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A BIOMIMETIC NOSE

FOR ADVANCED THREAT DETECTION

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Message from the Director

Stuart Stough
HDIAC Director

HDIAC identifies Department of Defense (DoD) gaps and requirements, partnering with Subject Matter Experts (SME) across industry, government, and academia to develop novel solutions to these challenges. Over the course of the last quarter, HDIAC has identified several prevalent, recurring trends. HDIAC evaluated research requirements to forecast potential solutions to the government's most challenging problems.

Force Health Protection

HDIAC has observed a gradual but steady increase in research regarding force health protection. HDIAC received several Technical Inquiries after presenting at Auburn University's Tactical Athlete Human Factors Summit related to tinnitus. Later this year, HDIAC plans to attend the Military Health System Research Symposium to further explore how to fill critical research gaps related to blast-induced tinnitus. These early inquiries helped create a knowledge base on blast-induced tinnitus that HDIAC plans to share with relevant DoD communities of interest.

Furthermore, applied research and development is underway for tissue regeneration following traumatic injuries. HDIAC SMEs from the University of Sydney and ParaGen Technologies are developing methods to allow for better adherence of cells to scaffolding in order to promote tissue growth. Bone regeneration research taking place at the University of Sydney centers on using bioceramics materials to promote optimal balance between strength and bioactivity, while ParaGen uses electrospun nanofibers made from poly(lactic-co-glycolic) acid to build a scaffold on which soft tissue can grow.

In this journal, much needed research regarding force health is presented by U.S. Army Natick Soldier Research, Development and Engineering Center researchers. The article discusses the process of updating the burn injury model, which will allow for the development of improved protective garments that shield against traumatic burn injuries.

Power Generation Technologies

Overall HDIAC scientific and technical activities related to power generation center around a persistent theme regarding the desire for decreased dependence on traditional power technology. An objective of the 2016 Department of Defense Operational Energy Strategy supports the use of locally available energy to reduce the reliance on resupply, including solar, kinetic, and waste-to-energy powered devices.

In this Journal, we explore one of the ways that U.S. Army Garrison Fort Hunter Liggett has used a FastOx Gasification Facility to meet its commitment to the U.S. Army Net Zero Initiative. HDIAC also collaborated with Georgia Institute of Technology researchers to develop a multimodal energy harvesting system to increase the length of time required between battery recharge or resupply. This research was presented at the Department of Energy (DOE) sponsored 2017 Electrical Energy Storage Applications and Technologies Conference.

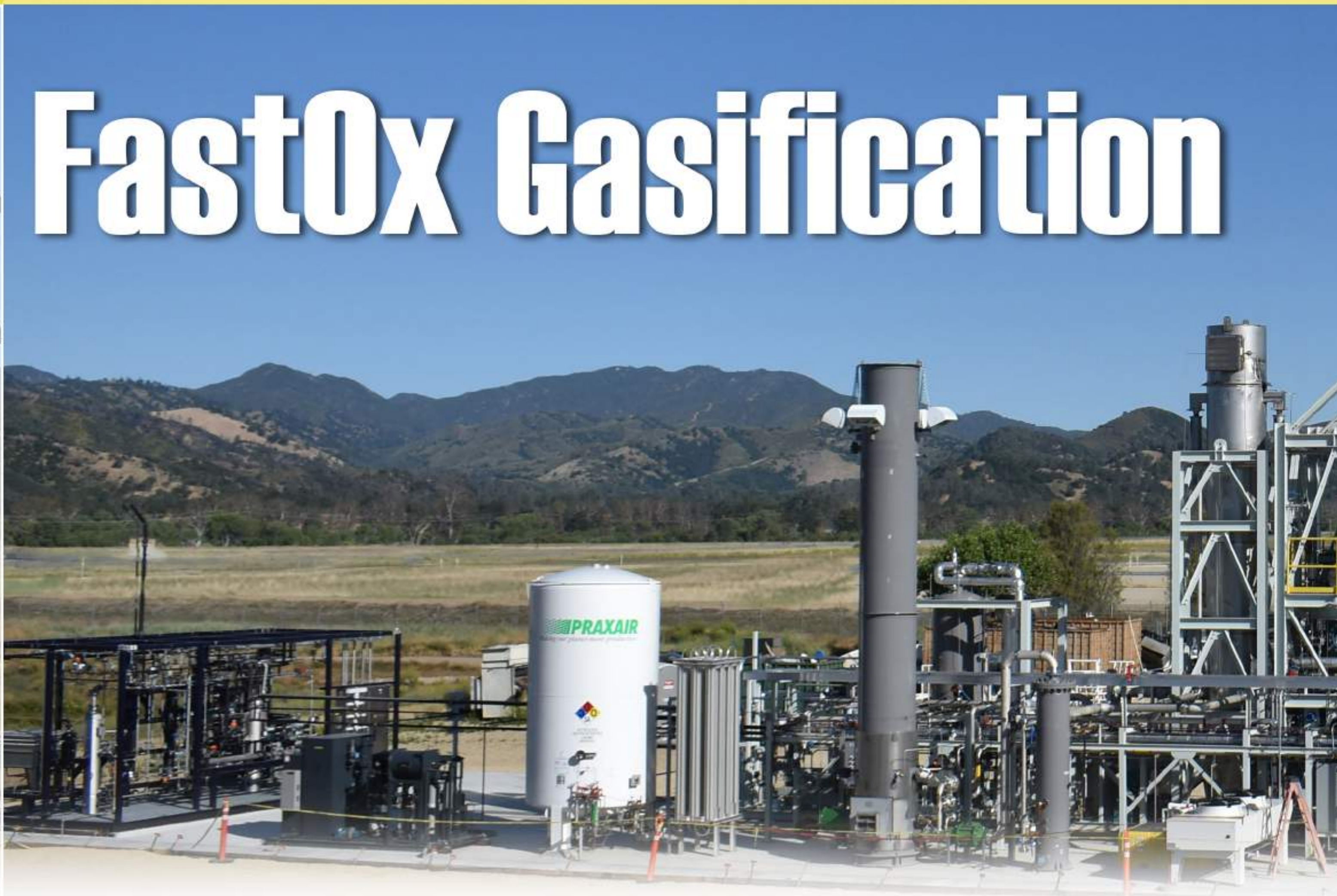
This cross-agency collaboration assisted in bridging a research gap, facilitating discussion between DOE expertise and DoD operational requirements. Additionally, HDIAC attended the 11th Operational Energy Summit to further discuss soldier power gaps and requirements and to share insights into HDIAC shear thickening electrolyte technology.

Future Trends

Materials and manufacturing is a key area of research emerging as a future trend. In this issue of the HDIAC Journal, HDIAC SMEs from Auburn University discuss the use of shape memory alloys to create an actuator that, opposed to traditional motor-based actuators, more closely functions like human muscle. Additionally, additive manufacturing is also a topic of enhanced interest that is being examined from both a materials and health perspective.

HDIAC SMEs from the National Institute for Occupational Safety and Health are exploring potential health effects of 3-D printing. HDIAC has also observed trends regarding future advanced manufacturing techniques, including research into 3-D printed active composites (Georgia Institute of Technology) and emerging techniques for metal powder consolidation (Army Research Laboratory). ■

FastOx Gasification



Rob White, Ph.D.

The Department of Defense (DoD) has charged the service branches with the mission of improving their use of energy and reducing energy-related emissions or byproducts on military bases [1]. Relatedly, the production of municipal solid waste (MSW) at military installations is an ever-present economic and logistical burden that DoD is seeking to mitigate. Hauling waste from often remote locations is expensive and creates unnecessary risk for military personnel (especially in forward operating theaters). Key to meeting both goals is the application of novel technological solutions. One particularly beneficial example is "waste-to-energy" systems, which use trash, MSW, and other waste-related feedstocks to produce electricity and/or fuels. DoD has been interested in fostering the development of such systems since at least 2010 [2,3].

The U.S. Army is helping meet DoD's energy and waste-related installation goals at U.S. Army Garrison Fort Hunter Liggett, which is one of the U.S. Army's 17 Net Zero Initiative pilot installations [4]. There, through a grant awarded by DoD's environmental technology demonstration and validation program (the Environmental Security Technology Certification Program), the Army has established a facility that processes post-recycled waste to produce energy and fuel without the use of combustion. This facility, known as a gasifier, was built and installed by Sierra Energy. The facility heats up waste feedstocks to approximately 4,000 degrees Fahrenheit. This breaks down the feedstock to the molecular level. Organic material is converted into an energy-dense synthesis gas (syngas) while inorganic materials are transformed into non-leaching stone. The syngas can be used to power a generator to create electricity, or further refined into a diesel fuel. The stone is salable as construction aggregate, road base, or cement clinker, potentially providing DoD with additional revenue to defray costs. The Environmental Protection Agency has also certified that the stone is non-leaching and environmentally safe for use [5].

The gasifier plant at U.S. Army Garrison Fort Hunter Liggett is a modification of traditional gasifier and/or blast furnace technology. Sierra Energy's key innovation over the state-of-the-art is a process where steam and purified oxygen are injected into the gasifier vessel at supersonic rates [6]. The carbon in the waste chemically reacts with the steam and oxygen, raising the temperatures in the gasifier. The synthesis gas exits the top of the gasifier and is heated in a piece of equipment known as a polisher, which breaks apart any long-chain hydrocarbons in the gas. The syngas is then cooled in a heat exchanger. The system is designed to operate continuously, as long as waste is available around the clock.

Due to the extremely high operating temperature, the system is suitable for all waste types except radioactive material. If metals or rocks get into the gasifier, for example, they will simply melt and be tapped out at the bottom, similar to the way slag is recovered from a blast furnace. Plastics, tires, oily rags, electronic waste, and medical waste all make excellent fuel for the system. This ability to take

Image Credit | *Photo Illustration created by HDIAC and adapted from photo by Sierra Energy (Released).*

mixed waste is suitable for use on DoD installations. This may be particularly true in areas where sorting waste streams may not feasible.

Since its start-up in December 2017, the gasifier at U.S. Army Garrison Fort Hunter Liggett is capable of handling up to 20 metric tons per day (mtpd) of waste. An attached generator will utilize the syngas to produce electricity, which is then fed into the Pacific Gas and Electric grid. If optimized to exclusively generate electricity, a 20 mtpd gasifier can produce more than 1 megawatt hour from a feedstock with high carbon content.

Simultaneously eliminating waste in a pollution-free manner and generating substantial amounts of installation power may aid DoD in making significant progress towards meeting its operational energy goals [3]. "Sierra Energy's gasification unit plays directly into our net-zero waste program and also benefits our net-zero energy program," said Director of Public Works at Fort Hunter Liggett Greg Vallery. "We also think of it as our part of being a good steward for the environment." ■

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Face Re

ecognition:

Security Contexts, Super-Recognizers & Sophisticated Fraud

David J. Robertson, Ph.D.

Unfamiliar face recognition, the visual identification of a person with whom you are unfamiliar, is commonly utilized in security settings. However, our continued reliance on unfamiliar face recognition for identity verification is not supported by findings from psychological science [1]. Research has shown that whether it be for face photos or live faces, specialists or student control groups, unfamiliar face recognition is prone to error and can be exploited by fraudsters seeking to deceive identity checkers.

The selection of super-recognizers (SRs)—professionals trained in unfamiliar face recognition for security-critical roles—would appear to be the best strategy at present to improve accuracy in unfamiliar face identification. However, the selection and deployment of these individuals must be standardized, with clear criteria for SR categorization, and individual SRs must be assessed across a variety of tests (i.e., matching and memory) to ensure effective deployment.

This article will review the state of the art in unfamiliar face recognition research, before discussing two newer forms of identity fraud: hyper-realistic masks and morphs. Advancements in surveillance and biometric technologies will not obviate the need for border and law enforcement agencies to have capabilities in human-based facial recognition.

Unfamiliar Face Recognition in Security Contexts

Border control officials are required to decide whether a traveler's passport photo matches their face, and the wrong decision in this context could result in an identity fraudster entering the country. Although psychological research has already established that matching unfamiliar faces is prone to error and can be exploited by fraudsters wishing to deceive ID checkers, authorities continue to rely heavily on unfamiliar face recognition for identity verification within the national security framework [2-4].

The Glasgow Face Matching Test (GFMT) is a well-established test of unfamiliar face recognition, which mirrors the photo-to-face matching task performed by border officials [5]. Test participants are asked to decide whether pairs of high-quality face photos show the same person or two different people (see Figure 1). Accuracy on this task is poor: error rates of between 15 and 20 percent are standard, rising to 30 percent when still photographs of faces are taken from poor quality closed-circuit television (CCTV) [6]. In addition, unfamiliar face matching error rates have been shown to reach 40 percent when the faces are of a different ethnic background than the viewer (for example, in U.K./Egyptian faces arrays) [7].

It is important to note that the level of face matching error reported in lab settings using face photos is replicated in tests which use face-photo-to-live-face matching [8,9]. The aforementioned studies were conducted with non-specialist viewers selected from samples of university students at the investigating institution, and, therefore, it is important to determine whether people who carry out these tasks professionally are able to perform more accurately than untrained viewers.

Researchers investigated whether the inclusion of a face photo on credit cards would reduce identity fraud [10]. The study found that motivated supermarket cashiers who frequently check photo-ID cards accepted fraudulent photo credit cards (i.e., the photo did not depict the bearer) as genuine on more than 50 percent of trials. For police officers with experience in forensic identification, error rates were found to be no better than student controls in a task that required matching unfamiliar face photos to CCTV image stills [11]—a core task in security contexts, such as border patrol and military installation base security. In addition, an international study of face recognition performance centered on Australian passport officials reported that this group incorrectly accepted a fake passport photo as genuine in 14 percent of trials—with performance on the GFMT being no different to student controls [12]. These findings suggest that training and professional experience alone do not lead to improved face recognition performance by specialists.

Super-recognizers

As previously outlined, research shows that trained and highly motivated face recognizers in law enforcement, border control, and the retail industry do not show an advantage in unfamiliar face matching performance relative to controls. However, tests of unfamiliar face recognition consistently show a wide range of individual differences in performance. Therefore, selecting SRs could hold the key to improved face matching accuracy [13].

Support for the use of SRs in security contexts has been provided by a small but growing field of literature on the SR advantage. The London Metropolitan Police utilize officers who have been tested and categorized as SRs to assist with the identification of suspects from photographs or still images captured from CCTV video. A recent review stated that individuals categorized as SRs score exceptionally well on standard tests of face recognition (such as the Cambridge Face Memory Test [CFMT]) [14,15] and tests that require both recognition memory for faces and simultaneous face matching [16]. SRs are also adept at recognizing familiar and unfamiliar faces [17,18], and eye-tracking data suggests there may be qualitative differences in the way in which SRs process faces [19].

Figure 1: An example of two trials from the Glasgow Face Matching Test. The top pair shows two instances of the same person (match trial), while the bottom pair shows two different people (mismatch trial) [5].

Research on super-recognition is still in its infancy, and while the London Metropolitan Police Super-Recogniser Unit has received positive feedback from within the force, researchers outline a number of insightful caveats in relation to the research findings, as well as a series of important recommendations [14]. The authors note that when group level analyses are performed (SRs vs controls), the SRs (as a group) outperform controls. However, further analysis of individual SR scores reveal that not all are performing above average on these tests, and, in some cases, SRs can perform exceptionally well on tests of face memory (useful in identifying bad actors) but poorly on tests of face matching (such as detecting a passport photo that does not match a travelers face at border control) [16]. Therefore, SRs cannot be solely selected on the basis of face memory test performance.

