lei, H. Ri Kim, Y. I. Song, Y.-J. Kim, K. S. Kim, B. Ozyilmaz, J.-H. Ahn, B. H. Hong, S. Iijima, *Nat. Nano.* **2010**, 5, 574.

[50] J. W. Anthony, R. A. Bideaux, K. W. Bladh, M. C. Nichols, *Handbook of Mineralogy*, Mineralogical Society of America, Chantilly, VA, USA **2011**.

[51] (a) B. T. Kelly, *Physics of graphite*, Applied Science, London, UK **1981**; (b) M. S. Dresselhaus, G. Dresselhaus, P. C. Eklund, *Science of fullerenes and carbon nanotubes: their properties and applications*, Academic press, San Diego, CA, USA **1996**.

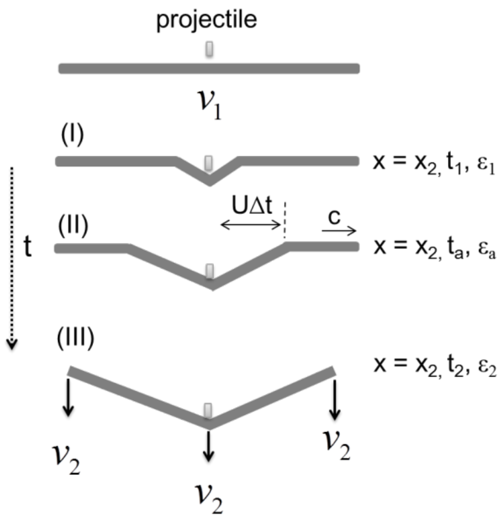
[52] Y. Budhoo, F. Delale, B. Liaw, in *Dynamic Behavior of Materials*, Vol. 1, (Eds: V. Chalivendra, B. Song, D. Casem), Springer, New York, USA **2013**, 303.

[53] P. M. Cunniff, M. A. Auerbach, E. Vetter, D. J. Sikkema, presented at 23rd. Army Science Conference, Orlando, FL, USA, Dec., **2002**.

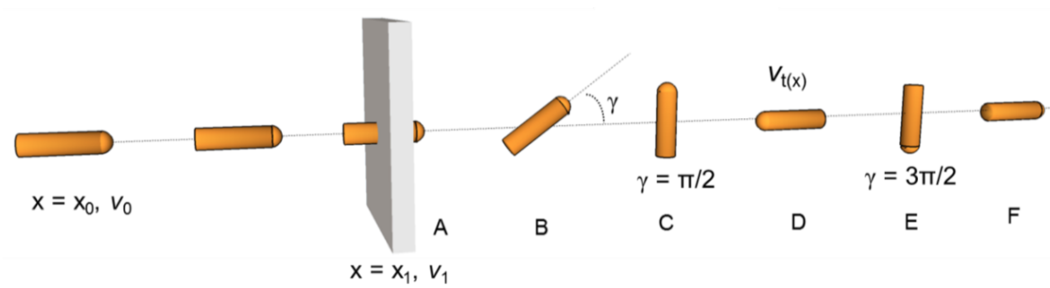
[54] R. L. McCoy, The Aerodynamic Characteristics of 7.62mm Match Bullets, http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA205633, Dec., **1988**.

[55] G. R. Cooper, K. S. Fansler, Yaw Card Perturbation of Projectile Dynamics, http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA320953, accessed: Jan., **1997**.

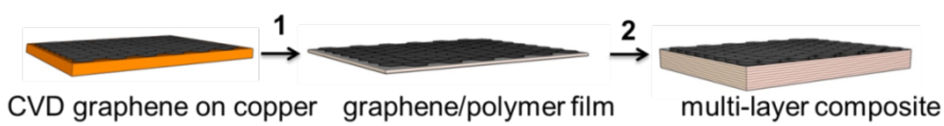
[56] C. O. White (Primex Technologies, Inc.), *US 5932836 A*, **1999**.



Scheme 2. The cross-sectional view of the wave formation and movement in the composite membrane impacted by a projectile transversely, c is the longitudinal wave speed and U is the transverse wave speed in laboratory coordinates.



Scheme 3. Gyroscopic destabilization of a projectile in a hypothetical AA scheme leading to tumbling after initial penetration, Here, γ is the inclination angle of the projectile when rotating off axis.



Scheme 4. The fabrication of multi-layer CVD graphene/polymer composite via stacking.

