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Tracking and engaging the future: the U.S. Air Force in 2030

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TRACKING AND ENGAGING THE FUTURE: U.S. AIR FORCE RESEARCH IN 2030

FINAL VERSION

September 28, 2018

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held in Boise, Idaho May 30 through June 1, 2018

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TRACKING AND ENGAGING THE FUTURE: US AIR FORCE RESEARCH IN 2030

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Executive Summary

A workshop was held in Boise, ID from May 30-June1, 2018. A group of 33 university researchers from 20 different universities met and discussed ideas for research topics for the Air Force in the year 2030. The workshop allowed participants to collaborate in a number of areas and develop research ideas individually or in groups. A workshop risk survey was sent to the participants in which they could evaluate the risk of the research idea. Participants generated 42 research ideas over a wide range of topics supporting the Air Force themes. The description of each topic including an Overview, Detailed Description and Actions, Timeline, Air Force Approach, and Risk Assessment were compiled for this report. Based on feedback from participants, recommendations for other actions to support university research are provided. These include a Science and Technology Implementation plan to move research from low TRL at universities to higher levels through collaboration with AFRL, improved flexibility in the Grants Process to allow university favorable grant start dates, and implementation of Future Research Workshops to support and expand collaborative opportunities and develop future Air Force research. The overwhelming feedback was that such a workshop was very valuable to participants.

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Table 1: Workshop Contributors

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1.0 Introduction

The goal of this report is to describe the science and technology research efforts recommended by university researchers for the U.S. Air Force by the year 2030. These areas of research are based on a workshop held in Boise, Idaho, from May 30-June 1, 2018. Participants were from universities primarily from the western U.S. An objective of this effort was to include researchers from a number of different universities to obtain a broad perspective. In addition, another objective was to make the process very open to encourage both collaboration and a broad range of ideas. In this report we will describe the process used to reach out to potential invitees and develop a limited scope of research areas to explore. The workshop activities and process for defining research topics will be described. Then the proposed research topics will be presented, including risk assessment based on participant feedback. Recommendations on methods for the U.S. Air Force to implement research developments at universities and to enhance university research efforts are presented followed by a summary of the report. A brief summary of research-related process recommendations will also be discussed. Lastly, we will address comments and recommendations on the workshop format, and recommendations for periodic convening of similar topical workshops to develop new ideas and collaborations.

2.0 Participant Outreach and Workshop Description

2.1 Participant Outreach

The workshop organizers used two basic approaches to recruit university participants for the workshop: contacting known individuals and contacting individuals based on their position at the university. In the first approach, faculty at both Boise State University and Michigan State University suggested possible participants' names and email addresses for contact, and in some cases, faculty reached out directly via email or by phone to these contacts. In the second approach, university contacts were acquired by researching each university's deans and department chairs in science and engineering. In addition, university research officials, such as the Vice President of Research, were also added to the list. Initially, the invitees were asked to fill out a research survey based on proposed research areas or their own areas of interest. These proposed areas included:

Proposed Areas List

- advanced manufacturing
- advanced material systems and modeling
- application computing
- bio-integrated electronics
- communications, including covert communications in restrictive environments
- core computational technology
- cybersecurity
- new electronic devices and approaches for harsh environments
- passive and active stealth
- resilience to electronic warfare attack and directed energy
- space system defenses for cyber, electronic, and kinetic threats
- space vehicle systems
- tracking technology (e.g. radar sources, distributed sensing)
- wireless power transmission (e.g. laser power beaming for cubesats, drones)

In all, 150 people were contacted by email and invited to participate in the workshop research topic survey. Respondents were later invited to attend the workshop. They were also encouraged to forward the invitation to colleagues who might be interested in participating, particularly for the case of university administrators. An example of the email invitation for the survey and workshop is shown in Appendix A. The most successful outreach was based on personal connections. Faculty who were contacted by someone known to them and told about the workshop were far more likely to participate. Invitations to university administrators were far less successful receiving responses, with the exception of personal outreach to nominate specific individuals, with requisite individual follow up. Less than one-third of those contacted opened the invitation email. Major issues with participation included the short time frame for holding the workshop and the competition with other Air Force workshops. Some university researchers received invitations to participate in multiple workshops, so it was necessary to make clear that our workshop was university only to differentiate it from other Air Force-run workshops.

One of the goals of the program was to recruit diverse participants representing primarily western universities of various research levels. To encourage this kind of participation, several follow-up contacts were made at universities that had not resulted in any response. Again, contact was made with department chairs or administrators. Over 30 universities were contacted.

After receiving 39 responses to the survey, we invited those respondents to attend the workshop. A website was created for the participants to use to arrange travel. This site also included details about the workshop, an itinerary, a handbook, and access to the digital workspace. The site and Workspace site are shown in Appendix A. After travel arrangements were made, the conference ended up with 33 participants from 20 different universities with most of the participants coming from the western U.S. A map of the locations of the representative universities is shown in Figure. 1.