The development of standardized tests for super-recognition and clear criteria for the categorization of such individuals in task related contexts (memory/matching) is recommended to further establish the utility of SR in face recognition contexts and to determine if there is a ceiling for unfamiliar face recognition. Additionally, further research is required to explore how superior SR capabilities may

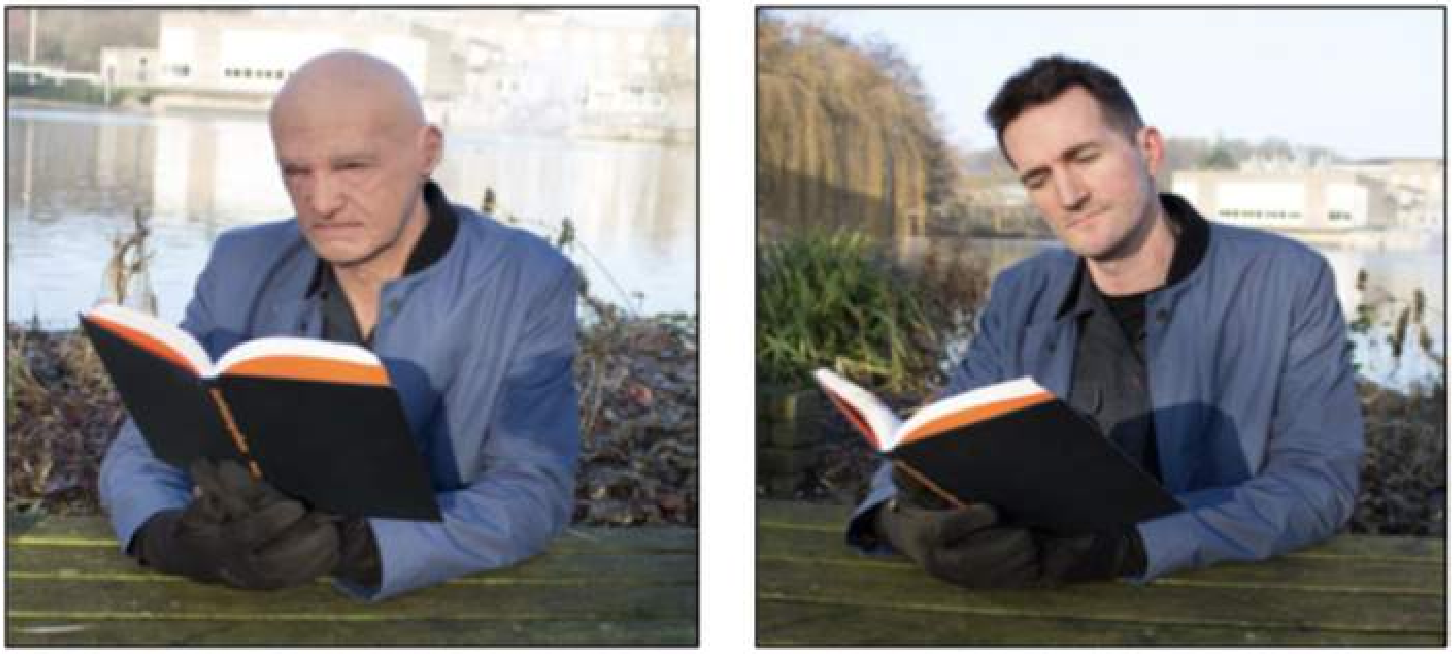

Figure 2: An illustration of the live mask detection experiment set in the middle of a university campus. The images show the participant wearing the hyper-realistic mask (Left) and the participant without the mask (Right) [25] (Released).

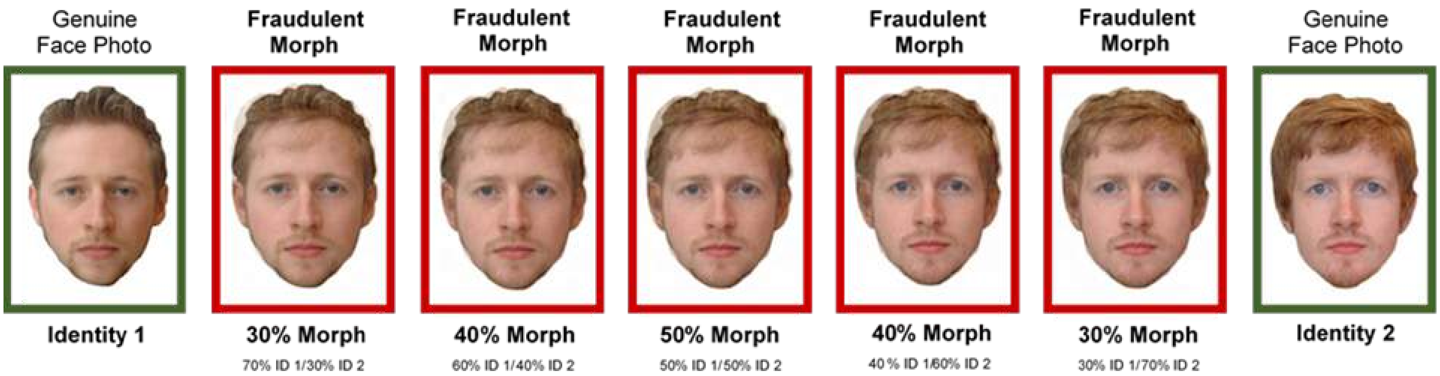

Figure 3: Examples of the morphed passport photos [29]

be utilized to bolster existing recognition algorithms [14].

Sophisticated Fraud: Hyper-Realistic Silicone Masks

It is possible for a fraudster to obtain a passport that displays a photograph of an individual who looks similar to, but is not, the fraudster. SRs have been shown effective in identifying this type of opportunistic face identity fraud. In fact, London Metropolitan Police SR's were found to exhibit above average scores on the GFMT mismatch subtest [20], which is analogous to this type of fraud. However, it is not clear whether SRs would display an advantage in the detection of deliberate disguise, in which a fraudster implements physical items such as glasses, wigs, and beards to physically alter their appearance in order to look more like the person in the stolen passport photo. It is important to note that deliberate disguise facilitates a direct route to identity fraud.

In 1994, researchers assessed the effects of using eyeglasses and beards as disguises [21]. Individuals who participated in this research studied a series of faces which included these disguises. Results indicated that when beards were removed recognition of the face was reduced by 30 percent, and when eyeglasses were removed, recognition was reduced by 40 percent. Similarly, a 2014 study determined that participants accepted two different, but disguised faces, as the same person 19 percent of the time when subjects are of the same ethic background, and 24 percent of the time for subjects of a different ethnic background [22]. While these single item physical disguises provide a route to identity fraud, fraudsters are seeking sophisticated disguises, such as hyper-realistic, over-head silicone face masks.

These silicone masks cover the neck and chest so that clothing can obscure the edges of the silicone. They are produced by a small number of companies and are used primarily in the entertainment industry. However, in a recent string of U.S. bank robberies, a white offender used one of these masks to disguise himself as black [23]. In a photo line-up, six out of the seven bank tellers who witnessed the robberies wrongly identified the culprit as black because they accepted the mask as a genuine face. The situation was only resolved when the girlfriend of the actual offender notified the police, at which point, the detained African American suspect was released from jail [23]. In another notable example, a young Asian man had obtained the passport of an elderly white Caucasian male [24]. Using a hyper-realistic mask, he was able to pass several identity checks at a Hong Kong airport. The use of the mask was only discovered when the perpetrator decided to remove it mid-flight [24]. Such reports represent a concerning new route to identity fraud, in which an individual can completely change their facial appearance to match stolen identification documents.

Despite the use of these masks by fraudsters, only one study assesses the ability to detect the presence of/be fooled by these masks [25]. In the study, a white Caucasian man wore a hyper-realistic white Caucasian mask, as seen in Figure 2, and sat on a bench in the middle of a university campus reading a book [25]. Passers-by were stopped and asked to rate the individual on task-irrelevant dimensions, such as attractiveness, from a distance of 5 meters (m) (near) or 10 m (far). Upon completing the rating, participants were then asked a spontaneous, prompted, or explicit mask-detection question. The study found that none of the participants in the far condition, and only 6 percent in the near condition reported the presence of a mask at spontaneous or prompted questioning. For the explicit report question—"Was that person wearing a hyper-realistic mask?"—57 percent of participants failed to detect that the man was wearing a mask. Detection rates were significantly higher for those viewing from 2 m than 10 m. This study shows that in a naturalistic context, with relatively close viewing distances, mask detection rates are low.

Sophisticated Fraud: Face Morphing

Internet and smartphone users now have access to a variety of face image manipulation apps that support the digital morphing of face photos. These apps can take two different photos of faces and merge (morph) them to become a new photo that retains facial information that is specific to both identities (see Figure 3 for examples). Identity fraudsters can utilize this digital tool in two ways. First, if a fraudster has a willing participant, a passport morph could fool a passport renewal official (as it looks somewhat like the participant's file photo) into issuing a fraudulently obtained genuine (FOG) passport, which both individuals can use [26-28]. Secondly, even without access to a participant, fraudsters can use stolen identity information to complete the same process to obtain a FOG passport for their own use.

Recent work showed that the acceptance rates for passport morphs as a match to a genuine target image was significantly greater than that for a similar looking foil, when human recognizers were unaware that there were morphs in the set [29]. While acceptance rates for 50/50 morphs (which are likely to confer the greatest deception in this context) were significantly reduced when participants were made aware of this type of fraud and were asked to actively detect such images, the acceptance rate still remained higher than that for a different, but similar looking, individual. Although, as noted above, there has not yet been any direct assessment of SR ability to detect physical disguise. The authors of this study reported that morph detection accuracy correlated with accuracy on the mismatch sub-test (but not the match subtest or overall accuracy) on the GFMT. This suggests a potential link between established super-recognition skills and the ability to detect passport morphs, and SRs could potentially serve as an effective countermeasure to morph fraud.

Conclusion

While the selection and recruitment of SRs is a welcome advance in improving the accuracy of unfamiliar face identification, the standardization of testing and selection criteria as well as subsequent effective deployment are key further considerations. Additionally, further research is required to ensure the development of effective counter-measures against this type of sophisticated fraud, such as enhancing machine learning techniques by integrating lessons learned from SRs. The Department of Defense may benefit from this research as border patrol and military installation base security sometimes still visually inspect persons and their corresponding identification to prevent unauthorized access. The aforementioned face recognition techniques could also be used for identification of individuals during surveillance missions and in body identification. ■

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A Biomimetic Nose

for Advanced Threat Detection

Thomas L. Spencer
Alexander B. Lee
& David L. Hu, Ph.D.

Current sensors capable of detecting chemical, biological, radiological, and nuclear agents are limited by range, volume, and environment. Due to these limitations, researchers at the Georgia Institute of Technology (Georgia Tech) are developing a biomimetic nose capable of detecting trace amounts of agents both in air and in liquids and at distances greater than currently possible. Agencies within the Department of Defense (DoD) and the Department of Homeland Security, such as Edgewood Chemical Biological Center, Defense Threat Reduction Agency, U.S. Coast Guard, and U.S. Customs and Border Protection, rely on sensors to protect people, animals, and food products from contamination and to impede drug trafficking and smuggling of banned items. In many cases, sensors are used for early detection of possible chemical/biological agents, providing early warning of these threats. However, as good as current sensor technology has become, there are still significant limitations that can hinder security and military operations.

For example, ion and mass spectrometry separates ions based on their mobility and mass-to-charge ratio and can even detect trace

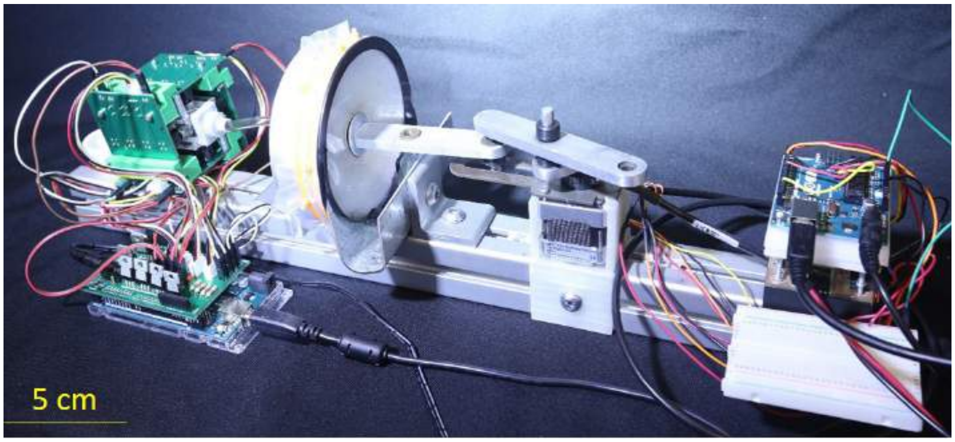

Figure 1: G.R.O.M.I.T. electronic nose

amounts of fentanyl wiped off a surface [1]. Colorimetric sensor arrays change color when exposed to chemical aerosols [2-4], and microcantilever devices produce a measurable deflection due to the gas causing a chemical reaction, surface stress, or resonant frequency change [5]. For liquids, methods such as fluorescence quenching for explosive detection [6] and microfluidics for medical diagnosis [7] have shown much promise.

Despite these advances, a universal challenge remains—these sensors are proximity limited. They must be placed close to the target chemical or the chemical must be placed directly on the sensor, and detection is only possible if the chemical is present in sufficient concentrations. This is a significant limitation of modern sensors because the location and/or presence of target chemicals is often unknown, such as in the detection of narcotics at an airport or explosives in the field. Moreover, a more advanced challenge is the detection of contaminants underwater, an application that would be useful for port and harbor security, pipeline management, and securing public drinking water. However, contaminants (such as chlorine and salt) present in liquids (i.e., drinking water and seawater) cause existing underwater sensors to degrade over time, requiring the sensor to be replaced or recalibrated. With these challenges still outstanding, researchers at Georgia Tech have taken a step toward countering traditional limitations associated with sensors used for chemical detection.

Gaseous Recognition Oscillatory Machine Integrating Technology

Olfaction is defined as the chemoreception that forms the sense of smell. In 1964, the first device to perform olfaction was built using microelectrodes [8,9]. The device was only capable of registering a change between differing volatiles. It could not classify or identify the odorant, which is the contemporary goal of machine olfaction. In 1988, the term "electronic nose" was introduced at a conference in the U.K. [10], and the term has evolved to include any device intended to detect odors using a sensor array [11]. Current goals in the field of chemical detection include reducing device size, decreasing cost, enhancing sensitivity using multi-sensor arrays (such as those found in "nose-on-a-chip" technologies [12]), and improving signal processing [13]. Work by scientists at both the National Institute of Standards and Technology and the Food and Drug Administration has focused on improving the detection sensitivity of sensors by replicating the mechanism seen in canine sniffing [14]. Researchers at Georgia Tech attempted to advance the capabilities of detection even further by combining the use of this phenomenon with machine learning, developing a new type of biomimetic nose, which features enhanced sensitivity for applications in both air and underwater.

At a conference last year, the Georgia Tech team participated in a student competition to design and build an electronic nose capable of distinguishing multiple types of cheeses [15]. Competing teams were restricted to the use of the same type of simple, inexpensive, non-selective metal oxide