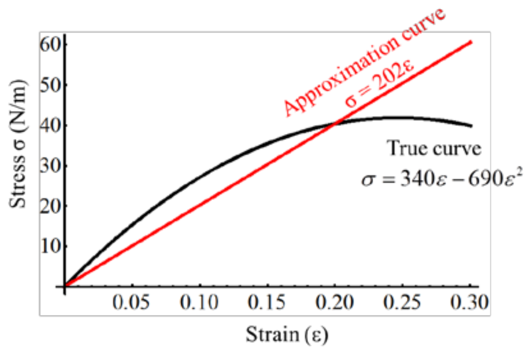


Figure 1. Linearization of the nonlinear stress-strain curve of graphene while maintaining strain energy

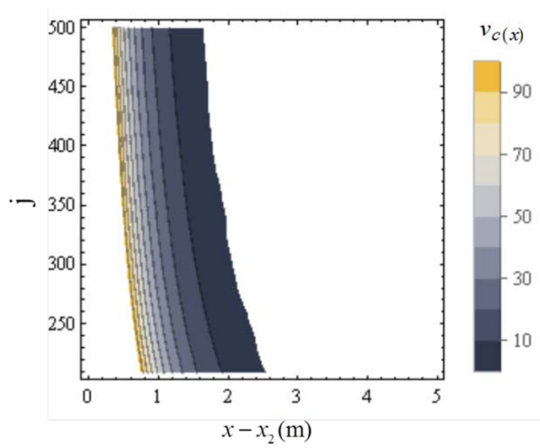


Figure 2. The contour plot of $v_{c(x)}$ (3-95.8 m/s) against the $x - x_2$ (the stopping distance) and j when M5 Goal fiber-based composite membrane (Γ_0 = 0.035, φ_f = 0.88) was used for the AA.

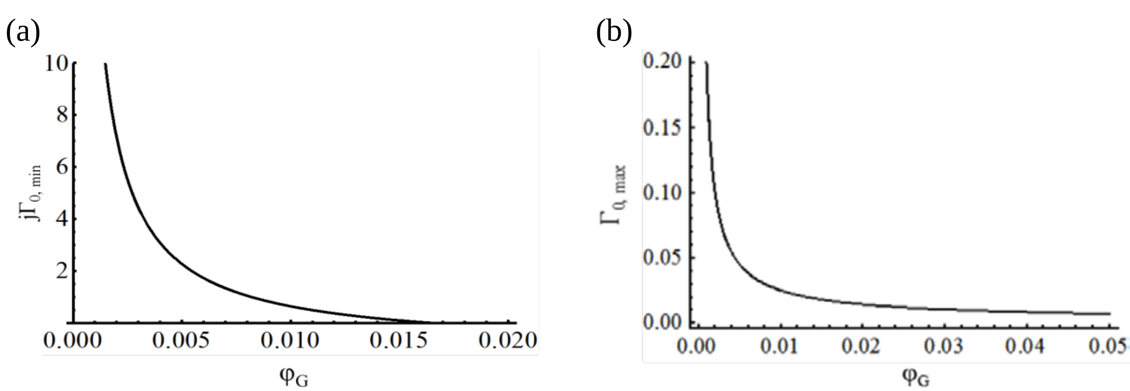


Figure 3. (a) The plot of $j\Gamma_{0,\ min}$ against φ_G and (b) $\Gamma_{0,\ max}$ against φ_G for the free composite body.

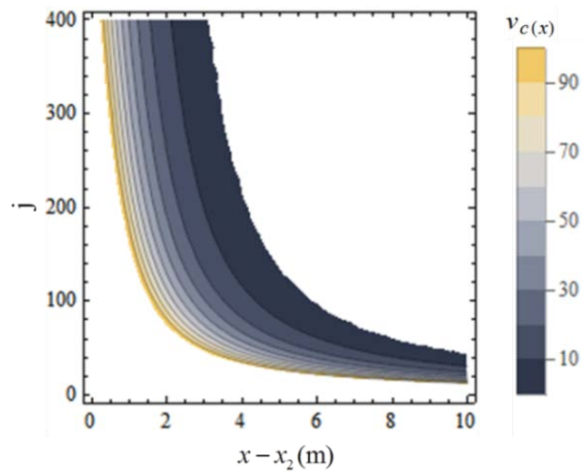


Figure 4. The contour plot of $v_{c(x)}$ (3-100 m/s) against $x - x_2$ (0-10 m) and j (0-400) when the multilayer graphene/polymer nanocomposite membrane (Γ_0 = 0.013, φ_G = 0.02) was used for the AA system.