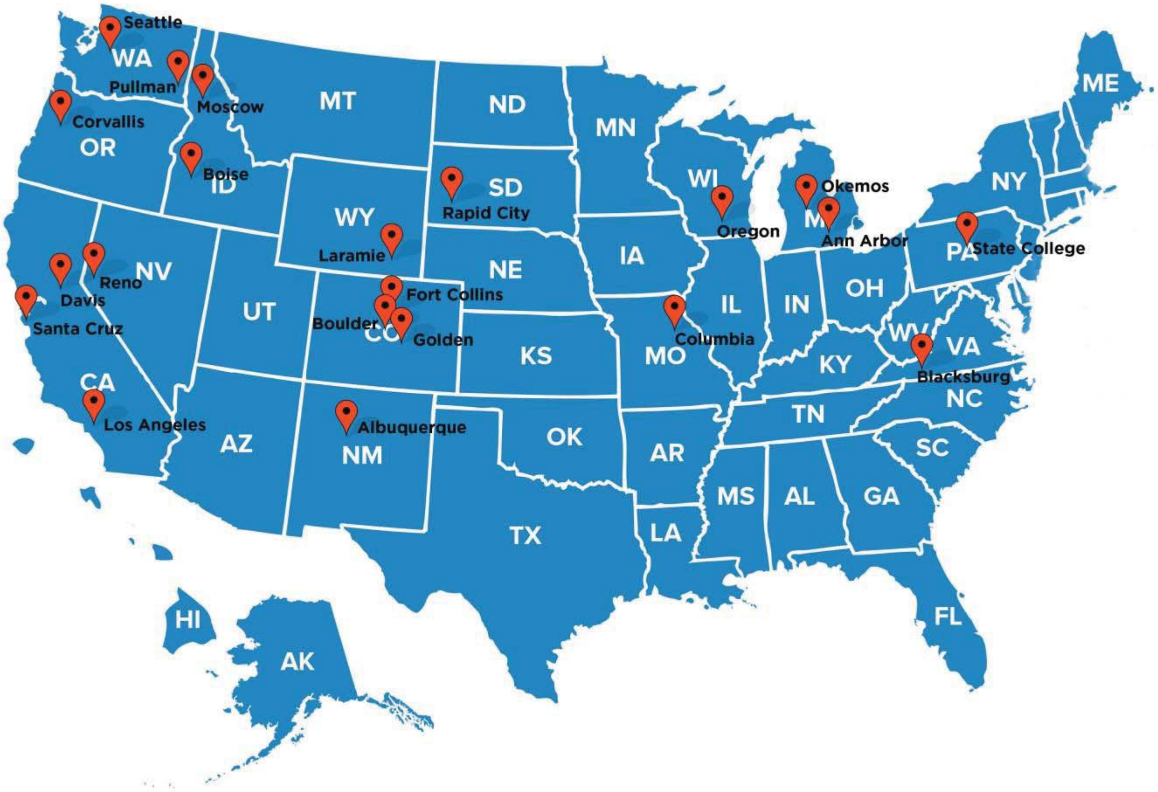

Figure 1: Locations of contributing University Faculty

As mentioned, a digital workspace was provided for the workshop participants. This workspace was a shared website to which all participants had access. They were contacted just before the workshop and provided with the access and descriptions of the user site. Based on the survey information, we divided the research topics into eight general areas. Each invitee had been asked to pick a topic or suggest a new topic for the workshop. They were allowed to pick two or three topics of interest. We then combined these topics based on the interests shown in the survey. These areas were loosely connected for some topics and had very little connections in others. The eight areas included: Tracking Technology; Communications and Dynamics; Cybersecurity and Resistance to Electronic Warfare; Application Computing and Core Computational Technology; Advanced Manufacturing and Advanced Material Systems and Modeling; Bio-Integrated Electronics, Electronic Devices for Harsh Environments; Metamaterials, Metastructures, Passive and Active Stealth, and Space Vehicle Systems; and Blue Sky Projects.

The eight groups were initially sat together to begin discussions, and each area had a worksheet template for recording the workshop information (Appendix A). This template was designed to capture the relevant information before and during the workshop. This method allowed for great diversity of ideas. Not only could multiple scientists collaborate and create their ideas with comments and suggestions from others, but individual faculty could create their own ideas. As a consequence, there was no impediment to people generating their ideas, and all ideas were captured. As described below, this technique was very successful in stimulating ideas and collaborative thinking.

2.2 Workshop

The workshop took place over three days. The first evening was a networking dinner designed to generate some familiarity among participants to reduce barriers to open discussion during the workshop. The workshop program activities started on the first full day. Participants were introduced to the workshop agenda and the digital workspace. The requirement to complete the template for capturing their ideas was explained with an understanding that it be fully completed by the end of the second day. It was made clear that multiple ideas were encouraged and that the goal was to consider ideas that might be out of the current Air Force mainstream research plans for the year 2030. Otherwise, participants were given free rein to collaborate and generate ideas. Eight large tables were set up with topical signage for the eight general areas, allowing faculty to self-identify and participate in any group based on interests. Faculty members gave brief biographies to describe their affiliation and research interests.

In the first morning, faculty were encouraged to collaborate and generate ideas via a brainstorming process with limited analysis and judgement of initial ideas. They created a document in the digital workspace with a title indicating their idea. Then they provided their name and a short summary of the idea. Over the next day of the workshop, they and others filled out the document with the following: title with a short two-sentence description, contributor names, a short summary of the idea, a detailed description of the idea, and suggestions for how the Air Force could approach the research. Meeting facilitators were hired to help guide the participants and keep the process on track to ensure that the digital workspace templates were being generated. This collaborative effort continued through the afternoon, and some participants joined other tables to further collaborate.

In the evening of the first full day of the workshop, Dr. Rob Leland, Associate Director, National Renewable Energy Laboratory, gave a talk describing the history of innovation, including approaches used by industry and various laboratories through the years. Dr. Leland emphasized serendipity, the environment of national need, and recent science breakthroughs as common elements in a major technology advance. The goal of the talk was to stimulate innovative thinking about ideas and strategies for implementation for the remainder of the workshop meetings and to encourage discussions on these topics.

On the final day, participants were encouraged to complete their idea documents and provide enough background and detail for writing this report. The workshop facilitators both encouraged and helped with document completion. They then captured the project titles and the short two sentence descriptions, which were placed in a summary file. In the afternoon, participants briefly presented their ideas to the entire workshop group explaining motivation and the basic research concept. They then answered questions and took feedback, which resulted in augmentation of some of the research ideas.

A simple risk analysis was conducted on the Research Areas by asking the participants to consider risks to successfully completing the ideas proposed. A brief discussion of the purpose of the risk analysis and the risk categories was held near the end of the Workshop. The risk categories were titled Cost, Technical, Deployment, Defendable, and Competitive. Descriptions of these risk categories are provided in Table A1 in Appendix 6.2. The risks are briefly described in the following list:

- Cost- could the technology cost too much to develop
- Technical- is the technology attainable, does it require multiple scientific breakthroughs
- Deployment- are there unreasonable requirements of infrastructure, talent, or supplies
- Defendable- can the technology be protected, or is it vulnerable to hacking
- Competitive- could it be developed by others first, or bar the US from using it.

The participants were invited to complete a Risk Survey online. Twenty-one of them completed the survey for Research Areas they believed they understood well enough to assess. Risk levels were *Low, Medium, and High*. The results for each Research Area are provided in the relevant section of the report in tables showing the number of responses for the level of risk for each risk category. Table 1 shows the risk assessment survey categories with detailed explanations.

Table 1: Risk Assessment Survey categories

Risk Area	**Description**
Cost	What is it likely to cost to complete the research phase of this technology? How many different parties are required to complete the work? What sort of equipment and infrastructure will be required? Does it require any materials from politically unstable or challenging countries? Yes = high, No = low risk
Technical	Consider whether or not this technology can be successfully developed. Does it require advancing just a few technologies, or multiple scientific breakthroughs? Is it likely to take a very long time to complete? Yes = high, No = low risk
Deployment	Will this be to transition from research to development? Will it require significantly new infrastructure, or at significantly larger scales than are expected to be available? What about the workforce? Yes = high, No = low risk
Defendable	Will it be difficult to protect this technology? Is it likely others could neutralize it, or render it ineffective? Consider whether or not other parties will be able to acquire it without authorization, or will be able to hack it. Yes = high, No = low risk
Competitive	Is it likely other countries or groups could develop this technology before the US? Could they then threaten the ability of the US to use it as intended? Yes = high, No = low risk.

3.0 Science and Technology Research Area Description

The results of the workshop were captured in documents for each of the 42 ideas. Participants created the original descriptions as described in Section 2.0. After the information in each section was uploaded and revised, participants were given the opportunity to edit the documents again for clarity and detail based on the final format. These ideas are provided in this section. Each section has a Descriptive title, Contributors, an Overview, a Detailed Description and Actions, suggested Air Force Approach, Timeline, Survey Risk table, and References. The survey on risks are provided in table form. Note that some topics were not updated in the survey, so risk assessments are not provided for those areas.