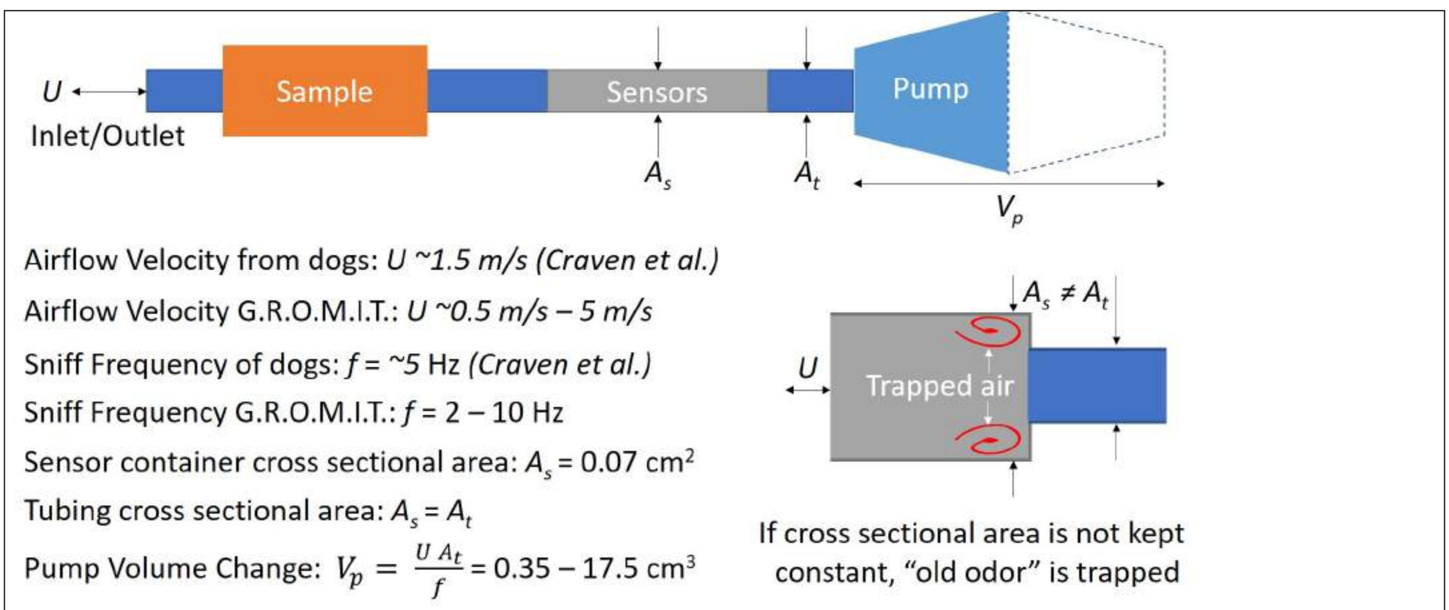

Figure 2: G.R.O.M.I.T. physical constraints

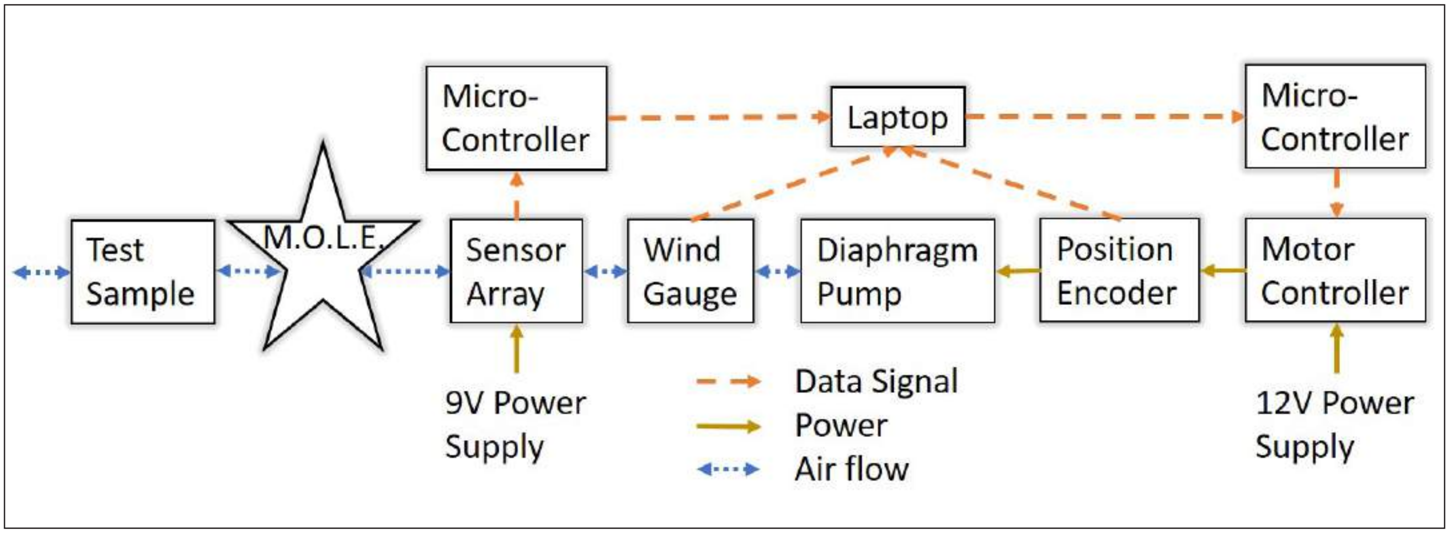

Figure 3: G.R.O.M.I.T. data, power, and air flow diagram

sensor, which required significant modifications in post-processing by Georgia Tech researchers. This limitation led researchers to incorporate machine learning and a pre-concentrator into the electronic nose design. Although the goal of the competition was to develop a device capable of distinguishing between types of cheese, the underlying science remains the same regardless of the sample tested. Therefore, this technique may be capable of improving the sensitivity of detecting airborne particles, such as TNT, PETN, and RDX from explosives [16], lending itself to DoD- and DHS-relevant applications.

A review of studies regarding mammalian olfaction revealed that mammals sniff at a frequency ranging from 2 to 10 hertz (Hz) [17-20]. Therefore, researchers sought to mimic this range with Gaseous Recognition Oscillatory Machine Integrating Technology (G.R.O.M.I.T.), which can be set to sniff at a specific frequency. In order to mimic the mechanics of a sniff, Georgia Tech researchers developed a 3-D printed diaphragm pump resembling a bellows (see Figure 1), making the motion of air repeatable and controllable, evacuating the bellows by moving air at a specific velocity and frequency. Given the cross-sectional area of the tubing, A_t, the corresponding equation is **$\Delta V = (U A_t)/f$** where ΔV is the volume change of the bellows, U is the desired air velocity, and f is the desired frequency of sniffing. For initial testing, the device was set to mimic the frequency/velocity of a dog's sniff—a frequency of 5 Hz and velocity of 1.5 meters per second (m/s) [19] (see Figure 2).

The pump can move air at a speed of up to 5.5 m/s and within the aforementioned frequency range. A section for the sample requiring detection and a previously calibrated metal oxide sensor are in series with the pump [21]. The entire system is controlled by two microcontrollers and computer program, as illustrated in Figure 3. G.R.O.M.I.T. may be the first step in identifying how sniffing improves detection. While a number of theories exist, there is no clear consensus, but using G.R.O.M.I.T. in experiments may help to test competing hypotheses. The Georgia Tech team hypothesizes that sniffing can temporarily increase the concentration of target particles.

In a typical sensing system, air is either stagnant or moved quickly across the sensors causing a decrease in pressure [22]. Both possibilities are disadvantageous to sensing, but sniffing can avoid this problem. The transition from inhalation to exhalation in sniffing causes fluids (e.g., air and water) to reverse direction, creating a brief spike in internal pressure. This pressure brings the chemical molecules closer together, maximizing their number in the detection volume of the sensor. Moreover, larger particles respond less to these pressure fluctuations because it takes a greater force to overcome the inertia of such particles [23]. Therefore, sniffing affords the ability to perform particle size discernment whereas traditional sensing systems rely on chemical reactions alone. To take advantage of the brief period (the time between inhalation and exhalation) of high particle count, the G.R.O.M.I.T. needs a brain, which was created utilizing machine learning.

Machine learning allows computers to find their own solutions to problems without the programmer writing the solutions out. This can be done by separating complex tasks into simpler tasks that the computer can handle, such as grouping things based on a set of metrics. For example, humans categorize produce as vegetables or fruits—a delineation based on the sugar content of food. Similarly, in machine olfaction, the computer is presented the task of identifying various odors. To accomplish this task, the programs group data points based on a set of metrics. However, the central challenge of machine olfaction is in identifying these metrics, referred to as features, based on the data collected.

As G.R.O.M.I.T. "sniffs," the odorants displace oxygen directly atop the sensor, in turn changing the sensor's voltage. These voltage readings on their own are of little use. Instead, relevant features must be measured from them. In the produce example, the relevant feature was the sugar content of the produce. During recent testing of G.R.O.M.I.T. [15], a signature unique to each type of cheese was derived from three features: the rate at which the voltage readings change, the variation in these changes, and the rate at which the odorant was expelled from the system [20]. These features allowed G.R.O.M.I.T. to group similar odors as coming from the same source. If each feature represents an axis in three-dimensional space, then every odor sample can be assigned a position in space based on G.R.O.M.I.T.'s measurements. A Nearest Neighbors algorithm was applied to group the samples based on their distance to other samples,

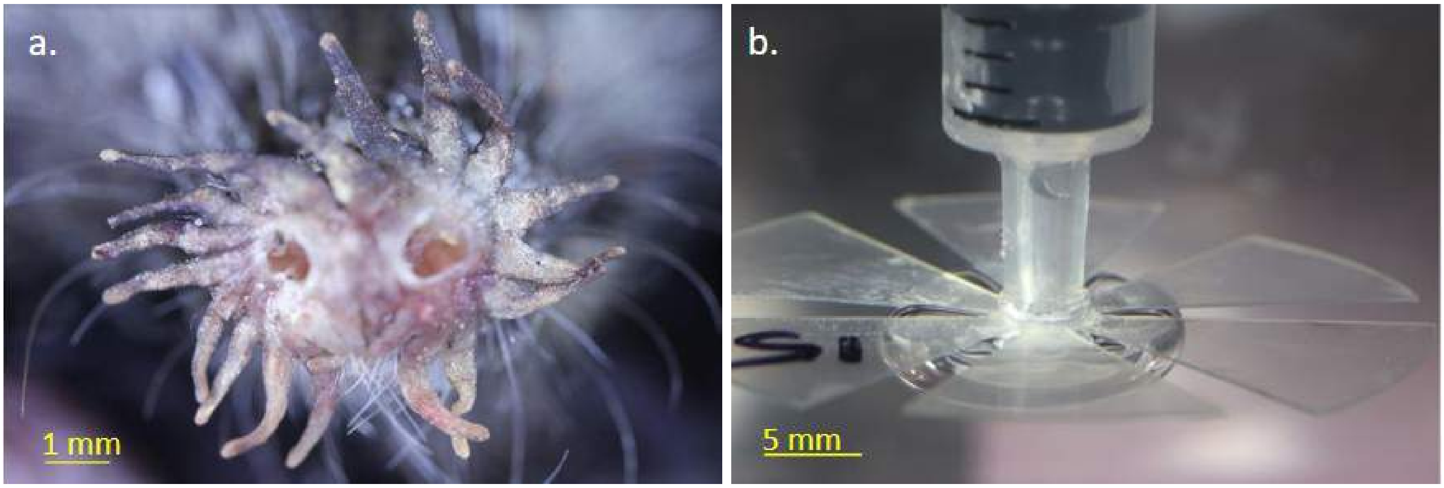

Figure 4: (A) Star nose mole and (B) M.O.L.E. attachment for use with G.R.O.M.I.T.

and then a Support Vector Machine algorithm forms boundaries which establish the training data. This training data is G.R.O.M.I.T.'s life experience—in other words, as G.R.O.M.I.T. is given a new sample, it can identify the source based on what it has previously identified. The system proved to be a successful proof of concept, successfully distinguishing 83 percent of cheese pairings [15]. Further research is needed to better distinguish between samples with nearly identical chemical composition. The success rate could be improved by replacing the existing rudimentary sensor with a more advanced sensor, such as microcantilever sensor or colorimetric sensor array.

Underwater Detection

Machine olfaction has generally been used for air-based applications, but there are many potential applications for employing this technique underwater, including monitoring ship hulls, entrances to harbors, and within critical pipelines. However, several challenges exist with sensing in an all-liquid environment. Specifically, submergence gives rise to unwanted biofilms that impede measurements [24], and overexposure to harsh chemicals requires sensor recalibration after only a few days of use [25]. However, nature may offer solutions to overcoming these challenges. Georgia Tech researchers drew inspiration from a number of species of semi-aquatic mammals that have the ability to smell underwater: star-nosed moles (see Figure 4a), American water shrews [26], and Russian desmans [27]. These rodents track the scent of their prey at the bottom of swamps by utilizing coordinated sniffing. They blow bubbles out their noses, quickly sucking them back in before the bubble can float away. The inhaled bubble is coated with molecules of the target smell, enabling the animal to pinpoint the target's location.

Based on the anatomy of the star-nose mole, Georgia Tech researchers developed an attachment, the Marine Olfaction Laser-cut End-effector (M.O.L.E.), for use with G.R.O.M.I.T that can be submerged in a liquid without encountering the aforementioned challenges. The Georgia Tech team investigated how the unique shape of the star-nosed mole allows it to perform bubble-based sniffing. Researchers developed laser-cut plastic stars mimicking a mole nose and affixed them to syringes which, like the mole, blow bubbles underwater (see Figure 4b). By testing a range of star shapes, the team elucidated how the star shape prevents bubbles from escaping—bubbles are stabilized by deformation by the arms of the star. As a mole blows a bubble, the bubble tries to rise through the gaps in the star while surface tension tries to minimize the bubble's surface area. Arms at a proper spacing cause a bubble to stay balanced on the star, even as the mole moves around during sniffing. Researchers fitted G.R.O.M.I.T. with the plastic star shapes and found that bubbles from multiple sniffs could be stabilized. Such star-shaped adapters would allow G.R.O.M.I.T. to stabilize bubbles long enough for chemicals to diffuse into them.

By mimicking the distinct shape of a mole nose, standard gas sensors can be employed rather than traditionally used sensors that must be immersed in a target liquid. The M.O.L.E. can be submerged, while still connected to G.R.O.M.I.T. stationed a distance away at a dry location. Together, the G.R.O.M.I.T. and M.O.L.E. are the first step in the design of an electronic nose capable of extended underwater detection.

Conclusion

The G.R.O.M.I.T. is a novel device that provides enhanced chemical detection and characterization. It employs machine learning algorithms to continually improve agent characterization and also mimics animal sniffing. Although current detection methods (e.g., long inhales or exposure to stagnant air) face limitations regarding sample proximity, the G.R.O.M.I.T. may fill this gap. Additionally, the M.O.L.E. allows for enhanced chemical detection underwater. Further research is required to determine if employing a higher quality sensor can enhance machine olfaction and also to evaluate alternative methods for introducing chemical samples into the sensor. The G.R.O.M.I.T. and M.O.L.E. may prove a valuable, versatile tool for CBRN threat detection in air and underwater with applications ranging from military use (such as maritime and active combat operations) to critical infrastructure protection. ■

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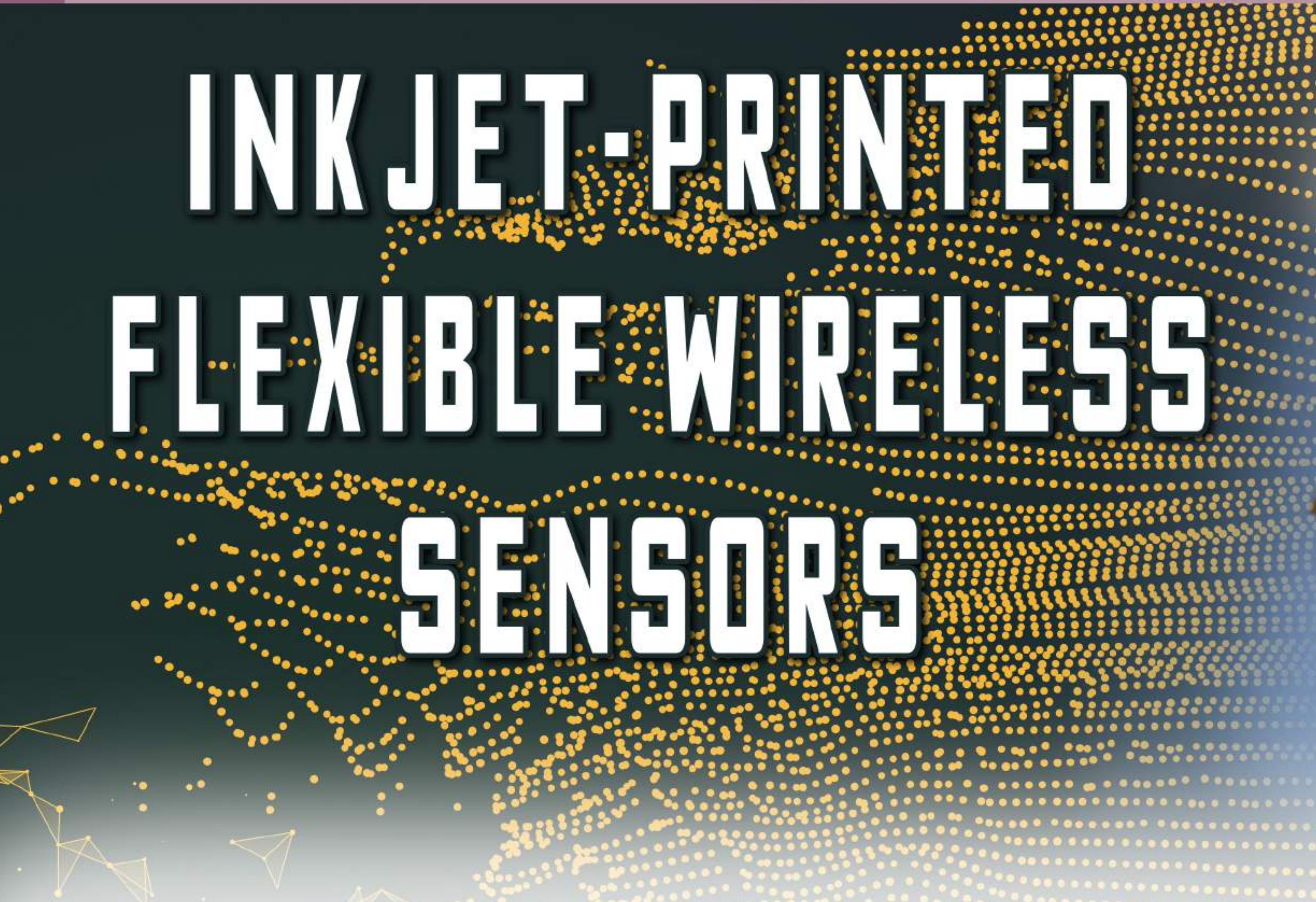
INKJET-PRINTED FLEXIBLE WIRELESS SENSORS



Yunnan Fang, Ph.D.
Jimmy G. D. Hester
& Manos M. Tentzeris, Ph.D.

Chemical warfare agents (CWAs) remain a major concern worldwide. This is especially true for nerve agents, which have played a dominant role among CWAs since World War II. There is evidence to suggest that the Islamic State of Iraq and Syria has pursued an aggressive CWA development program in recent years and has likely done so with the help of scientists from a number of countries [1,2]. Consequently, detecting CWAs and providing early warnings have become increasingly important for protecting civilians and military personnel alike.

Currently, CWA detection continues to rely mostly on laboratory-based analytical techniques, such as nuclear magnetic resonance, mass spectrometry, and enzyme-linked immunosorbent assay. These techniques are associated with a number of factors—such as bulky equipment, lengthy sample preparation, solvent management, and wet solutions—that hinder portability and ease of use in the field. Skin- or clothing-based wearable sensors provide excellent portability. However, applications for either wearable sensors and/or wide-area surveillance for CWA detection are typically hard-wired and can come with high installation and maintenance costs, as well as reliability concerns. These factors present the need for wireless sensing.