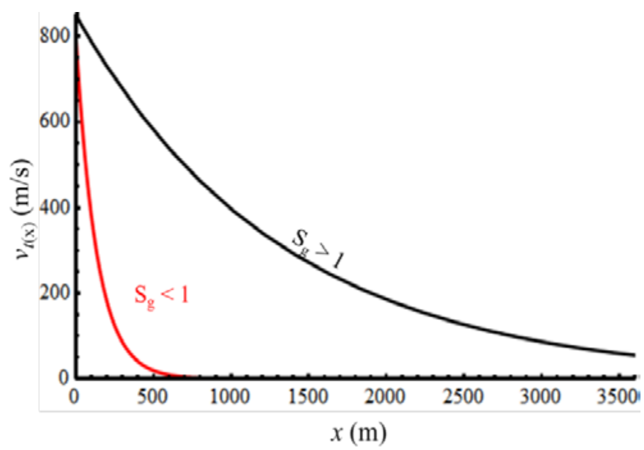
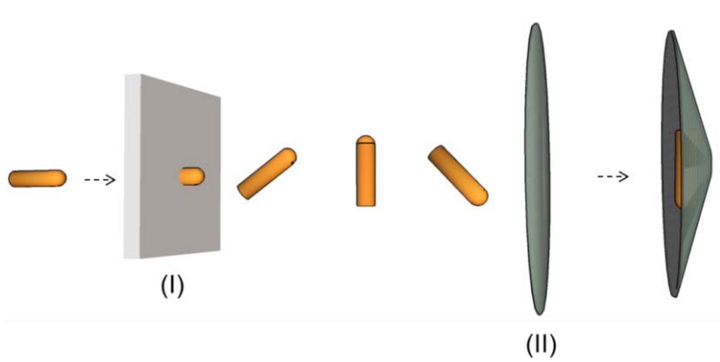


Figure 5. The plot of the velocity ($v_{t(x)}$) against the distance x for the gyroscopically unstable (S_g < 1) projectile which is destabilized by the composite body of AA. The velocity curve of the stable (S_g >1) projectile in air is also include for comparison. Both projectiles have a same initial velocity v_1 = 850 m/s.



Scheme 5. The interception of the projectile with a combination of two composite bodies (I) and (II) in AA, (I) is a regular composite body used to destabilize the projectile and make it tumbling while (II) is the graphene/polymer multilayer composite used to capture the projectile and increase its air drag force.

Supporting Information (Appendix)

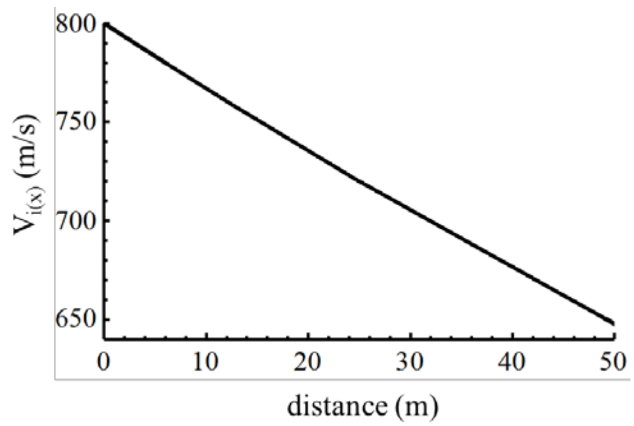


Figure S1. (a) The deceleration curve of the projectile (a 16 grain (m_p = 1 g) flat-nosed,

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1. REPORT DATE June 2016	2. REPORT TYPE Final		3. DATES COVERED *(From–To)* Dec 2014 – February 2015
4. TITLE AND SUBTITLE Defense Science Study Group (DSSG): Think Pieces of the 2014–2015 DSSG Class			5a. CONTRACT NUMBER HQ0034-14-D-0001
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Robert Roberts, Katherine Gliwa, Ryan Bailey, Jacopo Buongiorno, Manish Butte, John Dabiri, Matthew DeLisa, Gregory Engel, Gregory Fiete, Samuel Graham, Jr., Ayanna Howard, Tadayoshi Kohno, Jack McNamara, Todd Murphey, Christina Smolke, Michael Strano, Douglas Weibel			5d. PROJECT NUMBER DA-2-2895
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Institute for Defense Analyses 4850 Mark Center Drive Alexandria, VA 22311-1882			8. PERFORMING ORGANIZATION REPORT NUMBER IDA Document NS D-5828 Log: H 16-000679
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Projects Agency Defense Science Office 675 North Randolph Street Arlington, VA 22203-2114			10. SPONSOR/MONITOR'S ACRONYM(S) DARPA DSO
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
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15. SUBJECT TERMS Defense Science Study Group (DSSG), defense science, defense technology			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Dr. Prem Kumar
a. REPORT Uncl.	b. ABSTRACT Uncl.	c. THIS PAGE Uncl.	SAR	171	19b. TELEPHONE NUMBER *(include area code)* (703) 526-2709

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