3.1 New Electronic and Imaging Devices and Platforms

3.1.1 Hybrid Electronics

CONTRIBUTORS

Jim Browning, Kris Campbell, Scott Kovaleski, Majid Manteghi, Sal Portillo, John Verboncoeur, Peng Zhang

OVERVIEW

An array of new material and device platforms are being developed and continue to evolve. Each technology has advantages and disadvantages depending upon application and environment. Combining these technologies or materials platforms to create hybrid devices could enable systems using the best capabilities of that technology. This approach could include complete integration on a single substrate or a combination of multi-chip modules.

Silicon based electronics have limitations in harsh environments, which include both high temperature and radiation. Silicon is also susceptible to electronic warfare attacks. Devices based on graphene [1,2], chalcogenides (such as GeSe) [3],vacuum electronics [4-8], silicon carbide [9-11], or diamond offer capabilities in high temperature (>350 C) and high radiation environments and are less susceptible to electronic warfare attacks. Plasma sheaths as varactors for parametric amplifiers are another example of such technology. These devices could be integrated into hybrid systems using advantages and functionality that support the application from full integration on a single substrate to multi-chip modules. Hence, a hybrid of various technologies and material systems could be developed to support new applications. This effort offers an opportunity for a convergence of new and old technologies to support applications that are accessible with a single platform. [12]

DETAILED DESCRIPTION AND ACTIONS

Hybrid electronic devices could take advantage of the best features of different technologies while minimizing the disadvantages. Two or more device technologies could be merged through integration at the substrate/wafer level or through integration of multi-chip modules (stacked substrates). In addition to silicon, these technologies could include vacuum electron devices (vacuum nano-transistors), silicon carbide, diamond, graphene, chalcogenide glass, and plasma based systems. Such hybrid electronics would support a range of applications in both high temperature (>350 °C) and high radiation environments.

Chalcogenide-based materials (e.g., Ge2Se3) are used in various devices, such as optically-gated transistors, phase-change memory, and ion-conducting (SDC) memristor devices [3]. The Ge2Se3 film structure is amorphous in these devices and has a glass transition temperature of approximately 350 °C, making them high-temperature tolerant. Because of their amorphous structure, they are also radiation tolerant. These devices could be integrated with other materials systems in which the chalcogenide device properties are desirable and unachievable in the other material system.

Sensors in harsh environments (for instance, high temperature environments like jet engines) are limited in their processing power by the thermal capabilities of semiconductors. Plasma-based devices (similar to plasma filled vacuum electronics) may be designed to survive these environments. A basic component of most electronic systems is the amplifier. The voltage dependent capacitance present in a traditional plasma sheath allows it to be used in a parametric amplifier. In the traditional parametric amplifier, a varactor diode mixes a signal and pump RF input, transferring energy from the pump to the signal and thereby amplifying it. In this case, a plasma sheath can be substituted for the varactor diode.

Gated field emission arrays (GFEAs) are being adapted to create vacuum nano-transistors (VNTs). These devices typically operate at higher voltages (10-15 V), but they have already been operated at high temperatures (400 °C) and are not susceptible to gamma radiation. Neutron damage could cause problems in large doses. GFEAs have been integrated on single crystal silicon wafers with NMOS circuitry including analog and logic structures. These hybrid devices allowed control of electron emission from the GFEAs using the high voltage (HV) silicon transistors. Similar hybrid devices could be fabricated by integrating technologies including silicon carbide, diamond, plasma, and graphene based systems and structures.

A comprehensive theoretical understanding of the physics for these new hybrid, electronic devices would be essential [11]. Issues such as electron emission and transport across interfaces of dissimilar materials (including vacuum), thermal management, ultrafast processes, electrical and thermal contacts and interconnects, and breakdown mechanisms have to be investigated systematically.

The research effort should include:

- Analysis of the various technologies and capabilities to determine what functionality and advantages can be achieved. Some analysis and research on possible applications should be included.
- Process integration research is needed on compatible technologies to determine which areas offer the best opportunity for development. Fundamental research in these processes is required based on material systems, process compatibility, and device design.
- When technologies are not compatible through direct integration, research is needed to evaluate where the systems can be developed in separate modules (devices systems). Then a method to combine these separate devices into a fully integrated system would be needed. Full integration of hybrid technologies requires understanding of the basic materials and device performance limitations.

- The theoretical understanding of the device systems and transport mechanisms must be greatly improved to allow development of these integrated systems, particularly interfaces among systems.
- Finally, research should expand to include other material systems, device structures, and capabilities. An entirely new generation of currently unknown devices could be developed once researchers have access to the hybrid technology capabilities.

AIR FORCE APPROACH

This development would require multi-year and multi-university efforts directed both at fundamental research on the integration of the various material and technology systems as well as development of applications that take advantage of the hybrid systems. Such efforts could include MURI research efforts, traditional BAA directed calls, and STTRs when industry capabilities are required. Initial efforts should be based on the fundamental understanding of device/technology integration.

TIMELINE

5-10 Years

SURVEY RISK

	Low	Medium	High
Cost	2	9	7
Technical	4	7	7
Deployment	4	11	3
Defendable	2	14	2
Competitive	2	9	7

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3.1.2 Optically-Gated Transistor Interface for Harsh Environment, Resiliency, and Redundancy

CONTRIBUTORS

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OVERVIEW

Optically-gated transistors are being considered for many applications because they can be used to isolate electronics that might be sensitive to the environment of the system they are interfaced with. Optically-gated transistors using Ge2Se3 amorphous materials doped with elements, such as metals or carbon, that are radiation and temperature tolerant (glass transition temperature ~ 350 °C and melting T > 400 °C), have recently been under investigation. These transistors can have very low dark current; however, the transistor characteristics vary significantly depending upon the dopant. The ability to vary the transistor characteristics would allow electronic tuning to the particular circuit application.

Two potential applications of optically-gated transistors are a) security, or protecting a system (electronics) against disruptive pulse (via optical isolation), and b) protecting a system against harsh environments such as radiation or temperature extremes.

DETAILED DESCRIPTION AND ACTIONS

Optically-gated transistors can be used to isolate sensitive electronics (particularly silicon based devices) from exploitation or damage by providing electrical isolation between systems. These devices, placed between the electronics and the outside world (e.g., antennas), would provide the needed isolation. In addition, some material systems would also be capable of operating in high temperature and high radiation environments, further providing needed capabilities. An example includes protection of satellites from electronic warfare (EW) attacks or high radiation events.

With optical interfaces between electronics/photonics circuits and the outside world, signal transmission and conversion through these interfaces would be critical. Research and development efforts include the basic understanding of the physics on the coupling and conversion between optical and electrical signals, via technologies such as plasmonics [1], waveguides, electrically pumped optical devices [2], and advanced interconnects and electrical contacts [3]. Issues such as efficiency, reliability, thermal management, and the related limiting factors need to be researched.

The research approach should focus initially on the current work in optically-gated devices and optical transmission. However, new areas of research must be pursued with the following research actions:

- New materials technologies and their incorporation into a transistor device.
- Understanding the physics of photoemission, optical field emission, and their combination under different inputs, with consideration for various material properties.