Our work seeks to wirelessly detect CWA-relevant chemicals from ultra-long distances through the use of robust, flexible, ultra-lightweight, miniature-sized, wearable sensors. These sensors can also be rapidly mass-produced at low cost. Accordingly, we have modified the surfaces of commonly used flexible substrates, such as Kapton polyimide films. Our modifications allow for the greater printability of both water- and organic solvent-based inkjet inks; enhance the robustness and durability of the sensor; and allow for the development of ultra-long-range wireless sensing of CWA-relevant chemicals. This ability enables units in the field to efficiently create an agnostic sensing network on-demand. In addition, the wireless feature provides units the capacity to assess the threat while remaining at a safe distance from potentially harmful agents.

Surface Modification for Enhanced Printability and Robustness

Most commonly-used flexible substrates, such as Kapton polyimide or polyethylene terephthalate films, are highly hydrophobic and relatively inert. These characteristics inhibit the deposition of water-based inks. However, the complete inkjet printing of an entire device often requires the deposition of both water- and organic solvent-based inks onto the same substrate surface.

As an improvement on traditional surface modification methods—such as UV/ozone treatment [3,4], plasma etching [4,5], ion-beam etching [6,7], acid [4,8], and/or base treatments [9-11], and laser ablation [12-14]—we recently developed

Image Credit | *The newly-established Flexible Hybrid Electronics Manufacturing Innovation Institute will help enable a new class of stretchable, conformal devices that can add Deneault. (Available for viewing at https://media.defense.gov/2015/Sep/25/2001304096/-1/-1/0/150925-F-FX606-001.JPG)*

several facile, environmentally-friendly, gentle, and inexpensive methods to surface-modify flexible Kapton substrates. These methods have the added benefits of not compromising the structural integrity and properties of the substrates or generating environmentally-harmful byproducts or waste.

For example, a computer-automated layer-by-layer (LbL) deposition process was used to apply polyelectrolyte multilayers (PEMs) to flexible and inherently hydrophobic Kapton HN films to tune their surface hydrophobicity [15]. This surface

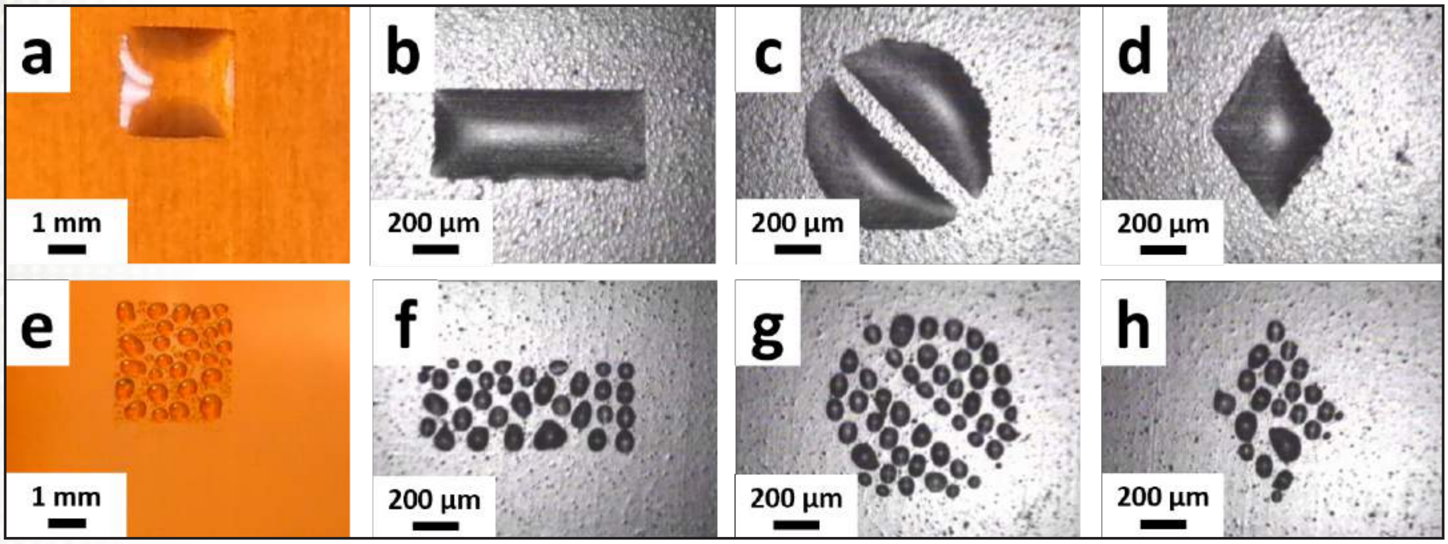


Figure 1: Optical (A and E) [15] (used with permission from the Royal Society of Chemistry) and optical microscopic (B, C, D, F, G and H) images of various patterns printed surface modified (upper panel) and unmodified (lower panel) Kapton substrates with water-based inkjet inks [17] (licensed under Creative Commons Attribution 4.0 International License).

greater utility to existing products and make possible new tools and technologies. Photo Illustration created by HDIAC and adapted from U.S. Air Force photo by James

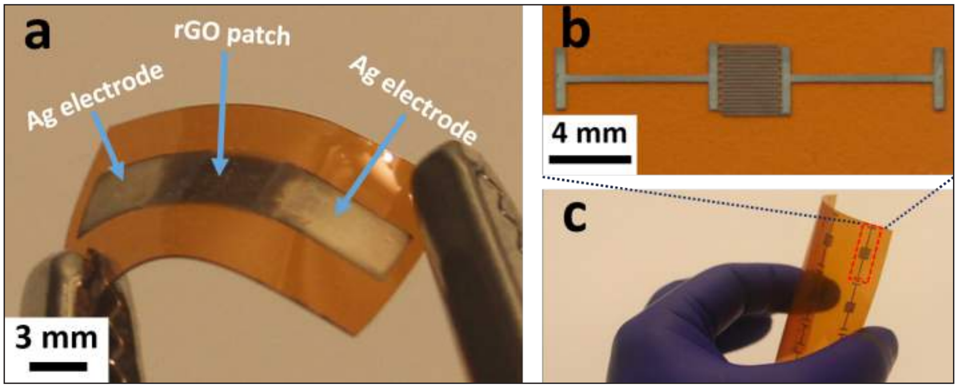


Figure 2: (A) Inkjet-printed flexible, robust, ultra-lightweight, miniature-sized and wearable CWA-relevant sensors. (B) A reduced graphene oxide-based sensor on surface modified Kapton substrate. (C) Single-walled carbon nanotube-based sensors on surface functionalized Kapton substrate [17,18] (licensed under Creative Commons Attribution 4.0 International License).

modification enabled a higher degree of printability of both water- and organic solvent-based inkjet inks onto the substrates. To our knowledge, this PEM-based Kapton surface modification method was the first to use only weak polyelectrolytes. Compared to prior work, which used strong polyelectrolytes, our weak-polyelectrolyte method can systematically and easily control the substrate's properties by varying the pH of the polyelectrolyte solutions [16]. These properties include the thickness and interpenetration of the PEM layers and the wettability of the resulting Kapton surfaces.

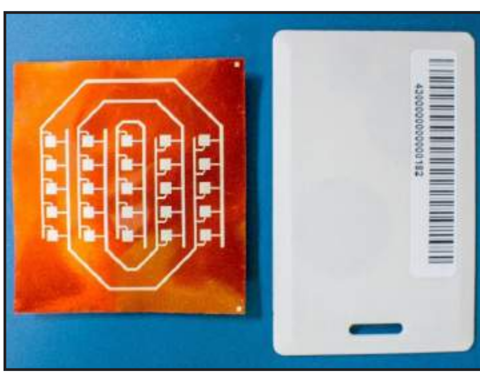
In another instance, we developed a bio-enabled and maximally mild LbL approach to surface-modify Kapton HN substrates [17]. Similar to the aforementioned PEM-based surface modification method, this novel bio-inspired method also significantly reduced the inherent surface hydrophobicity of the substrates, enabling a higher degree of wettability of both water- and organic solvent-based inkjet inks. As shown in Figure 1, multiple precisely-controlled shapes (a square, a rectangle, a circle with a 100 µm-wide gap in the center, and a diamond) were able to be inkjet-printed as designed on surface-modified Kapton substrates (upper panel, Figure 1, a-d). In contrast, the water-based ink drops made isolated small "islands" when printed on surface-unmodified Kapton substrates (lower panel, Figure 1, e-h).

Aside from allowing for the enhanced printability of both water- and organic solvent-based inkjet inks, our surface modification approaches also significantly enhanced adhesion between the inkjet-printed traces and the resulting substrates. Figure 2 shows some of our flexible, robust, ultra-lightweight (< 25 mg), miniature-sized (as small as 1.0 cm x 1.0 cm) and wearable CWA-relevant sensors, inkjet-printed with various water- and organic solvent-based inks on surface-modified Kapton substrates. Bend and adhesion tests proved their excellent robustness and flexibility [15,17,18]. The strong adhesion of sensor to substrate, the insensitivity of the wearable sensors to repeated bending, and their ultra-lightweight and miniature-sized nature allow for ease of wear.

Our novel and facile surface modification methods, which generally tune the surface properties of the substrates, benefit the inkjet-printing process and facilitate the general deposition of functional materials with various solutions or suspensions. In addition, since these methods can produce substrates bearing positive or negative surface charges, they offer an additional advantage as it pertains to deposition from an electrically charged solutions/dispersions/inkjet ink: the "coffee ring effect" can be drastically reduced. This results in a significant enhancement of the uniformity of the resulting thin films [15]. This advantage is realized by the local electrostatic interactions created between the oppositely charged substrates and the particles in the solutions/dispersions/ink; the electrostatic interaction prevents the particles from migrating to the substrate perimeter during the drying process after deposition.

Wired Sensing of CWA-relevant Chemicals

Our inkjet-printed flexible sensors have sensed, in a wired fashion, simulants of different types of CWAs. For nerve agent-relevant sensing, we have sensed a number of simulants such as dimethyl methylphosphonate (DMMP), diethyl ethylphosphonate (DEEP), diethyl methylphosphonate, and pinacolyl methylphosphonate. In one example, a proof-of-concept sensor was inkjet-printed with a graphene oxide ink, and the inherent properties of reduced graphene oxide were used to sense DEEP [15]. In another example, a hexafluoroisopropanol group-containing chemoselective compound (selector), which has been shown to interact with the aforementioned organophosphate-based simulants via hydrogen bonding [19, 20], was used to functionalize our sensing materials for enhanced sensitivity and selectivity. A small and structurally simple compound (containing only one hexafluoroisopropanol group per molecule), 2-(2-hydroxy-1, 1, 1, 3, 3, 3-hexafluoropropyl)-1-naphthol, was employed as our selector to sense DMMP [17] and DEEP [18]. Based on the assumption that more target molecules absorbed to a sensor will result in greater measurable changes, we used a bifunctional polymer comprising multiple hexafluoroisopropanol groups



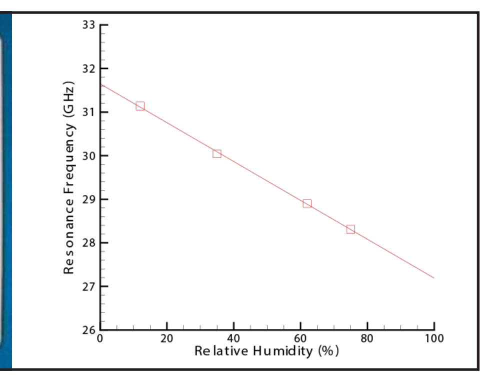


Figure 3 (Left): Optical image picture of the fully-inkjet-printed chipless Van Atta tag next to a standard-size credit card [23]

Figure 4 (Right): Measured variations of the tag resonant frequency relative to the ambient relative humidity level [23]

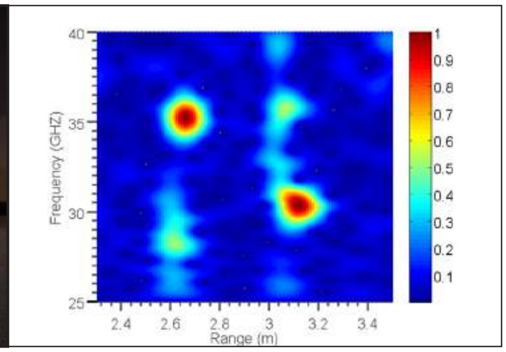


Figure 5 (Left): Configuration used for the 30 m-range interrogation of the chipless tag/sensor [26]

Figure 6 (Right): Measured spectrogram of a multi-sensor/tag configuration [26]

and a naphthalene group in our nerve agent-relevant sensors. This bifunctional compound binded to both our sensing materials (semiconducting single-walled carbon nanotubes) via π-π interaction (which facilitated its uniform and thin deposition on the sensing materials) and our target vapor via hydrogen bonding interactions.

So far, our inkjet-printed flexible, ultra-lightweight, and miniature-sized chemiresistive sensors have detected the aforementioned nerve agent simulants at a parts-per-billion (ppb) level. We are also developing efficient ways to enhance the sensitivity of our inkjet-printed sensors. We developed a facile, mild, and generic wet chemical approach to modify the material and geometry of the inkjet-printed interdigitated electrodes of our semiconducting carbon nanotube-based sensors. As a result, the sensitivity to DEEP was enhanced by at least five times [18]. This work suggests that the electrode material and the Schottky contacts between the semiconducting sensing elements and electrodes might play an important role in the gas sensing process. This finding can be applied on a generic scientific basis to other semiconducting material-based sensors for sensitivity enhancement.

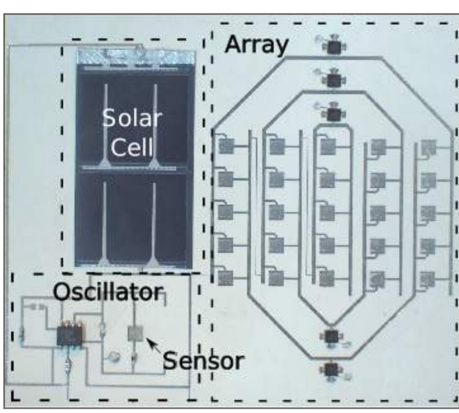
Aside from nerve agent-relevant sensing, we have also sensed simulants of other types of CWAs. Methyl salicylate, which is a simulant of the blister agent mustard gas, has been one of our sensing targets. We have utilized different techniques to screen for the correct selectors for this compound. In one instance, we screened selectors based on Hansen solubility parameters [21], and, as a result, some commercially available, low-cost polymers such as poly(ethylene-co-vinyl acetate) were used to functionalize our inkjet-printed sensors. In another example, we screened selectors for this simulant based on its interactions with biological molecules. Salicylic acid-binding protein 2, which exhibits strong esterase activity and high and specific binding affinity for this compound [22], was chosen as a selector. We have detected methyl salicylate vapor at ppb levels and are developing various ways to further enhance the sensitivity.

Fully-inkjet-printed Chipless RFID Cross-polarizing Van Atta Sticker

The Van Atta sticker, pictured in Figure 3, follows a sensing, chipless RFID approach that allows for a reading range more than one order of magnitude higher than the previous state of the art. Chipless RFIDs are electromagnetic circuits and structures able to encode data or translate environmental properties into a remotely-detectable electromagnetic signature. The main advantage of chipless RFIDs is their lack of requirement for active components—as their name indicates—and therefore an ability to operate independent of a power source. Consequently, most such designs can also be fully-printed onto flexible substrates to produce ultra-low-cost stickers. Nevertheless, their linear behavior has traditionally made their detection and interrogation quite challenging at ranges in excess of 1 m.

This work constitutes the combination of a high-performance cross-polarizing mm-wave Van Atta tag and a high-resolution signal processing detection approach. The tag (shown in Figure 3), smaller than a regular credit card, operates in the Ka band (26.5 – 40 GHz), which allows it to display both a small size and a high gain, thereby enhancing its detectability. The tag's Van Atta configuration allows it to display this property regardless of its orientation to the reader. Moreover, the structure is engineered to cross-polarize its response relative to that of the interrogation wave impinging from the reader, thereby greatly enhancing the contrast of its response to the mostly co-polarized background interference.

As a preliminary demonstration of this tag's utility, the device was printed onto a polyimide film (Kapton) that has a humidity-sensitive dielectric permittivity, which creates a detuning of the resonant frequency of the device and can directly be associated with a given humidity level (shown in Figure 4). Coupled with a high-performance matched-window spectrogram data-processing approach, this structure was localizable at a range in excess of 30m (shown in Figure 5), and is compatible with high-density implementations. In such a context, it has the ability to discriminate among different tags in both frequency and range dimensions (shown in Figure 6). Using a high-performance reader, a reading range on the order of 50 m was reported for a similar structure [24].