AIR FORCE APPROACH

It is suggested that the Air Force use a BAA for optically-gated transistor development. The R&D effort could include investigation and refinement/development of the optically-gated transistor technology (new technology, uncharacterized to date). Efforts could also include development of robust transistor technologies, which would lead to deployable applications with AFRL or industry involvement.

TIMELINE

5+Years

SURVEY RISK

	Low	Medium	High
Cost	4	10	2
Technical	2	8	6
Deployment	4	9	3
Defendable	5	9	2
Competitive	2	8	6

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3.1.3 Integrated Vacuum Electron Sources and Optically-Gated Transistors

CONTRIBUTORS

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OVERVIEW

Gated field emission arrays (GFEAs) as electron sources are limited in modulation frequency by array capacitances and resistances. However, these arrays offer many opportunities [1-5] for use in a range of vacuum electron devices, such as magnetron, crossed-field amplifiers, traveling wave tubes, and high-power switches. Optically-gated transistors used as backplanes for the arrays would allow modulation at higher frequencies with spatial control. The research would allow direct optical gating of arrays of electron emitters using integrated photonic circuits and local control circuits. Such devices could be used in an array of vacuum electron devices. These devices could also be combined with complex 3D metallized structures for complementary metamaterials to generate frequencies much different than allowed by that geometric shape and size.

DETAILED DESCRIPTION AND ACTIONS

The application of cold cathode vacuum electron sources in microwave devices and switches is limited by modulation frequency. While the sources can be modulated, the arrays of devices generally have large capacitance, which can limit the frequency. While the emitters can produce large current densities (100 A/cm2), proximity space charge often limits the array total current. Modulating the emitters at high frequency (10 GHz) would allow for new applications. One method to limit the capacitance issues is to divide the arrays into smaller areas with controlling circuitry at each location. Optically gated transistors could provide a backplane for uses with the emitters and allow higher modulation frequency as well as spatial control.

GFEAs offer significant opportunities for electron sources in vacuum devices including microwave sources and electronic warfare applications. An issue with such devices is the frequency modulation limitation because of the array capacitance for large area structures. Optically gated transistors could be integrated with the GFEAs to control the emission current with small (1 emitter) to many (10-20 emitters) per transistor. Arrays of transistors interconnected with the GFEAs would allow modulation at high frequency (~10 GHz) of the electron sources.

One approach that has recently been shown to enable direct optical gating of electron field emitters has been the use of integrated photonic circuits. Specifically, the ability to control and guide photons and controllably interact them with electron emitters can be done by taking advantage of the well-established silicon integrated photonics processing.

Creation of metallic complementary metamaterials driven by electron beams and used as slow wave structures will yield much different frequencies that are normally not possible within the dispersion found in a specific sized cavity. These ‘out of band’ dispersion frequencies would yield novel capabilities with present or similar sized tubes

One type of optically-gated transistor is based on electron emission excited by the combination of dc bias and optical field [6]. Understanding the underlying physics of optical induced/assisted electron emission and transport is of fundamental importance. It is also important to the development of photocathodes used in accelerators and ultrafast electron microscopes. Basic theoretical and computational modeling is needed to find the scaling laws governing the electron emission process as a function of field strength, optical frequency, and material properties. The limits on the maximum operation frequency need to be identified.

Actions to develop this research would include:

- Development of optically-gated transistor technology that is compatible with high temperature (>500^{o} C) processing. This technology should be capable of integrating with vacuum electron devices with near 100% yield of arrays of devices.
- Interconnects and optical transmission technologies must also be developed and be compatible with the vacuum systems. In particular, multiple interconnects or methods of transmission may be required.
- Other research must look at the integration of the transistor arrays with the field emission arrays. The process development could include full hybrid integration of the two technologies on one substrate or fabrication of two separately yielded arrays of devices with integration of the two arrays after each device structure is complete.
- Finally, a clear study of the electron transport and performance limitations is required to provide a theoretical foundation for both technologies as well as their integration.

AIR FORCE APPROACH

A multi-university approach with multidisciplinary teams is needed to not only fully investigate the physics but also to engineer these devices so that they provide the needed energies. Additionally, a collaboration with end DoD users is critical to ensure a successful coupling of fundamental research and industry. This technology would be applicable both for the Air Force and other industries.

TIMELINE

5-10 Years

SURVEY RISK

Not Available

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3.1.4 Bio-Integration of Plants and Electronics for Applications to Security, Sensing, Communication, and Monitoring

CONTRIBUTORS

Kris Campbell, David Estrada

OVERVIEW

A potential new area of electronics, sensors, and other diagnostics includes interacting electronically with plants to measure the local environment of the plant, communicate between plants, communicate between spatial regions through the plants, monitor air/chemical environment, and security.

This project integrates biological and electrical engineering disciplines with the goals of a) investigating a method of electrical communication between plants and humans using the emergent electrical circuit element of memristance[1-5], and b) identifying characteristic features of memristor I-V curves that can be applied to any system in order to identify the type of ionic motion contributing to the memristance. Memristance has been measured in plants on the cellular scale, as well as on a large scale through plant stems[6]. Each type of memristance provides a distinctive I-V curve.

Measuring the I-V response of plants in certain regions (xylem, cell to cell, region dependent) shows that plants exhibit memristance, likely due to ionic movement between the electrodes defining the probed region. The memristance will be dependent on conditions of the plant as well as on any other signals incident on the plant ‘receiver’. The Air Force needs to monitor regions remotely, and plant monitoring can allow for incognito and secure communication and monitoring of regions.

DETAILED DESCRIPTION AND ACTIONS

Electric circuits in biological systems, such as plants and skin, can operate over large distances [7-10]. It has been shown that triggering the hair on the open trap of a Venus flytrap generates an electrical action potential that causes the trap to close. When this action potential is electrically shared with a Mimosa pudica (a plant that ‘collapses’ when touched) by attaching a wire from the Venus flytrap to the stem of the Mimosa pudica, the action potential causes it to respond by collapsing as if it were responding to its own generated action potential [11]. Electrical communication has also been demonstrated recently between two separate Aloe vera plants [12].

Outstanding research questions in this area include the following: Will the memristance be changed via electrical signal (options: detected via graphene tattoo transmission) dependent upon environment (options: electronic interference sending signal to the plant through the measurement hardware; chemical environment through roots, through air)? Can this be used for communication or security (environmental or electronic)? Can the plant be used as a security ‘key’? Can we reverse the movement of the plant through electrical memristance?

Research actions to advance this technology would include:

- Determine memristor response of identified (target) plants under various conditions.
- Investigate the signal transmission to and from graphene tattoo and the solar power energy harvesting required to operate measurements.
- Longer term studies would include the ability to deliver electronic signals to plants via electronic tattoo (wireless delivery) to cause plant positional change; delivery of voltage sweeps via wireless delivery for memristor characterization, simultaneously sending a response back wirelessly; and investigation of IV response memristor characterization via wireless control/transmission under different environmental conditions.
- Finally, the research would include the ability to communicate securely and wirelessly through a plant network by controlling and measuring memristive response. This can be done over large distances without the need for drones.

AIR FORCE APPROACH

This project requires a multidisciplinary team in the areas of electrical engineering, plant physiology, and physics. Various aspects of the plant physiology need to be understood in order to understand how to send and receive signals to the plant for the desired response (e.g., movement). This includes understanding the action potentials and where to apply and receive them. It also requires investigation of signal transmission from the plants via electrical connections to the plant, such as graphene tattoos.

TIMELINE

5+ Years

SURVEY RISK

	Low	Medium	High
Cost	3	4	9
Technical	1	2	13
Deployment	1	4	11
Defendable	2	8	6
Competitive	5	5	6

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3.1.5 Bioengineered Nano-Bio-Catalysis: Protein Functionalized Nanomaterials

CONTRIBUTORS

Kris Campbell, Su Ha

OVERVIEW

We can combine various proteins with nanomaterials to create unique hybrid nanomaterials with special electrochemical and optical properties. To increase the functionality of these nanobiocatalytic materials, the structures of proteins can be modified via an advanced bioengineering process and the interactions between the proteins and nanomaterials at their interfaces can be precisely tuned.

The integration of biomolecules with electronic elements to produce various functional bioelectronics devices is important for both the basic fundamental scientific questions and the potential practical applications of the system. Establishing a direct electrochemical communication between the active site of protein and the electronic supports, while maintaining a long-term protein stability, is a critical step for development of any practical bioelectronics devices (e.g., biosensors and biofuel cells). To address these scientific challenges, the first goal of this research is to bioengineer a target protein for increasing the charge transfer rate between its active site and the electrode without significantly losing its enzymatic activity. The second goal of this research is to improve the enzyme stability and maintain the high electrochemical activity by nano-confining bioengineered proteins using various nanomaterials.

DETAILED DESCRIPTION AND ACTIONS

To achieve high electrochemical performances from the protein-based electrodes, previous investigators have created functional enzyme electrodes by immobilizing the enzyme on the external surface of nanomaterials, either by entrapping it in sol-gel or polymers or by using bulk composite. However, either a poor electrical connection of these immobilized enzymes to electrodes (i.e., a poor electrochemical activity) or their short lifetime hinders the development of practical high performance bioelectronic devices. Our idea can address this challenge by a) bioengineering the naturally available proteins to have desired electrochemical properties by modifying their secondary structures, and b) immobilizing these bioengineered proteins over the specially designed nanomaterials to enhance their long-term stability by tuning their interfaces and modifying the protein's surrounding nano-environments.

Actions needed to support this research area include:

- The first objective is to a) identify peripheral secondary structures of various oxidases (i.e., enzymes that catalyzes an oxidation or reduction reactions) that can be removed without significantly reducing their enzymatic activities, and b) selectively remove these identified secondary structures using advanced bioengineering tools. Molecular dynamics simulation also needs to be used for predicting the effect of protein engineering on their structural stabilities. The relationship between protein structures and electrochemical properties (e.g., electron charge transfer efficiency, electron transfer rate constant, and electrochemical impedance) for bioengineered oxidases needs to be established using electrochemical analysis methods.
- The second objective is to improve the long-term stability of bioengineered oxidases using the novel nanoscale enzyme reactor (NER) design. The various carbon nanomaterials with unique nano-structures (e.g., mesoporous carbon foams) need to be synthesized, and novel enzyme immobilization methods need to be developed using these nanomaterials. The long-term stability of bioengineered oxidases needs to be dramatically improved by optimizing the interfacial structure and interaction between the enzymes and surface of nanomaterials via nano-confinement and multipoint chemical linkage effects.

AIR FORCE APPROACH

The Air Force should support the basic science research efforts to fundamentally understand the protein structure-electrochemical activity relationship. Furthermore, it should also support the research efforts to understand how the interfaces between the proteins and conductive nanomaterials affect the charge transport rate and protein stability. Based on this fundamental understanding, one can design high performance protein-based electrodes for efficient bioelectronic devices.

Some protein-based devices have been previously studied (e.g. enzymatic biofuel cells [1], glucose sensors [2], photosystem I (PSI) protein-based transistors [3], and solar cells [4]). A well-studied system such as glucose oxidase, laccase, and PSI could be used initially to investigate the protein structure-electrochemical activity relationship. This could lead the direction for other protein complexes or enzymes as well as the appropriate design of electrode material and contact.

TIMELINE

5+ Years

SURVEY RISK

	Low	Medium	High
Cost	1	9	0
Technical	2	4	0
Deployment	2	11	0
Defendable	2	12	0
Competitive	4	9	0

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3.1.6 Controlled Laser Delivery to the Retina for Therapeutic Applications

CONTRIBUTORS

Steven F. Barrett, Cameron H.G. Wright

OVERVIEW

In the 1990s the researchers developed an automated laser delivery system for the retina for therapeutic purposes[1-11]. The purpose of this research effort is to design, develop, and prototype a system using cutting-edge equipment and technology. The prior scanning systems employed active tracking of retinal features (retinal vessel fingerprints) to track and compensate for the natural movement of the retina. The system worked with a standard fundus imaging camera to deliver a stabilized argon laser beam to the surface of the retina via the dilated pupil. The system was able to compensate for retinal movement and safely deliver the laser energy to the retinal surface for the treatment of retinal diseases, abnormalities, and injury. Full system development was hampered by 1990s equipment cost and capability (computer speed, camera frame rate and resolution, and interface bandwidth). New research efforts are needed to design, develop, and prototype a system using cutting-edge equipment and technology.

DETAILED DESCRIPTION AND ACTIONS

Laser photocoagulation has been used for decades to treat retinal disorders, diseases, and injury. Typically an argon (green) laser is used to treat the retina. It is manually delivered to the patient's retina via a dilated pupil. The ophthalmologist typically delivers the laser energy to the retinal surface with a preset irradiation interval. The green laser passes through the cornea and interior of the eye unimpeded. The argon laser generates heat, and hence coagulates a spot of the retina, due to light absorbing material within the retinal layers. Multiple lesions may be required to treat diabetic retinopathy, macular degeneration, and retinal tears [1, 3, 5-11]. The system has also been employed to study the effects of different laser technologies on the human retina [4].

In the early 2000s, Naess was able to significantly reduce the footprint of the laser delivery system [3]; however, system development was still hampered by available computer speed, camera frame rate and resolution, and interface bandwidth. Recent and ongoing developments have resulted in high performance computers with small footprints and low cost, high resolution and frame rate cameras, and high-speed camera frame grabbers with high data throughput.

The purpose of this research effort is to design, develop, and prototype a system using cutting-edge equipment and technology with the goal of developing a small footprint, low cost prototype.

Actions needed to support this research include:

- Fund research team to develop and test prototype.

AIR FORCE APPROACH

Integrate use of this technology in healthcare arena.