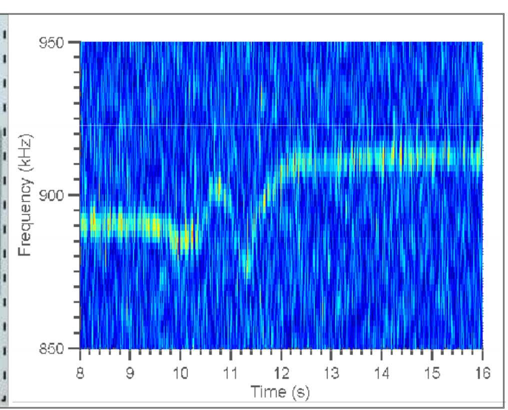


Figure 7 (Left): Picture of the printed semi-passive Van Atta tag [27]

Figure 8 (Right): Measured real-time spectrogram of the tag during an ammonia detection event [27]

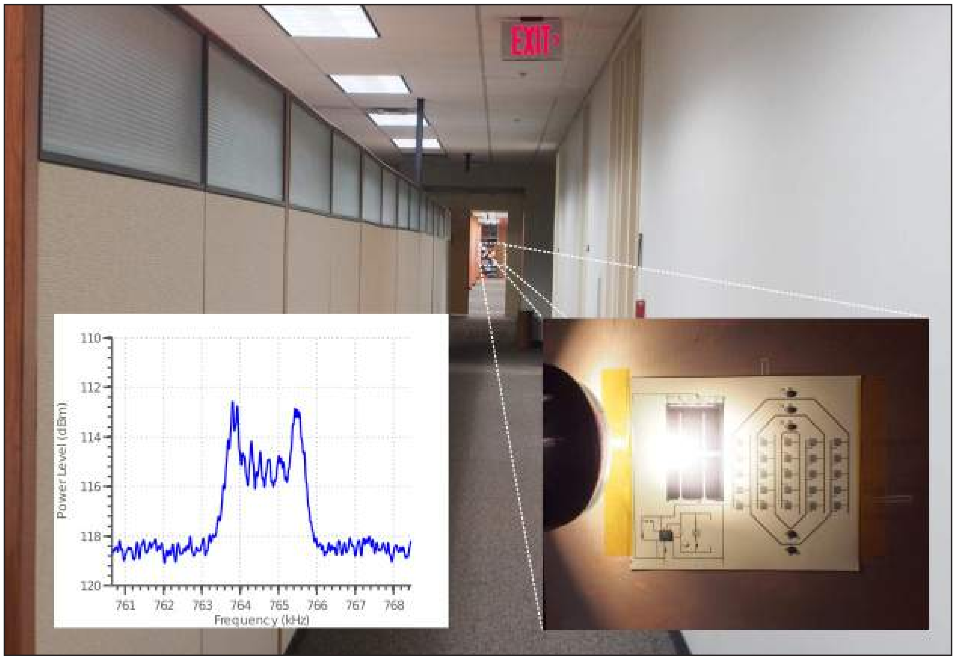


Figure 9: Configuration used for the 80 m range interrogation of the semi-passive tag/ sensor [27]

This approach allows for the fabrication and detection of constellations of fully-printed, component-less, battery-less, ultra-low-cost "smart skins" stickers for ubiquitous humidity and gas-presence monitoring. The approach could be readily adapted and applied to the detection of CWA-relevant chemicals. For example, DMMP sensing with polymer substrates whose dielectric permittivity is sensitive to the analyte has been demonstrated [25].

Semi-passive Kilometer-range-compatible Energy-autonomous Millimeter-wave RFID

This RFID device is based on a millimeter-wave Van Atta reflect array semi-passive backscatter front-end, for real-time gas monitoring at kilometer-range. Its operational frequency was set at 28 GHz in what is to become one of the future 5G mobile bands. This device can operate using power levels of low two-digit microwatts—three to four orders of magnitude lower than that of the standard active communications technologies used in Internet of Things devices—and can therefore operate autonomously, exclusively on harvested ambient energy. Switches were used to turn the tag "on" and "off," thereby modulating its radar-cross-section and introducing detectable non-linearities in the response received by the reader. In the sensing tag, the switches are cycled at the sensing-dependent oscillation frequency of a 555 timer.

One of the most valuable attributes of this approach is its ability to seamlessly integrate inkjet-printed resistometric sensors. Indeed, the oscillation frequency is determined by an RC constant where, in this scenario, the printed sensor constitutes the gas-dependent resistive element. The system, shown in Figure 7, was inkjet-printed onto a flexible piece of seven millimeter-thick Rogers ULTRALAM 3850 liquid crystal polymer substrate, where the lumped components, timer, flexible amorphous silicon solar cell, array, switches, and inkjet-printed CNT-PABS ammonia sensor were integrated into a thin and flexible energy-autonomous sticker. The RFID was interrogated by sending a 28 GHz continuous wave (CW) towards the tag, before using this CW to down-convert the received signal. A real-time spectrogram of the signal obtained during an ammonia sensing event is shown in Figure 8. This test demonstrates the ability to carry out real-time gas detection using the tag in an energy-autonomous fashion. The tag was also interrogated at a range of 80 m indoors in the configuration shown on Figure 9. Further improvements in timer stability will extend this range to distances on the order of a kilometer.

In addition, this approach is readily capable of integrating any single (or set of) resistometric or capacitive printed sensor(s) to target different analytes or implement electronic nose configurations into an inconspicuous long-range-readable energy-autonomous sensing "smart skin" for real-time ubiquitous sensing and tracking. Efforts are underway to integrate this device with our other inkjet-printed sensors to realize ultra-long range wireless sensing of CWA-relevant chemicals.

Summary

Aiming at wirelessly sensing CWA-relevant chemicals from ultra-long distances, we have produced inkjet-printed, robust, flexible, ultra-lightweight, miniature-sized, wearable sensors and utilized these sensors to detect simulants of different types of CWAs (i.e., nerve and blister agents) at ppb levels. RFID-based ultra-long-range wireless sensing platforms, which are capable of integrating any single or set of resistometric or capacitive printed sensors, have been developed and tested as proof-of-concept. Efforts are underway to integrate our CWA-relevant sensors to wireless sensing platforms. The low cost and portability of sticker-based detection may significantly contribute to protecting the warfighter at home and abroad. Taken as a whole, these advances in flexible substrate modification techniques, chipless RFID sensing stickers, and energy-autonomous tags represent a significant step towards the provision of using lightweight, flexible stickers for detecting CWAs. ■

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DEFENDING AGAINST AGROTERRORISM:

Modeling Pathogen Dispersion Pathways

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It is widely recognized that American farmers and ranchers make a major contribution to the U.S. economy by providing a safe and reliable food supply, which promotes energy security, job growth, and economic development. The U.S. Department of Agriculture (USDA) reports that in 2015, agriculture, food, and allied industries contributed more than $992 billion to the gross domestic product (GDP)—representing a 5.5 percent share of the total [1]. America's farms alone contributed $136.7 billion in GDP [1]. Furthermore, the USDA indicates that the U.S. food and beverage manufacturing sectors together employ more than 1 percent (1.5 million people) of all non-farm employment [1]. An attack on American agricultural assets would threaten the security, safety, and availability of U.S. food supplies and cause significant economic damage to the U.S.

Response Planning

Agroterrorism is the deliberate introduction of one or more animal or plant diseases in order to generate fear, cause economic loss, and undermine social stability [2]. It is a subset of bioterrorism, a broader designation that generally refers to attacks aimed at human populations. Agroterrorism is attractive to some nation-states or groups because successfully disrupting a food supply can cause social as well as economic harm [3,4]. These concerns were exacerbated by the 9/11 terrorist attacks and subsequent anthrax attacks (which killed five and infected 17 others).

Current federal strategies for preventing, detecting, and responding to agroterrorism and bioterrorism alike are informed by what is known about the Soviet Union's biological warfare agency, Biopreparat (Биопрепарат), and the 1979 anthrax leak at Sverdlovsk (now Yekaterinburg), which infected at least 94 people and led to 64 fatalities [5]. The resulting U.S. agro-defense strategy, valid at the time, has undergone significant refinement and must continue to do so as scientific breakthroughs continue to occur in biotechnology, cyber, and the fast approaching quantum computing.

Fortunately, there has not yet been an actual agroterrorism event in the U.S., but other countries have experienced examples where state actors used biological weapons against agriculture [4]. Serious questions exist regarding how we can most efficiently and accurately detect and—most importantly—discriminate between naturally occurring and terror-inspired disease events. Timely detection of an agroterrorism event is critical if we are to protect food supply and consumer health. Moreover, understanding the scope and nature of an agroterrorism attempt soon after its incidence may provide an early warning of potential ramifications for human populations.

The book *Agroterrorism: A Guide for First Responders* by R. Withers [6] explains why livestock are a more likely target for terrorism than crops—"Developing biological weapons to destroy livestock is much easier than developing chemical weapons for the same purpose. There are far more highly contagious and lethal biological agents that can be used. … [and] the high-mobility breeding and rearing practices contribute to the ease of dissemination of a disease." In line with the greater threat posed by animal-focused agroterrorism, we limit the discussion in this article to potential attacks on animal agriculture.

Potential Threats

Understanding the scope and nature of an agroterrorism attempt is important for protecting against the possibility of harm to human populations. "Because animals may be sentinels of disease in humans and many of the high-threat bio-agents…are zoonoses," Withers writes, "it is possible that veterinarians might recognize an event in animals before it is recognized in humans [7]." Only moderate levels of expertise and fiscal investment are needed to weaponize certain biological materials, and that task is made even easier if a weaponeer has access to pathogens through veterinary and/or medical diagnostic laboratory systems. It is safe to surmise that any advanced bioweapons program developed by an adversary would pursue the use of biological weapons in multipronged attacks that target both civilian and military targets.

As RAND Corporation expert Bruce W. Bennett testified before the House Armed Services Committee in 2013, "While there is evidence of North Korean biological weapons, little is known with certainty about the biological weapon agents the North has developed, which of these agents it has weaponized, and how it would use them [8]."

A recent unclassified report by scholars at Harvard contends that North Korea may already possess as many as 13 potential biological warfare agents, several of which could be pathogenic to both animals and humans [9]. As history has shown, biological weapons programs can be exceedingly difficult to detect. As Bennett continued, "Biological weapon programs are easier to hide than most military programs because they can be developed in a university setting or hidden within efforts to develop related vaccines [8]."

Given the ease with which biological weapons programs can be obscured from surveillance, it is imperative that the U.S. bolster its capabilities for detection, containment, and remediation of the agriculture domain, given that the confirmation that a hostile bioweapons program exists may only occur at the point of weapon delivery. In any agroterrorism event, delay of any type exponentially increases the scope and ultimate effects of the event.

Identifying Intentional Versus Natural Infections

The Department of Homeland Security has declared the Food and Agriculture industrial sector, which accounts for approximately one-fifth of all economic activity in the U.S., to be critical infrastructure and thus a necessary element of national security. The animal production industry is a network—both dispersed and concentrated—composed of complex production, processing, and delivery systems [4].

The mobility of animals and their by-products across jurisdictional boundaries (e.g., states, counties, nations, etc.) creates opportunities for uncontrolled natural and terrorist-planned outbreaks [10]. Such incidents could bring significant physical and economic harm. For example, in 2011, an outbreak of foot-and-mouth disease in the U.K. caused an estimated $25–30 billion in losses [11]. The 2014–15 outbreak of avian influenza (originating from wild birds) resulted in an estimated $3.3 billion in losses to the U.S. economy—the single largest animal health disaster in the United States [12].

Compounding the difficulties of detecting an incident, agroterrorism defense programs must consider the potential for contaminants to persist on farm grounds, facilities, and processing and transport equipment. It took several years to fully decontaminate the congressional office buildings and U.S. Postal Service sorting facilities where anthrax spores were spread in 2001, and those facilities were out of service until decontamination was completed.

An agroterror agent could similarly spread throughout the animal production chain for an indeterminate length of time, requiring ample resources for recommissioning. Differentiating an intentional disease outbreak from a naturally-occurring one remains challenging [13], and scholarly works have covered this topic extensively [14,15]. Time plays a critical role in making this determination. Many of the downstream impacts of mortality events, whether natural or terrorism, remain the same. The presentation of animal mortality can and has been confusing when deaths could be linked to a natural event just as easily as to an infection.

A classic example of unclear mortality presentation is anthrax, whose spores can lie dormant in the soil for decades and then produce sudden high-mortality outbreaks in unvaccinated, healthy animals. A July 2016 anthrax outbreak in the Yamalo-Nenets region of Siberia was Russia's first in 75 years, causing the deaths of thousands of reindeer and displacing dozens of traditional reindeer-herding families [16]. Initial reports on the event postulated that lightning strikes from a single storm event were the cause. Only after reindeer continued to die was it correctly identified as a natural anthrax outbreak. Ultimately, as many as 250,000 reindeer were destroyed by the end of the year as a regional animal depopulation measure [17].

It is reasonable to have concluded that the reindeer deaths were the result of lightning strikes. Indeed, shortly after the Yamalo-Nenets event, a separate lightning event killed 300 reindeer in Norway. The obvious question that follows is, what would this delay have meant in an actual agroterrorism event?

The Regulatory Context of Detection

The USDA has delegated its authority to prevent, detect, and respond to agroterrorism to the Office of Homeland Security and Emergency Coordination (OHSEC). Responsibility for complying with Homeland Security Presidential Directive/HSPD–9—Defense of United States Agriculture and Food also falls to OHSEC. This directive lays out national priorities for the defense of agriculture and food systems against terrorist attacks, major disasters, and other food supply emergencies. However, a recent audit report completed in March 2017 by the department's Office of the Inspector General (OIG) concluded that OHSEC's planning efforts for agroterrorism prevention, detection, and response were deficient. At present, the OIG concluded, OHSEC does not present an integrated and actionable statement of critical needs [18].

The functions necessary to do this correctly include intelligence analysis, law enforcement, animal health, plant health, public health, environmental remediation, and outbreak response and recovery. The 2008 Food and Agriculture Incident Annex (FAIA) to the National Response Framework, which addresses only the response and recovery element of agrodefense, lists USDA and HHS as Coordinating Agencies and a suite of strategic supporting agency partners. The update to the FAIA (expected in 2018) will provide additional specifics to the span of responsibility, along with blueprints for coordination.

Outbreaks first present themselves at the farm or facility level, so that USDA's National Animal Health Emergency Response Plan (NAHERP) assumes that detection of an animal disease takes place at the most local level [6]. Initial detection is therefore highly dependent on farming staff recognizing an unusual clinical presentation or a spike in cases, and thereafter reacting properly and in a timely manner. Ideally, these observations would then be immediately reported to a qualified veterinarian. In the United States, veterinarians who work with livestock herds must be accredited by the USDA and must be trained to recognize the clinical syndromes of Foreign Animal Diseases of concern, thereby increasing the likelihood of rapid recognition that an animal disease event has occurred. If the index of suspicion of an outbreak is high, the State Veterinarian's Office is then alerted.

Response and Containment: Modeling the Host Environment

Per NAHERP, should the presence of a foreign animal disease be confirmed, the premises will be placed under a quarantine order and a "movement hold" of all susceptible and affected animals will be established for a minimum of 72 hours [6]. The USDA Animal and Plant Health Inspection Service (APHIS) directs the response (containment and remediation), while local law enforcement establishes control zones and controls access. The FBI and USDA OIG oversees documentation, evidence collection, and chain-of-custody procedures with support from local/state law enforcement agencies [2,6,19].

When an outbreak is determined to be verified and a coordinated response is mounted, one challenge is the lack of environmental modeling tools, which we describe below. Necessary planning components include the key area of characterization, risk determination, potential course of action, and a means of assessing the value of these measures to health. Outside the realm of biosurveillance, ecologists and epidemiologists have long been using environmental models to predict the transport, fate, and effects of contaminants on ecological receptors and on humans [20]. The transport and fate of materials released from natural disasters or anthropogenic events vary—as do their deleterious impacts to all life—by the biogeochemical processes of the host ecosystem. Therefore, regardless of why or how pathogens are released, both preparedness and response should be informed by those biogeochemical processes [21].

Rapid diagnostics, including patient-side diagnostics, may arguably be the most important element of an animal disease stockpile. The National Veterinary Stockpile, administered by USDA's APHIS, lacks both therapeutics and rapid diagnostics. Current biosensors for the detection of pathogens in food, livestock, and agricultural products include antibody- or immunologically- based tests and polymerase chain reaction (PCR) assays. Antibody tests have an advantage over PCR testing when it comes to speed and cost—little to no sample preparation is required to conduct an antibody test. However, compared to a PCR assay, an antibody test has a relatively low sensitivity and specificity, and it typically requires laboratory-based PCR testing for confirmation. PCR testing, considered the gold standard, provides high-confidence results with excellent sensitivity and specificity, although a PCR test requires a rather rigorous sample preparation. The ability to quickly deploy a user-friendly diagnostic capability is essential to successfully contain an agroterrorism event.

One purpose of the Food Systems Institute at Auburn University is to provide meaningful preparedness and response tools based on risks to livestock, starting with poultry, beef, and pork, which are consumed by large segments of the human population. Epidemiological risk assessments have been conducted on historical animal disease events, but they lack comprehensive risk analysis and do not incorporate a broader picture to include ecological complexity along with human health.