TIMELINE

5+ Years

SURVEY RISK

	Low	Medium	High
Cost	5	9	3
Technical	4	10	3
Deployment	7	7	3
Defendable	2	12	3
Competitive	6	9	2

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3.1.7 High-Speed Imaging Arrays in High-Energy Radiation Environments Using Novel Semiconductors (CEH)

CONTRIBUTORS

Charles E. Hunt

OVERVIEW

Pixelated array large-area optoelectronic backside imagers working in the short-wavelength (THz-Xray) spectra, can be hybridized to rad-hard CMOS Read-Out ICs. The objective is to simultaneously solve the four barriers: 1) low quantum efficiency (QE), 2) high speed, 3) large-area (> 500x1000 pixels), and 4) performance uniformity. Imaging transient radiation bursts in either high-temperature or high-dose environments is challenging because present-day silicon technology limits the energy range, temperature, and the speed of the detection. An emerging solution, being developed at some national labs, is to separate the large-area (~ 500x1000 pixel) detector array, made from one material, from the (radiation-hard) CMOS signal-processing device, and either flip-chip bonding or wafer bonding the two functional devices together. The Si back-side imager CCD technology discovered 20 years ago for astronomical imagers is the pioneering example of this approach. Design and implementation of CMOS Read-Out ICs (“ROIC”s) has proceeded independently of the optoelectronic arrays to which they are hybridized. However, four specific challenges remain for the opto arrays: 1) quantum efficiency at short wavelengths, 2) high-speed of data transfer to the ROICs, 3) design and fabrication of large-area arrays from novel semiconductors, and 4) obtaining uniform performance over the array with sufficient signal/noise. These four challenges need to be simultaneously solved before useful high-energy imagers can be obtained.

DETAILED DESCRIPTION AND ACTIONS:

The four optoelectronic challenges are addressed here. It is likely that ROICs will continue to be developed independently, since these are integrated into a diverse family of sensor and imager applications.

- Obtaining high QE is almost exclusively the consequence of employing absorber materials with higher atomic numbers (eg. Z>25, for Si, Z=14). This constrains us to the use of GaAs, GaSb, Ge, CdTe, TlBr, and a large collection of ternary compounds. Use of these materials, however, demonstrates problems with one or more of the other three requirements (eg. carrier mobility, adaptability to large-area pixelated imagers, and high S/N.) It is vital that there be exploration of new materials (such as metamaterials) as well as new fabrication techniques with existing materials.
- Speed in some of the high-Z materials (e.g., CdTe or TlBr) is poor. The only way to avoid eliminating considering such absorber materials is to employ speed enhancing

techniques, which might include strain layers, formation in nano-tubes or nano-crystals, inclusion in electron-hopping meta-materials, or yet-unexamined approaches. For example, TlBr crystals, which could effectively absorb hard xrays, might be embedded in a matrix of high-mobility dissimilar material(s) which transport the signal to the ROIC. In principle, this approach might be simple, but nothing like this has been experimentally demonstrated.

- Large-area implementation of absorber arrays, such as what can be achieved with Si, simply doesn't exist. Even well-understood materials like GaAs have uniformity problems as areas get larger. Research in this arena has to be progressed, even if success in the other three areas is achieved.
- Signal to Noise Ratio (S/N) impedes the use of otherwise promising materials, especially Ge (with its small bandgap energy). Solving this problem requires the employment of a) existing (such as heterojunction barriers and graded-composition absorption layers) and yet-untried device design methods and b) materials systems which otherwise have demonstrated low S/N.

AIR FORCE APPROACH

Although research exists, and calls for research in one of more of these four arenas are out from various agencies, the success of obtaining large-area, high-speed imaging arrays for the shorter wavelengths demands simultaneous investigation in all four arenas. The Air Force should start by bringing members of these disparate communities together in one or more workshops in order to narrow the focus and scope of the program objectives to best serve the needs of the Air Force. These workshops would enable collaborative coalitions, which could then submit to one or more subsequent RFPs from the Air Force in this field.

TIMELINE

5+ years for development of the materials. 5+ years to hybridize to electronics. High-risk; high-payoff.

SURVEY RISK

	Low	Medium	High
Cost	1	8	6
Technical	2	5	8
Deployment	3	10	2
Defendable	3	9	3
Competitive	1	10	4

3.2 Tracking, Drone, and Stealth Technologies

3.2.1 LIDAR and Drone for Change Detection

CONTRIBUTORS

Anura Jayasumana, Jinsub Kim, Yelda Turkan, Leming Qu

OVERVIEW

Aerial LIDAR and drones can be used to detect objects/features of interest automatically and near real time. The major setback associated with their use for such applications is the large data sizes, which require longer processing times. This study aims to use/develop machine learning algorithms, such as adaptive wavelet neural networks (WNN), to process 3D LIDAR point cloud data or drone images near real time and at low computational cost. [1-3]

DETAILED DESCRIPTION AND ACTIONS

LIDAR images are 3D point clouds, i.e., each point in a LIDAR image has x, y, z coordinates, as well as intensity and RGB (color) information. Large data files present a major hurdle for wider implementation of LIDAR point clouds for object detection and tracking because they require long data processing times. Machine learning algorithms such as adaptive wavelet neural networks (WNN) can be used to process the LIDAR data faster (near real-time) while obtaining high accuracy results. Self-adaptive WNNs are capable of representing LIDAR data in low resolution while keeping object/feature characteristics that are required for identification.

Drones, also known as unmanned aerial vehicles (UAVs), are a cheaper alternative to flying airplanes to collect such information (detecting and tracking features/objects of interest). UAVs are typically equipped with digital cameras but can be equipped with thermal cameras as well as LIDAR devices (low resolution/low accuracy LIDAR). Drone images can be processed using structure from motion (SfM) and other computer vision algorithms to develop 3D point clouds. Though the resulting 3D point cloud is not as accurate as LIDAR 3D point clouds, it is accurate enough for detecting large objects such as buildings, trees, etc. Similar to 3D LIDAR data point cloud processing, developing 3D point clouds from drone images and processing those 3D point clouds for object detection/tracking can be tedious.

TIMELINE

3-5 Years

SURVEY RISK

Not Available

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3.2.2 Adversarial Tracking via Dynamic Sampling and Resource Allocation

CONTRIBUTORS

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OVERVIEW

The capability to detect and track target objects is essential for many Air Force missions. The advance in stealth technology has made detection and tracking of target objects much more challenging than ever before. Traditional stationary tracking strategies are likely to fail in the presence of a resourceful adversary with the knowledge of stationary strategies who actively falsifies the input data to perturb the decision of tracking algorithms. There is a critical need to advance tracking technology such that it can succeed even in a challenging adversarial environment. To fill this gap, we propose to develop an active tracking framework that will dynamically adapt tracking system configurations (e.g., sensing resolutions, sensor deployment).

DETAILED DESCRIPTION AND ACTIONS:

Most existing tracking systems are stationary in a sense that their configurations (e.g., sensing resolutions, sensor deployment) do not adapt to changing environments. Such a system with a fixed configuration can be suboptimal, especially when data indicate that certain parts of the environment need to be sensed more thoroughly than others (e.g., when data indicate active movement of objects in certain small regions). Furthermore, in the presence of an active adversary capable of compromising part of the input data, a stationary tracking system may fail to provide reliable decisions because the adversary can possibly learn the tracking strategy and exploit it to perturb the system decisions. For example, the adversary can design falsification of input data such that certain target objects will not be detectable by the tracking system. It has been known that measurement data from sensor networks or large-scale control networks are prone to be vulnerable to data falsification attacks.

In order to address this shortcoming, we propose to develop an active tracking framework where the tracking system actively adapts its data sampling strategy in response to the time-varying environment (estimated based on observations) in order to reinforce its decisions. The adaptation options may include, but are not limited to, dynamic activation of sensors, adapting sensing modalities, and dynamic deployment of additional mobile sensors or UAVs to certain regions or relocating them.

For instance, if the system has a high confidence that a target object is present in certain small regions, it can adjust the sensing configuration to obtain higher resolution data for the region (e.g., increasing sensing resolution, deploying more sensors, sending additional UAVs) to reinforce its decisions. If some subset of sensors is suspected of being compromised, the system can dynamically adjust the configuration such that trustworthiness of those sensors can be verified. Furthermore, one can consider a randomized strategy of system adaptation to make it difficult for an adversary to predict how the tracking system would adapt.

Data falsification attacks on signal processing algorithms (e.g., state estimation, see [1]) and machine learning algorithms have been studied actively in the recent decade. However, data falsification attacks and countermeasures have not been investigated in the context of tracking problems. At a high level, the active tracking problem can be seen as an instance of adversarial machine learning [2], which has drawn the attention of the machine learning research community, especially in the last two years. In adversarial machine learning, a typical objective is to make a learning algorithm resilient to data falsification by an adversary (e.g., falsification of test data). The sequential decision making setup of active tracking makes it a much more challenging problem than the adversarial machine learning problems studied in the literature.

The following actions should support this program development:

- We can start by modelling adversaries with different capabilities. A strong adversary may be capable of compromising many sensors as well as acquiring much knowledge of the tracking system; on the other hand, a weak adversary may be able to perturb only a few input data to the tracking system and have limited knowledge about the system.
- Then, we can perform vulnerability analysis of existing stationary tracking strategies: what capability does an attacker need to perturb decisions of stationary tracking strategies?
- Then, we can develop an active strategy to enhance resilience to adversarial data manipulation or an active stealth technique. A game-theoretic analysis would be helpful to understand fundamental characteristics of this problem. The cost-benefit analysis should be made to characterize the tradeoff between the performance enhancement and the overhead incurred due to the active scheme.
- Once theoretical study and numerical simulations show promising results, we can test the idea in a government lab for validation and verification.

TIMELINE

5 Years

SURVEY RISK

	Low	Medium	High
Cost	6	9	1
Technical	1	11	4
Deployment	4	11	1
Defendable	5	11	0
Competitive	2	12	2

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3.2.3 Low Cost, Optical Tracking System

CONTRIBUTORS

Steven F. Barrett, Cameron H.G. Wright

OVERVIEW

In the 1990s the researchers, Barrett and Wright, developed an automated laser delivery system for the retina for therapeutic purposes. The system employed active tracking of retinal features (retinal vessel fingerprints), to track and compensate for the natural movement of the retina. Although developed for a specific task, the developed tracking techniques may be generalized for use in a wide variety of tracking tasks. Full system development was hampered by then current (1990s) equipment cost and capability (computer speed, camera frame rate and resolution, and interface bandwidth). The purpose of this research effort is to design, develop, and prototype a generic, portable tracking system using cutting-edge equipment and technology.

DETAILED DESCRIPTION AND ACTIONS

In the 1990s researchers developed an automated laser delivery system for the retina for therapeutic purposes [1-3]. The system employed active tracking of retinal features (retinal vessel fingerprints) to track and compensate for the natural movement of the retina. Retinal movement was tracked frame-by-frame in a video sequence. Full system development was hampered by the then current (1990s) equipment cost and capability (computer speed, camera frame rate and resolution, and interface bandwidth).

Recent and ongoing developments have resulted in high performance computers in a small footprint and a corresponding low cost, high resolution and frame rate cameras, and high-speed camera frame grabbers with a corresponding high data throughput.

The purpose of this research effort is to design, develop, and prototype a system using cutting-edge equipment and technology with the goal of developing a small footprint, low cost prototype generic tracking system. By employing two (stereo) cameras, location of the object in 3D space is possible.

To achieve this research, the following actions should be undertaken:

- Fund research team to develop and test prototype.

AIR FORCE APPROACH

- Integrate use of this technology into future plans and concepts.

TIMELINE

5-10 years

SURVEY RISK

	Low	Medium	High
Cost	8	11	0
Technical	6	11	2
Deployment	9	9	0
Defendable	4	10	4
Competitive	4	11	3

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3.2.4 Simulation and Classification of Airborne and Land-Based Objects Using Scattering Patterns

CONTRIBUTORS

Firas A. Khasawneh

OVERVIEW

Object identification and classification using scattering patterns is important in many fields, including astronomy, astrodynamics, and celestial mechanics. The ability to accurately characterize these objects leads to an improved space situational awareness (SSA) and to an enhanced control over the ground. There are two types of observations of interest: space objects observations (looking up) and land objects observations (looking down). Typically, observations of the space objects are performed using earth-based or orbit-based sensors. These sensors typically collect scattered light information from the objects moving in space, which includes asteroids and resident space objects (RSOs). Land-object information, on the other hand, is often collected using satellite images or LIDAR data from drones.

The natural candidate for classifying the influx of the resulting data is machine learning algorithms. However, there are two challenges: these algorithms require a large amount of data for training, and the trained classifiers may not adapt to situations that have not been recorded in historic data. Therefore, this research aims to address these issues by proposing a) an investment in multi-physics simulation tools for scattering patterns and b) a focus on novel featurization tools from emerging fields such as topological data analysis, and novel machine learning tools for time series.

DETAILED DESCRIPTION AND ACTIONS:

The research area spans two parts: 1) data generation of scattering patterns to provide data for training on existing scenarios and to provide the ability to simulate data for future scenarios, and 2) data analysis based on new features extracted from the data as well as new machine learning tools that leverage these features.

For part one, data generation, in the case of looking up, several realistic conditions must be captured, including scattering of high aspect to mass ratio (HAMR) objects; objects with different reflectivity indices; objects subject to dynamic perturbation, such as a satellite spinning out of control; drones in distress; or problem flight patterns. For the case of looking down, it is important to be able to generate scattering data for different land objects of interest with and without obscurants. One straightforward application is detecting cracks in an aircraft after a mission (or damage in other vital infrastructure). Also, it is important to have the ability to simulate several obscurants that can change the scattering patterns.

For part two, data analysis, it is important to develop an understanding of how to extract information from patches of data coming from multiple sensors for the same target. For example, several earth-based sensors might be tracking the same satellite. The inputs of these spatially distributed sensors must be used as a collection in the data analysis to improve the classification of the tracked object.