Since 1900, there have been at least 15 documented cases involving the use of pathogenic agents/substrates to contaminate foods [2,22]. We analyzed example events from the last 100 years to inform both models and algorithms. We have further calibrated the resulting tools based on our event analysis. These models need appropriate parameters that illustrate the physiological landscape over which the events occur, including the routes that could lead to exposure of livestock.

With this approach, we can begin to predict a temporal likelihood for the incidence of infections and public health disasters, and optimize our surveillance and identification methodologies depending on data inputs such as the food source species and transport/processing routes leading to consumers, thereby producing a range of potential outcomes to inform public health and disaster response officials.

Data for Agroterrorism Event Modeling

Predictive models used in the forecasting of pathogen pathways are commonly based on a conceptual framework that considers the interactions among pathogens, hosts, and environmental conditions. Knowledge of the survivability of a given pathogen and an accurate characterization of the environment (ecosystem features, current weather conditions, etc.) are fundamental elements in forecasting dispersion patterns [11]. A variety of means exist for characterizing the natural landscape. For our purposes, ecoregions, used for characterizing the environment over large areas with similar physical and biological components, provide an appropriate and targeted representation of the landscape [23]. They are classified into hierarchical spatial groups that nest over large to small scales by analyzing the patterns and composition of a given area's geology, landforms, soils, vegetation, climate, land use, wildlife, and hydrology [24].

In our analysis, the highest resolution ecoregion level (IV) of the United States will be used to characterize each of the 15 documented case environments as an initial step in determining the environmental parameters that are favorable to pathogen survivability, which in turn can be used to assess the temporal and spatial risk of pathogen dispersal.

This modeling exercise requires a geographic tie, and spatial analytical tools within geographic information systems (GIS) need to (and should be) used as a platform for epidemic spread models [25,26]. Along with ecoregions, there are a variety of geospatial datasets available that support emergency management and ecological modeling which are applicable to our analyses.

Such GIS data includes land ownership, transportation, hydrology, elevation, the distribution of natural hazard zones, environmentally sensitive areas, land cover, animal species, climate variables, and soils, among others. Global food distribution models such as the Gridded Livestock of the World, v2 might be mined to inform the resource flows within our model.

Linking these datasets will ultimately aid in forecasting potential pathways, and also provide a model that can be used to simulate future scenarios under different pressures, such as increasing population, regulatory changes, climate change, natural disasters, etc. The utility of a successful comprehensive predictive model is to pinpoint a release origin, determine factors that influence origin type (natural or deliberate), and perhaps most importantly, to identify where response actions may be taken in the appropriate time frame. Armed with such a model, the ultimate product is risk reduction and preservation of human lives. ■

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Kris Senecal
& M. Nichole Rylander, Ph.D.

Historically, burns have accounted for 5 to 20 percent of combat injuries, with 4 percent of burn victims succumbing to their injuries. According to the United States Army Institute for Surgical Research Burn Center, participation in Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) have contributed to higher burn-injury rates than previously seen in other conflicts [1,2]. This increase is likely due to the use of improvised explosive devices (IEDs) by enemy combatants [1], which has not been experienced in past operations.

The burn potential and patterns inflicted by IEDs are unique and can be quite severe [3], making a significant contribution to the number of burns sustained by military personnel as the result of hostile action in areas of combat operations [4,5]. Burn injuries that occur in combat often result in a decrement in fighting strength and physical impairment, which may require rehabilitation or lead to lifelong disability and even death. In response to the increase in combat-related burn injuries, U.S. Army Natick Soldier Research, and Development and Engineering Center (NSRDEC), as part of its ongoing mission to protect and sustain the Soldier, continues to evaluate methods of developing new protective garments that can reduce the likelihood and severity of burns due to thermal threats on the battlefield.

Burn Injury Model

An essential aspect for evaluating protection against battlefield hazards lies in the means to predict the extent and severity of skin burns that can arise under specific thermal exposure conditions faced by the warfighter. As such, testing methods (e.g., ISO 17492 [6] and ASTM F1930 [7]) conducted at NSRDEC's Thermal Test Facility routinely assess thermal protection afforded by fabrics and garments by incorporating a burn injury model developed by Stoll and Chianta [8-10].

Limitations

Although protective garments are designed for all areas of the body, burn prediction testing currently used in military lab settings is based entirely on limited human test data for superficial second-degree burns on the volar surface of the forearm (indicated by formation of a blister within 24 hours), which does not take into account the considerable differences in tissue properties and thicknesses (affecting burn damage response) across the body. It is routine in garment testing to predict areas of significantly greater burn injury severity (deeper second- and third-degree), however, this prediction is based on specific yet limited data. Additionally, anesthetized animals and human cadavers have historically been used to research burn severity. An improved whole body burn injury model is needed that incorporates appropriate body-region-specific behavior for the development, performance, and assessment of protective clothing.

Human skin is a complex tissue, consisting of multiple layers, vascular networks, and cell types that together create a barrier against environmental factors. Current models used to recapitulate skin include 2-D cell cultures and animals. 2-D cell cultures are the most widely

Image Credit | *Photo Illustration created by HDIAC and adapted from photo at* http://asc.army.mil/web/wp-content/uploads/2017/12/8385661905_fe24151ff6_o.jpg

IMPROVED BIO-FIDELITY FOR SKIN BURN INJURY MODELS

used skin models as they provide a simple, inexpensive system for modeling single layers of cells found in skin. However, 2-D cell cultures do not mimic key 3-D cell-extracellular matrix interactions, chemotactic cell migration, blood flow, and other physiologic factors present in skin. As a result, these models do not mimic the skin's response to external stimuli, such as battlefield injuries, including burns, exposure to chemicals, and varying environmental stimuli (e.g., extreme temperature, moisture, and particulates), and contact with varying types of materials (e.g., protective garments). While animal models of skin provide better physiologic fidelity, they are expensive and do not fully replicate the human phenotype and its response. The development of an inexpensive, physiologically representative skin platform capable of characterizing skin response to battlefield injuries or severe environmental conditions in the presence or absence of protective materials could positively influence wound treatment.

Current Research

NSRDEC and University of Texas at Austin researcher M. Nichole Rylander are collaborating to develop a representative human skin simulant having 'true' human skin cell layers and vasculature that will allow for a more relevant testing approach to burn injury when testing to radiant and convective heat fluxes. These vascularized tissue platforms incorporate simulated blood perfusion and biologic materials so that biochemical markers and cellular responses involved in burn injury may be directly observed. The objective of this research is to develop skin burn injury models capable of predicting a range of skin injury from threshold second-degree burns to severe (deep second- and third-degree) burns and to validate the models against available human and animal model experimental data.

Approach

Researchers at the University of Texas at Austin's Rylander Lab have created a 3-D physiologically representative collection of skin platforms that range from single skin layers to complex, vascularized, full-thickness skin consisting of matrices prevalent in each skin layer: collagen (dermal layer) and keratin (epidermal layer). Researchers have created avascular single- and multi- layer skin with fibroblasts, keratinocytes, and endothelial cells (all cells present in the human skin) so injury may be studied independently for each layer (see Figure 1A).

In the fabrication of the multilayered skin model, differentiating keratinocytes were observed becoming corneocytes, which is characteristic of in vivo response of the human epidermis shown in Figure 1B. Further development of the skin model also includes a vascularized dermal skin model with fibroblasts (blue) with a confluent endothelialized blood vessel (red) (see Figure 1C), enabling the influence of blood perfusion.

The types of characterization employed include measurement of dynamic and spatial cell viability in its native state and in response to burn injury. As illustrated in Figure 2A, preliminary tissue injury following contact burns can be clearly distinguished with staining techniques. The dark region denotes dead cells and green cells are the live periphery where burn injury was sub-lethal. The cell-

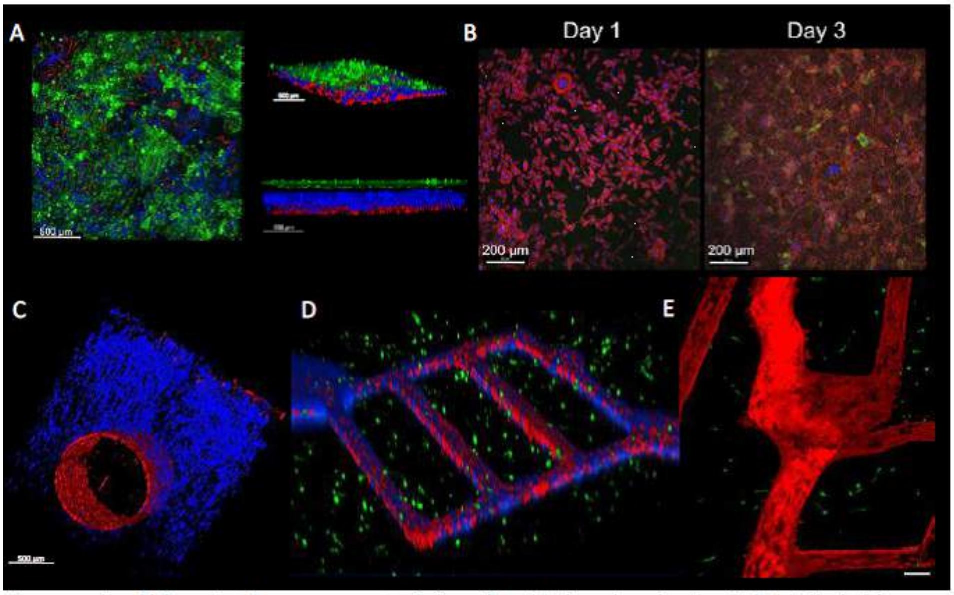

Figure 1: Skin platforms created by the Rylander Lab. (A) Full-thickness avascular skin platform flourescence images containing represetative cell types keratinocytes, fibroblasts, and endothelial cells with angled view (top), side view, and top view below (B) Differentiated keratinocytes expressing caspase 14 (green) after three days (C) Vascularized dermis with fibroblasts shown in blue and red endothelias cells lining a representative blood vessel within (D) Microvascular network integrated (red) within fibroblast containing dermis (green cells) showing capability to scale tissue size and characterize dynamic transport of therapeutics (blue nanoparticles) within the vessels (E) Tisssue-specific skin platform in which tissue properties and specific vascular patterns were generated based on clinical imaging data

growth kinetics have been quantified in response to varying thermal conditions.

Other types of cellular stress response markers, such as heat shock proteins, could serve as another metric of injury and a key parameter for predicting tissue survival and wound repair (see Figure 2B). The Rylander Group has developed the capability to determine mechanical properties of the skin platform determining how tissue integrity changes over time or in response to injury, which directly affects wound closure and healing. Structural properties of the skin platform determined using scanning electron microscopy shows tissue structure, porosity, and fiber diameter, and can be extended to any material characterization before and following thermal and chemical insults to understand the extent of material and tissue compromised (see Figure 2C).

The size of the tissue platform can be customized to desired dimensions and can mimic skin from different regions of the body. Researchers can scale the tissue size, tune the matrix and cellular composition, and incorporate multiple blood vessels or microvascular networks (see Figure 1D). The skin platform can also be adapted to represent patient or population-specific (e.g., gender, age, and ethnicity) types of skin by capturing tissue properties and vessel architecture from human imaging data (see Figure 1E). The platform can also remain stable at 37ºC for two weeks, allowing for long-term study and storage.

Recommendations for Further Research

Initially, the improved and validated burn simulants will be used principally in the way the current burn sensor injury models are used—implemented in a computational computer code that processes sensor data from flame and thermal testing of a textile/garment in order to predict the distribution and body surface areas that are theoretically burned as a result of the test exposure. These tissue phantoms may also be used in further development (as test devices in lieu of traditional instrumented forms) and as an experimental test bed to aid in the development of burn models for highly vasculated tissue.

As previously mentioned, the use of IEDs in OEF/OIF could be a contributing factor to the rise in combat-related burn injury rates. The burn patterns of IEDs typically affect the face and limbs [4], which rank first and second in burn injuries among the warfighters in Iraq and Afghanistan

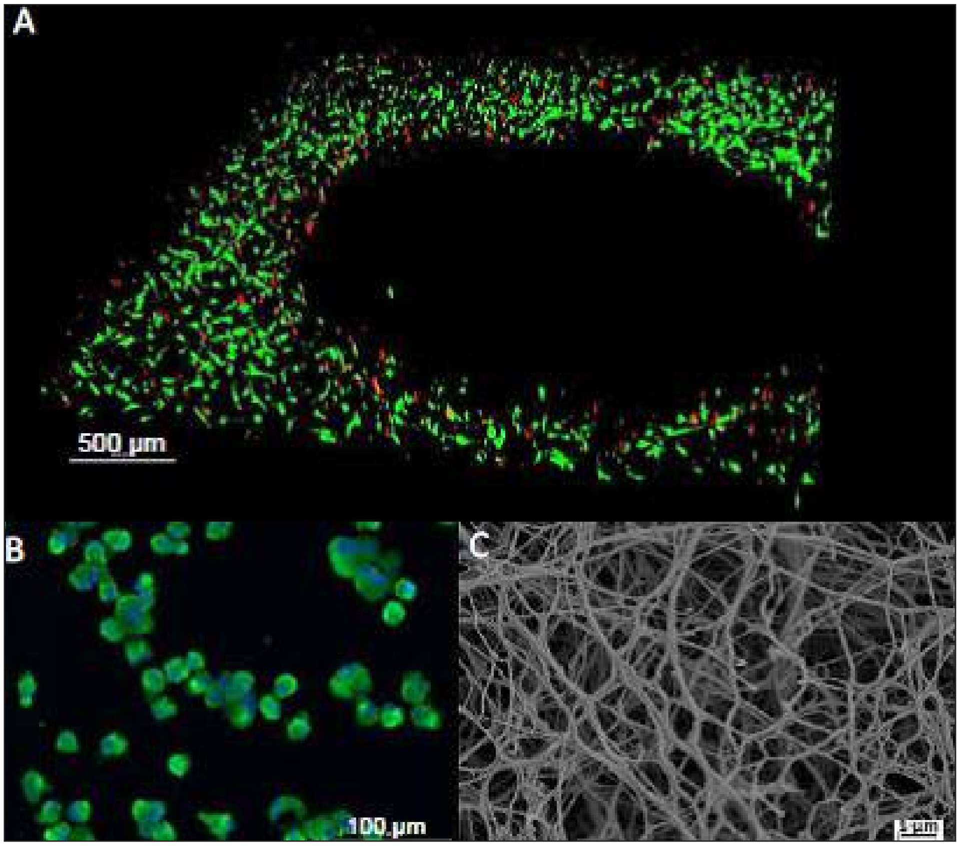

Figure 2: Characterization of the skin platform. (A) Burn injury profile in skin (green region is liver periphery and black central area is region of burn) (B) Heat shock protein expression of cells after burn (C) Scanning electron microscopy image of skin

[11]. This elevates the necessity of developing more accurate models that can be used to simulate these tissues. While the hands and face are not currently monitored in the standard ASTM F1930 manikin test, burns frequently occur in these tissues on the battlefield and have a significant impact on soldier quality of life. Blood perfusion through the human vasculature could strongly affect burn injury spread and severity by affecting physiologic burn response. To address fluid dynamics of burn injury, researchers are developing enhanced skin simulants, to include vasculature of veins/capillary. In order to develop the most realistic models for testing clothing and gear used in the protection of these sensitive and vascular areas, more research should be done to characterize the locations and patterns of burns witnessed in veterans of OIF/OEF. As it appears that burn injury rates have not been updated since 2006 [1], additional research may be necessary to provide an accurate representation of the classification of burns and new rates.

The simulants may also be used as a testing mechanism to characterize, develop, and optimize current or future protective gear for Soldiers in-theater. The skin platform could provide information on cellular response to a wide range of insults (e.g., chemical, thermal) and in operational climates (e.g., desert, jungle). Furthermore, the simulant can also be observed on a molecular and/or cellular level to independently evaluate the severity of injury (by evaluating cell death and/or biomarkers, such as heat shock proteins) that may result from specific thermal (radiant, convective) threat situations, providing further insight into wound healing research. DoD operates in a broad range of environments in which the warfighter could be exposed to a variety of contaminants. It is impractical to conduct field research and be prepared for each of the environments. However, using phantoms to simulate multiple environments would allow DoD to conduct necessary research on how these different contaminants could affect the warfighter prior to combat, thus enabling commands to be equipped with the proper protective equipment.

Conclusion

The skin platform is a cost-effective, high-throughput system that can be used instead of animal skin or other stand-ins to provide a living, growing tissue that can be customized for any given research endeavor by optimizing its characteristics including size, shape, layer thickness, cell and protein composition, vasculature geometry, and heterogeneous features such as hair follicles and pores. This versatile research and development effort of tailored multi-layered skin platforms promises to be an interesting test bed, not only in Soldier protection, but for future medical research. ■

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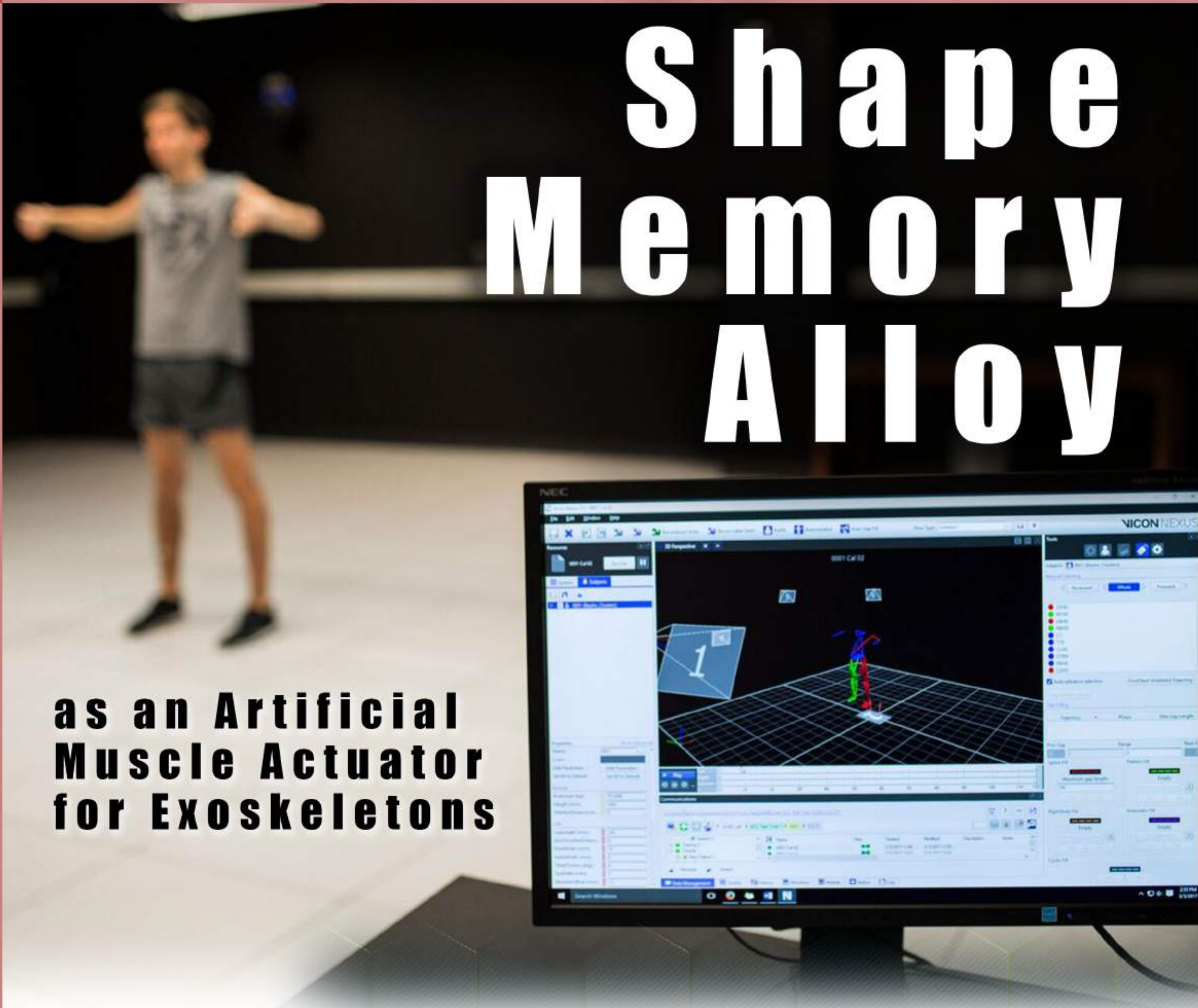

Shape Memory Alloy

as an Artificial Muscle Actuator for Exoskeletons

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Whether for injury rehabilitation or performance enhancement, the ultimate goal of exoskeleton research and development is to produce a wearable, human-like robot capable of detecting and enhancing the intended movement of the user. During rehabilitation, exoskeletons can be used to assist in the muscle retraining process. An example of this is when a neuromuscular injury is sustained that affects the injured warfighter's ability to walk. An exoskeleton can be used to move the person's leg to mimic their gait cycle, which retrains their muscles and can quicken the recovery process [1]. Exoskeletons can also be designed to enhance user strength and increase battlefield performance—such as the United States Special Operations Command's Tactical Assault Light Operator's Suit (known as TALOS) and those being developed through the Defense Advanced Research Projects Agency's Warrior Web Program. Exoskeletons may also be used to redistribute the load carried by the warfighter, which may reduce the number of injuries sustained by members of the U.S. Armed forces.

The most predominate actuation methods of modern exoskeleton designs include electric motors [2,3] or hydraulic actuators [4]. While these actuators can replicate simple joint movements such as knee flexion and extension, they are not able to replicate the naturalistic motion achieved by human skeletal muscles. These traditional forms of actuation are also limited to rotation about only one axis even though most joints in the human body have multiple degrees of freedom.

Unlike classical rotational or "pin" joints actuated by electric motors, rigid bones in the body are connected at the joints via soft tissue, such as ligaments, that restrain movement but still allow for multiple degrees of freedom. A more naturally operating actuator would allow for exoskeletons to account for these additional types of joint motions and create a more fluid, human-like movement of the exoskeleton.

Soft Robotics and Shape Memory

Due to the limitations associated with traditional actuators, research into novel actuators and soft robotics has increased. This includes, but is not limited to, shape memory alloys (SMA), shape memory polymers, dielectric elastomer actuators, and pneumatic artificial muscles. These actuators look to improve on the degrees of freedom, weight, and noise limitations of traditional motors and hydraulic actuators. These advancements could have an especially significant impact on performance enhancing exoskeletons by allowing a warfighter performing complex motions to wear additional armor while moving naturally and silently.

Shape memory alloys are typically manufactured as cylindrical wires and have been used as micro-actuators because they have a high strength-to-weight ratio compared to traditional actuators [5, 6]. Nitinol, an SMA that has a nearly equiatomic composition of nickel and titanium, is one of the most commonly used SMAs because it is commercially available (~$2 per foot), biocompatible [7], and has a functional strength of 25,000 pounds per square inch [8]. Nitinol exhibits two interesting effects that cause large amounts of recoverable strain in the material. When the temperature of nitinol is held constant and the stress is varied, the material exhibits the pseudo-elastic effect, also known as the super-elastic effect.

An increase in stress results in the formation of stress-induced martensite which causes the wire to extend. When the stress is reduced, the material returns to the austenite phase and recovers the strain. (This effect has been demonstrated by a protype glove, as illustrated in Figure 1.) The shape memory effect occurs when the stress is held constant and the temperature is varied. For linear nitinol actuators, the applied load will stretch the martensite phase and increase the wire length.

The temperature is then raised to the austenite transformation temperature and the nitinol contracts and the wire length is decreased. The shape memory effect is the dominate effect when nitinol is used as a linear actuator, but if the stress of the system varies, the super-elastic effect plays a role as well. SMAs do have limitations such as their actuation strain, which is normally 4 to 6 percent of the actuator's entire length [9]. Along with limited strain, large force SMA actuators have shown to exhibit a high power consumption to achieve realistic actuation times for use as an artificial muscle [10].

Biomimicry of Human Muscle

Biomimicry is the practice of imitating naturally occurring structures or processes to solve complex engineering or design problems. Since SMAs possess the ability to contract and expand in a similar fashion to human muscle, they are often referred to as "artificial muscle actuators." However, the geometry of human muscle fiber groupings are more intricate than simply bundling multiple wires together in a parallel configuration. A sarcomere forms the base unit of skeletal muscle and is constructed with overlapping layers of myosin and actin filaments that achieve a decrease in length by sliding over each other. This is known as the sliding filament theory [11]. Sarcomeres are connected in series along the length of the muscle to form a single myofibril (see Figure 2). This article proposes to use biomimicry of natural sarcomere and myofibril organization by placing an additional fiber into the center of a bundle of SMA wires (see Figure 3). This additional fiber will serve the purpose of conducting heat directly to the surrounding SMAs, thereby contracting the SMA fibers and replicating the sliding filament effect.

Theoretical Design

Nitinol is the SMA chosen for this design as it is commercially available and inexpensive. This alloy can also be pre-trained to contract when heated and extended when cooled. In most applications of SMA actuators, resistive heating is used to raise the temperature of the material and free convection with ambient air is used to lower the temperature [12,13]. However, resistive heating causes a high power consumption for the system. This is especially evident when multiple wires are aligned in a parallel configuration.

In order to increase efficiency, this design calls for a secondary material to conduct the heat directly into the SMA. The material chosen as a secondary heating element is nichrome. Nichrome, a nickel-chrome alloy, is commonly used in resistive heating applications due to its resistance to oxidation and high temperature stability. Electrical current is passed through the nichrome, which results in a temperature rise. This design is configured similar to that of a natural myofibril, with a central nichrome wire and 10 smaller Nitinol wires placed around its circumference, as shown in Figure 3.

In the model, the nichrome core was wrapped in Kapton tape (orange layer in Figure 3) to prevent current passing directly to the SMAs, and then thermal paste was applied to increase heat conduction between the nichrome and SMA. The diameter of the SMA was set to 0.008 inches, which corresponds to a published maximum pulling force of 1.26 pounds per wire [8], totaling 12.6 pounds pulling force for the pro-

Figure 1: Demonstration of how nitinol actuator woven into glove would assist in finger flexion.

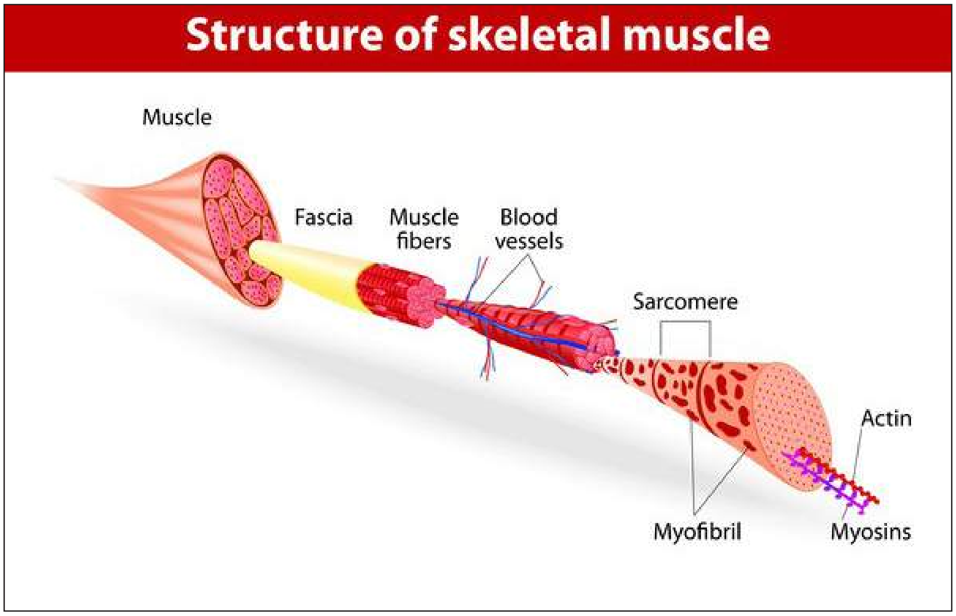

Figure 2: Structure of skeletal muscle [15] (Credit: Designua/Shutterstock.com)

posed artificial myofibril design. The overall effective diameter of the configuration is 0.035 inches, which is approximately 20 times smaller than the diameter of a U.S. dime. The effective diameter includes a 0.016 inch diameter nichrome core, a 0.008 inch SMA wire, and a 0.0015 inch thick layer of Kapton insulation.

For this analysis, the operational temperature range of the nitinol wire was set from 70 C to 105 C, which corresponds to an actuation strain of 4 percent the length of the wire [8]. A finite element thermal analysis in Solidworks was applied to the configuration to assess the transient thermal behavior. A contraction time of less than 1 second was chosen as a desired output of the design, as this roughly corresponds to the natural cadence of human gait. The input power was increased until the transient response yielded a contraction time of less than 1 second and found to be 4.25 watts.

Results

A temperature gradient forms between the nitinol and nichrome with an average temperature increase of 41.7 degrees Celsius per second in the SMA wire. During the initial phase of the simulation, the nichrome temperature increases at a faster rate than the SMA wire while the temperature gradient between the two materials grows larger. As the temperature gradient grows, the rate of change of the SMA temperature increases as well. The SMA wire reaches the start of the transformation region (70 C) at 0.80 seconds and reaches the end of the transformation region (105 C) at 1.64 seconds. This results in a contraction time of approximately 0.84 seconds.

Discussion

The proposed artificial myofibril design utilizes multiple nitinol wires positioned circumferentially around a secondary material, nichrome, used as a heating element. With this design, multiple actuators can be grouped together to form an artificial muscle fiber similar to the natural groupings in human skeletal muscle. Furthermore, since the actuator is a single artificial myofibril, the overall strength of the actuator can be altered by increasing or decreasing the number of actuators in a single muscle grouping.

Ultimately, an exoskeleton can be fitted with an actuator of this type, which would allow for the development of a custom artificial muscular system that would move more naturally, like the muscle system of the individual using the exoskeleton. This type of actuation holds the potential for an improved machine-human interface as the artificial muscles can be stimulated by electromyography signal of the warfighter's muscles. Additionally, this design will allow for actuation of exoskeleton joints around multiple axes. If exoskeleton limbs could replicate complex joint motions, it would allow the user to accomplish more complex tasks without inhibiting their own motion.

This technology is not limited to exoskeletons but can be applied to robotics in general. For example, Military Services members may sustain injuries resulting in the loss of

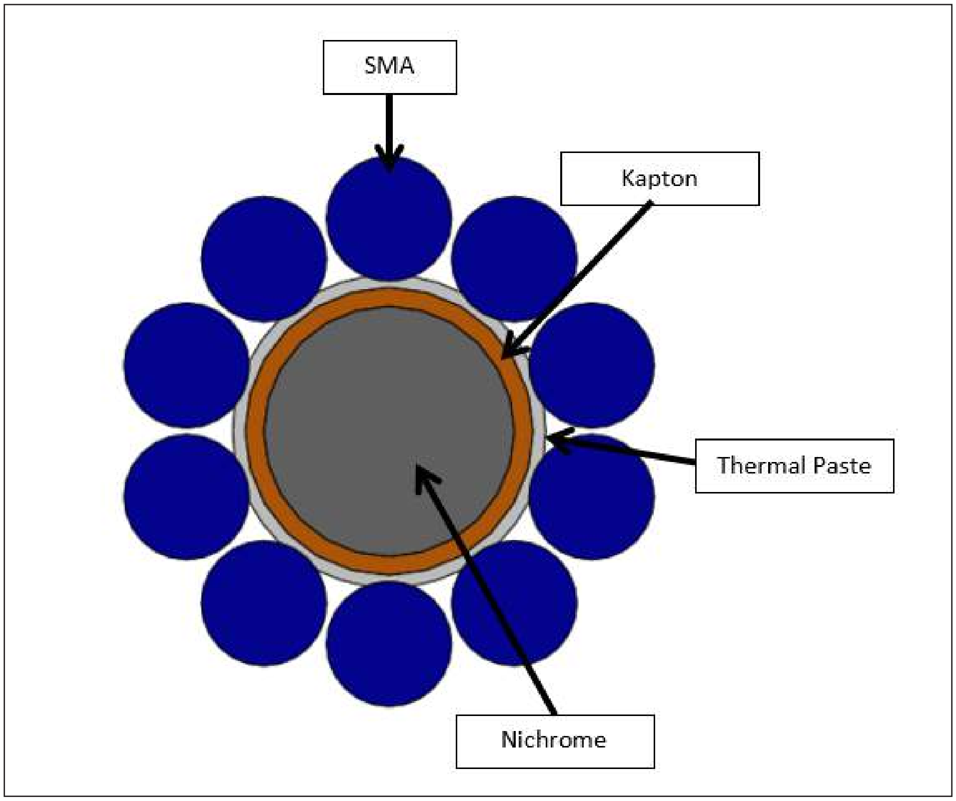

Figure 3: Cross section view of artificial myofibril design with a nichrome center and surrounding SMA wires.

a limb, which could require a prosthesis. Many common prostheses have no means of active actuation, and the SMA actuator would allow prostheses to be actuated by a low-cost, low-weight, and silent actuator. Actuated prostheses would increase functionality by allowing the user to be able to do tasks that they could not do otherwise.

This simulation has limitations that must be considered. First, it does not take into account the latent heat of transformation that occurs as the material transitions from martensite to austenite. Also, as the material changes phase, its properties (such as electrical resistivity, thermal expansion coefficient, and elastic modulus) also change. Lastly, the simulation does not account for the relative length change between materials during operation. Future work will involve incorporation of each of these effects during more advance simulations.

Conclusion

The presented design and theoretical model of a novel artificial actuator utilizes shape memory alloy wires positioned circumferentially around a central nichrome heating element to produce muscle-like contractions. Utilizing biomimicry to replicate the geometry and microscale movement of human skeletal muscle has the potential to lead to an efficient, high strength artificial muscle actuator for use in exoskeleton technology for the warfighter. An exoskeleton with greater ability to produce more natural, human-like movements will improve the ability of the device to contribute to neurological injury rehabilitation as well as improve the performance of the warfighter on the battlefield. ■

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As technology develops and allows for more sophisticated bioweapons and delivery systems to be created, the Department of Defense (DoD) must maintain the capacity to anticipate these new potential threats and develop methods to counter them. One of these new challenges includes the use of synthetic biology as a weapon of mass destruction (WMD). According to Nature, "synthetic biology is the design and construction of new biological parts, devices, and systems, and the re-design of existing, natural biological systems for useful purposes [1]." Therefore, the inherent challenge of preventing the use of synthetic biology in the development of WMD lies in the fact that it is a dual-use technology, which means legitimate applications can also be used for nefarious purposes [2].

A significant amount of DoD research is centered on harnessing the beneficial aspects of this technology. For example, The Defense Advanced Research Projects Agency (DARPA) is one of the largest spenders on synthetic biology research in the U.S. [3]. The agency invested $135 million on one synthetic biology-related program, Living Foundries, from 2011 to 2016 [4]. In terms of DARPA's annual spending on all synthetic biology programs, the most recent available figure places its 2014 research spending at $110 million [5]. Current DARPA programs regarding synthetic biology include Biological Robustness in Complex Settings [6], Engineered Living Materials [7], and Living Foundries [8], all of which focus on using biological systems to create materials for strategic use in defense applications.

Although these programs, and others like them, are designed to explore the beneficial aspects of synthetic biology, it is important to acknowledge that the facilities in which this research is conducted may be vulnerable to theft or attack by bad actors seeking access to the tools needed for nefarious purposes. In order to prepare for and counter the possibility of a threat from the use of synthetic biology in developing WMD, we must assume that not all individuals, organizations, or governments wish to focus on the non-harmful applications of synthetic biology. Dual-use technologies, such as synthetic biology, create situations that are complex, uncertain, and ambiguous [9]. According to the United Nations Interregional Crime and Justice Research Institute (UNICRI), "synthetic biology tools compound the dual-use nature of standard technology and pave the way for conceiving of biology in increasingly abstract terms" [2]. Accordingly, the potential for bioweapons engineered through synthetic biology has caused concern in many communities.

In 2015, the Global Challenges Foundation listed synthetic biology as one of 12 major global risks, with the possibility of an accident or terror-related incident occurring within 100 years as more likely than nuclear war [10]. The following year, then Secretary-General of the U.N. Ban Ki-moon delivered a speech on the non-proliferation of WMD. He described the U.N.'s commitment to eliminating WMD and expressed concern with the interface of emerging tech-

nologies—including synthetic biology—with WMD [11]. The current rapid expansion of biotechnology capabilities, such as gene editing (including clustered regularly interspaced short palindromic repeats, known as CRISPR), coupled with global support among governments and private industry, make the discussion of synthetic biology as a potential emerging technology for the proliferation or enhancements of WMDs an important topic of discussion.

Technology Growth and Funding

An important aspect of assessing the threat of synthetic biology is identifying where research is being conducted, where these capabilities exist, and, as a corollary, where such information is lacking. Synthetic biology research funded by national governments is easier to track than research conducted by private industry as several countries openly report aspects of scientific research funding. Although not comprehensive, Table 1 identifies several state-level organizations funding synthetic biology research programs. Most of these programs also provide details regarding the projects they fund.

The paucity of easily accessible information from even relatively open governments illustrates a lack of true awareness regarding global capabilities for synthetic biology research and manufacturing. Furthermore, synthetic biology research is likely supported by the governments of additional countries and agencies, but data are not easy to find or verify. Specifically, there is no publicly available information regarding the capacity for research and development or production of synthetic biology in Iran, North Korea, and Russia.

A much larger challenge exists with assessing the activities of private industry. The private sector is typically not held to the same level of transparency as most national governments unless regulations and statutes require specific reporting. Therefore, although general company location information and spending estimates may be available, specific details regarding research and development projects could be vague. In the U.S., universities are typically more likely than industry to provide information related to research, especially pertaining to government-funded projects; however, in some countries, like China and India, the line is blurred between university and state, increasing the difficulty in accurately assessing not only the level of research and production capacity but also potential threats. The Woodrow Wilson Center for Scholars estimated that in 2013, 192 companies worldwide partook in some aspect of synthetic biology research and development [12]. By 2021, the total market for synthetic biology could reach $11.4 million, with an annual growth rate projected at 24 percent [13].

A system capable of tracking and identifying synthetic biology capabilities is needed to ensure global security. The Synthetic Biology Project, part of the Woodrow Wilson International Center for Scholars, was founded in 2008 to track government entities and companies that conduct synthetic biology research [14]. Its efforts are notable but still fall short, particularly regarding the identification of details for government work and privately funded research and development. This lack of information could hamper the ability of DoD and the intelligence community to track potential threats associated with synthetic biology.

Tools, Applications, and Concerns

In order to understand why there is concern regarding the weaponization of synthetic biology, a brief overview of the technology is needed in order to evaluate the capabilities that could be used for nefarious purposes. Synthetic biology is a set of tools that can be used to create completely new forms of living systems or significantly alter existing ones. Broadly, these tools fit relatively neatly into a cycle composed of three categories: design, build, and test [15].

In terms of functionality, the design and build phases are the two aspects of synthetic biology that would play a major role in the development of new types of bioweapons, as the conceptualization of prospective organisms or systems would be created in the design phase using a suite of techniques, including: automated biological design, metabolic engineering, phenotype engineering, horizontal transfer and transmissibility, and xenobiology [15].

Metabolic engineering allows scientists to alter pathways in a cell, which could allow toxins naturally produced by the cell to be more potent, or even allow the cell to create compounds foreign to it, as in the example of opiate-producing yeast [16]. Horizontal transfer and transmissibility allows genes to be move more easily from one organism to another, which has already been modestly demonstrated with the influenza virus [17,18]. Finally, one of the most ground-breaking concepts of synthetic biology involves xenobiology, which is the development and/or use of components that do not naturally occur on Earth [19]. Nucleic acids, such as DNA and RNA, are created from building blocks known as nucleotides, which are composed of phosphate, base pairs (adenosine, cytosine, guanine, thymine, and uracil) and a sugar (deoxyribose or ribose). The arrangements of the base pairs dictates the genetic codes of organisms. Xenonucleic acids (XNAs) are nucleic acids that are not composed of the standard nucleotides because the sugar has been replaced with another type of molecule and are thus artificial and not naturally occurring [20]. These nucleic acids could produce biological components not yet present on Earth, opening up a new world of possibilities in terms of biological agents.

The build function of synthetic biology hosts a variety of tools and techniques used in the construction of pieces [15], but the most important regard DNA synthesis and gene/genome editing. The construction of DNA using individual components goes hand-in-hand with gene editing techniques, which allow genes of a cell to be modified [15]. A variety of techniques for both are now available [21], but perhaps the most important advance in gene editing has been CRISPR, which allows for the manipulation of genes relatively easily with little downstream alterations [22,23]. According to the National Academies of Sciences, CRISPR “may allow engineering in many new species, providing convenient paths to the further identification of altered phenotypes via either high-throughput screening or directed evolution of organisms with radically new phenotypes and genome-wide sequence changes [15]." In regards to gene editing, former Director of National Intelligence James Clapper stated to Congress that “given the broad distribution, low cost, and accelerated pace of development of this dual-use technology, its deliberate or unintentional misuse might lead to far-reaching economic and national security implications” [24]. In fact, the National Intelligence Council has reported that “existential risks” can be found with synthetic biology and genome editing [25], and a report from the Center for Strategic & International Studies predicted that in a future world, synthetic biology would make it possible to develop “DNA-targeted bioweapons” that could be in the arsenal of non-state actors by 2045 [26].

One of the greatest concerns regarding synthetic biology is its use as a tool to create virulent pathogens. Furthermore, synthetic biology even goes beyond biotechnology in this capacity because it is not only possible to genetically engineer pathogens to make them more virulent, but synthetic biology makes it possible to actually build pathogens from the ground up. For example, in March 2017 it was announced that researchers were able to build components of horsepox, an extinct member of the pox family of viruses, and assemble them, resurrecting the virus [27]. Horsepox cannot be contracted by humans, but a closely related virus, smallpox, is fatal to humans. Smallpox was eradicated in 1980 [28], but samples still exist in labs in the U.S. and Russia [29]. Following the terror attacks of September 11, 2001, there was concern that smallpox could be used as a weapon by terror groups [30]. However, an even greater threat, demonstrated by the horsepox experiment, now exists because of synthetic biology. In fact, the World Health Organization released a report in 2015 regarding this new concern for smallpox, stating that “with the development of these technologies, public health agencies have to be aware that henceforth there will always be the potential to recreate variola virus, and therefore the risk of smallpox re-emerging can never be fully eradicated [29]."

In the short term, it is unlikely that synthetic biology will be used to create entirely new classes of threats, but it could make it easier to produce bioweapons, particularly for less technically skilled people [2] by minimizing or eliminating traditional challenges that exist to bioweapon proliferation [15]. However, experts have concluded that bioweapons created by synthetic biology are currently too sophisticated to be developed by non-state actors and would likely still need to be supported by state actors [2,31], hence the importance of tracking synthetic biology funding and R&D efforts. The likelihood of terror groups or “garage scientists” developing synthetic bioweapons is low—but possible [2,33]. However, it is more likely that terror groups would either steal synthetic or bioengineered organisms from a reputable facility or acquire them through transactions with rogue nations [32] or possibly through companies that offer DNA printing services. The misappropriation of research by a disgruntled scientist is also plausible [2], and an accidental release of an agent created through synthetic biology research could lead to the severe, possibly irreparable, damage to the physical environment [31,34].

Counterproliferation and Mitigation

There has always been an enhanced possibility for biological agents to be used as weapons, thus DoD works to ensure that bioweapons are not created and dispersed. However, as the advent of synthetic biology has created new challenges, additional governmental agencies/organizations have created programs and initiatives tailored

Country/ Region	Funding Organization
Australia	Commonwealth Scientific and Industrial Research Organisation [41]
Austria	Austrian Science Fund [42]
	Austrian Genome Research Programme [43]
Canada	Western Diversification Program (Western Diversification Program) [44]
China	National Basic Research Program [45]
	Chinese Academy of Science/Knowledge Innovation Program [35]
	Chinese Academy of Engineering [35]
	China Academy of Machinery Science and Technology [35]
	National Natural Science Foundation of China [35]
	973 Program [45]
Europe	European Research Council [46]
	European Commission [46]
Finland	Academy of Finland [47]
France	French National Research Agency (L'Agence nationale de la recherché) [43]
	National Centre for Scientific Research (Centre National de la Recherche Scientifique) [43]
	Genopole [43,48,49]
	inter-EPST Bioinformatique [43]
Germany	German Research Foundation (Deutsche Forschungsgemeinschaft) [43]
	German state of Hessen [43]
	Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung) [43]
	Volkswagen Foundation [43]
	German National Environment Foundation (Deutsche Bundesstiftung Umwelt) [43]
	Bertelsmann Foundation [43]
India	Department of Biotechnology [47]
	New Delhi [47]
	Council of Scientific and Industrial Research [47]
Japan	RIKEN [50]
The Netherlands	Organisation for Scientific Research [43,51]
	Netherlands Genomics Initiative [43,51]
	Dutch Technology Foundation [43,51]
	Delft University of Technology [43]
	University of Groningen [43]
	Eindhoven University of Technology [43]
Switzerland	Swiss National Science Foundation [43]
	Department of Biosystems Science and Engineering [43]
	SystemsX.ch [43]
United Kingdom	Biotechnological and Biological Sciences Research Council [43]
	Engineering and Physical Sciences Research Council [43]
	Economic and Social Research Council [43]
	Medical Research Council [43]
	Arts and Humanities Research Council [43]
	Royal Society [52]
	Defence Science and Technology Laboratory [533]
United States	National Science Foundation [4,35]
	Department of Defense [4]
	Department of Energy [4,35]
	Department of Health and Human Services [4]
	Department of Agriculture [4]
	National Aeronautics and Space Administration [4]

Table 1: Major state-level funding organizations of synthetic biology research

to combat the use or misuse of synthetic biology in the weaponization of biological organisms (see Table 2).

Although a robust network of programs has developed to thwart the potential misuse of synthetic biology, experts urge that awareness of proper safety and security procedures is still a necessary first step to preventing the intentional or accidental release of a synthetic threat [2,9,35]. In March 2017, senior members of DoD discussed with Congress programs to counter new threats of WMD posed by synthetic biology [36]. Aside from government-sponsored programs to counter major synthetic biology threats, efforts to understand the work of scientists and researchers who are part of the "do-it-yourself" community are underway [37]. The concept of responsible innovation, the idea that "researchers bear the primary responsibility for the integrity of their

Organization	Program/Mission
Defense Advanced Research Projects Agency	Safe Genes – "the program aims to create a layered, modular, and adaptable solution set to access translational applications of genome editing technologies while protecting against intentional or accidental misuse of these tools" [54]
U.S. Department of Defense's Chemical and Biological Defense Program, The National Academies of Sciences, Engineering, and Medicine	Created an "ad hoc committee to address the changing nature of the biodefense threat in the age of synthetic biology" [55]
FBI	Tripwire Initiative – "partnership with the U.S. synthetic biology industry to report suspicious requests for genetic sequences" [56,57]
Intelligence Advanced Research Projects Activity	FELIX – "aims to develop new tools and approaches to improve and augment detection capabilities to expedite appropriate responses to the presence of engineered organisms" [58]
	FunGCAT – "intends to develop new approaches and tools for the screening of nucleic acid sequences, and for the functional annotation and characterization of genes of concern, with the goal of preventing the accidental or intentional creation of a biological threat." [59]
United Nations Interregional Crime and Justice Research Institute	Biotechnology Initiative/International Observatory - "group of stakeholders will work towards creating a shared responsibility of politics, industry, science and society to reinforce the culture of safety and security while ensuring that beneficial research is not impeded" [60]

Table 2: Initiatives aimed at reducing likelihood of the misuse of synthetic biology

work [38]," has never been more important due to the advent of synthetic biology and other emerging dual-threat technologies.

Conclusion

Synthetic biology is still in its infancy, which poses a twofold challenge. First, the full capacity, both for beneficial and potentially dangerous uses, is still unknown. Second, since the technology is still nascent, it is difficult to assess tracking methods and gain a strong understanding of how the technology is actually being utilized. In addition, the dual-use nature of synthetic biology poses legitimate concerns regarding how to prevent the potential weaponization of the technology without hindering sound, beneficial research and development.

While several initiatives are underway to minimize the nefarious use of synthetic biology, promoting awareness of the technology and ensuring that proper security, safety, and responsible techniques are being practiced will most likely be the best defense against the development of a new type of super weapon. Inevitably, science and technology change the way wars are fought as new discoveries initially meant for one purpose are often implemented as weapons (e.g., the airplane, the flamethrower, the radio, etc.) [39].

Therefore, as the pace of innovation quickens, it is imperative for the U.S. and its allies to identify new threats by remaining vigilant, tracking an ever-expanding toolkit, imagining possibilities, and making adjustments as needed, allowing the DoD to continually develop new strategies for countering these new weapons. As Thomas Jefferson said, "… as new discoveries are made, new truths discovered and manners and opinions change, with the change of circumstances, institutions must advance also to keep pace with the times [40]." ■

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Gregory Nichols is an HDIAC Subject Matter Expert. Previously, he managed the Nanotechnology Studies Program at ORAU in Oak Ridge, Tennessee, where he provided expertise on nanotechnology-related topics and conducted research. Prior to ORAU, Nichols spent 10 years in various healthcare roles including five years as a Hospital Corpsman in the U.S. Navy. He has published and presented on a variety of topics including nanotechnology, public health and risk assessment. He has a bachelor's degree in philosophy and a Master of Public Health degree, both from the University of Tennessee and holds the Certified in Public Health credential.

Calendar of Events

April 2018

04/03/18 • Leavenworth, KS
HDS Mission Command Industry Engagement Symposium

04/03/18 - 04/05/18 • Washington, DC
CBRN NCT USA 2018

04/10/18 - 04/11/18 • Springfield, VA
HDS Ground Robotics Capabilities Conference & Exhibition

04/18/18 - 04/19/18 • San Francisco, CA
HDS Offset Symposium

May 2018

05/07/18 - 05/10/18 • Indianapolis, IN
HDS Armament Systems Forum

05/15/18 - 05/17/18 • Baltimore, MD
HDS Defensive Cyber Operations Symposium

05/21/18 - 05/24/18 • Tampa, FL
CBRN SOFIC 2018

June 2018

06/04/18 - 06/07/18 • Boston, MA
AE, M BIO International Convention 2018

06/07/18 • Chantilly, VA
HDS Classified Cyber Forum

06/19/18 - 06/20/18 • Columbus, OH
HDS DLA Land and Maritime Supplier Conference & Exposition

06/28/18 • Springfield, VA
HDS Army Intelligence Industry Day