This work would be supported by the following actions:

- **Part One - Data Generation.** For data generation, it is necessary to build multi-physics models that leverage high performance computing facilities. For concreteness, consider the example of simulating the measurement of the light intensity of a satellite using an earth-based camera. This involves creating a pipeline that starts from a specified orbit and a satellite shape. Certain laws of motion for the satellite will have to be prescribed, e.g., satellite body always facing earth, while the solar panels always face the sun. Next, we simulate the source of the rays we are capturing. In our example, this would be the sunlight which we can simulate as directional light, and obtain the scattering pattern, which will be a function of time since the variables change as the satellite moves in space. Once the scattering pattern at the satellite surface is found, we need to simulate the data capture performed by the sensor and account for the distance between the sensor and the object. A similar procedure can be used for other types of objects and scattered arrays. Resources are needed to obtain experimental data of tagged space and land objects to test the accuracy of the data generation scheme.
- **Part Two - Data Analysis.** For the data analytics, new tools in machine learning need to be developed in order to perform tasks such as distinguishing between debris (such as a solar panel or part of a damaged satellite) versus an actual satellite, or decide if there is a defect in the monitored object. For earth-based measurements, it is necessary to extract parameterized features such as those derived from changing the wavelength of the laser in LIDAR measurements instead of the current practice of using lasers safe for the eye. If the target is obscured (for example part of an aircraft, or a supply line on the ground), then it is also interesting to classify the obscurant. The extracted features can come from emerging fields such as topological data analysis (TDA) and new advances in time series analysis. The advantage of using TDA is its resilience to noise and its ability to reveal underlying features that are invisible to other methods. Applying machine learning tools to the extracted data will be facilitated by utilizing high performance computing facilities.

TIMELINE

7-10 Years

SURVEY RISK

Not Available

3.2.5 Detection and Tracking in Complex Multimodal Data Spaces

CONTRIBUTORS

Anura Jayasumana, Firas A. Khasawneh, Jinsub Kim, Leming Qu, Yelda Turkan

OVERVIEW

Real and virtual applications are increasingly characterized by multidimensional numerical and non-numerical data. Fundamental advances are needed in theory and algorithms to detect and track objects and phenomena that emerge and morph in such spaces.

Object identification and classification in physical and virtual spaces is a topic of extreme importance. Physical spaces include space, land, and sea, and virtual spaces encapsulate gaming environments, social networks, and large-scale multimodal databases, within which objects emerge and morph. The term multimodality encompasses a combination of different types of data and acquisitions, metadata descriptions, reliability of data, and the conditions under which data was acquired. [1-11]

DETAILED DESCRIPTION AND ACTIONS

One of the important tools for physical space monitoring is utilizing scattering patterns for object characterization. These objects can be airborne or land-based, so the ability to accurately characterize them leads to an improved space situational awareness (SSA) and to an enhanced control over the ground.

Virtual environments, on the other hand, reflect or impact real world situations, e.g., social network of radicals may point to a subset of actors prone to violence. Botnets in cyberspace can attack physical facilities. It is necessary to identify complex objects, emergence of phenomena in such spaces, track them, place audit trails, and facilitate forensics. These environments are characterized by multimodal attributes (numerical, text, etc.) and require a combination of mathematical and algorithmic approaches.

The natural candidate for classifying the influx of the resulting data is machine learning algorithms. However, leveraging these tools requires an investment in multiphysics simulation tools for generating training data, as well as advancing promising featurization tools from emerging fields such as topological data analysis and novel machine learning tools for time series.

Tracking in complex multimodal high-dimensional spaces requires:

- Theoretical fundamentals to define and detect targets in multidimensional spaces and graphs (networks), in which some of the dimensions may be characterized by non-numeric fields such as labels and voice clips, while others may be numeric values.
- Efficient techniques to detect patterns, manifolds on which data resides etc. in very large data sets.
- Ability to deal with unknown, incomplete, and stale values and deal with principles to rank the outcomes.
- Non-linear transformations that overcome limitations of current techniques.
- Learning algorithms and methods to transfer them to adapt learning algorithms to new environments that may be quite different from the environment in which the algorithms are trained.
- Tools and platforms for specification, tracking, and detection.

AIR FORCE APPROACH

Fund multiple small to medium scale projects to develop the theoretical foundations. Interdisciplinary projects that include expertise in areas such as engineering, social sciences, data science, gaming, mathematics, statistics, computer science, biology, should be encouraged. SBIR and STTR funding may be used to get industrial participation and commercialization of technology.

TIMELINE

7-12 Years

SURVEY RISK

	Low	Medium	High
Cost	6	8	3
Technical	3	8	6
Deployment	7	6	4
Defendable	4	9	4
Competitive	2	9	6

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3.2.6 UAV Swarms

CONTRIBUTORS

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OVERVIEW

Swarms of 100s to 1000s of small UAVs have numerous potential applications in national defense, battlefields, homeland security, agriculture, manufacturing and commerce. UAVs range from those that are inexpensive and disposable to those that carry expensive sensors. Facilitating such swarms requires research and development in multiple technologies (e.g., aerospace, miniaturization, wireless communication) and advances in fundamentals in areas such as signal processing, networking, data analytics, distributed algorithms and human computer interface.

Different system-level perspectives have to be considered. The swarm itself may be viewed as a system to be optimized, where nodes (members) may even sacrifice themselves for the overall goal. Alternatively, each node may be programmed to achieve its own sub-objective within the overall objective. System state has to be estimated and maintained in a distributed manner for autonomous operation of the swarm. Resilient operation requires individual nodes to be aware of their status (state, position, role, etc.) within the swarm. Different members may have different and even inconsistent views of their state and status as well as those of others. Tradeoffs between the survivability of the swarm versus that of individual nodes has to be characterized, and adaptive and scalable algorithms need to be developed to achieve such objectives. [1,2]

DETAILED DESCRIPTION AND ACTIONS:

This research is supported by the following actions:

- Testbeds and platforms - Provide platforms (equivalent to Geni, planetlab etc. for Internet research) to facilitate
- Tracking based on information sensed by individual nodes, with or without the ability to communicate with each other.
- Tracking based on minimal information based on capability of nodes (expensive sensors may be able to detect actual distance, but cheap tiny drones may not have such sensors).
- Algorithms that adapt to heterogeneous capabilities and resources of nodes.
- Tracking techniques that are resilient to environmental conditions (e.g., in the case of a swarm, signal strength will not provide accurate distance information, clock drifts may cause time based distance estimation difficult, adversary may interfere with GPS).

- Tracking of swarms using external sensors, with and without the collaboration of the nodes.
- Tracking in domains beyond physical space (e.g., communication topology, line-of-sight based manifolds).
- Autonomous operation of swarms of inexpensive UAVs.
- Nodes in the swarm need to be aware of their position relative to others (network-aware nodes, self-aware nodes, phenomena-aware nodes), shape of the swarm, etc. Need to go beyond traditional techniques based on signal strength, beacons, radar, etc.
- Capture and maintain the state of the swarm in a distributed manner. Allow for different nodes to operate using each node's own estimate of global state of the system. Advance the theory to provide error and uncertainty bounds.
- Machine learning approaches that use interactive games played by human players to achieve swarm objectives and swarm survivability.
- Secure operation and privacy constraints.
- Develop techniques that make swarms resilient to hacking and hijacking.
- Build in autonomous actions to be taken on such events.
- Fail-safe modes of operation.
- Non-programmable hardware-based limits to limit damage (in case of a security violation) or to limit privacy violations.
- Standards for operation of multiple autonomous swarms in common physical space.
- Modular in-air assembly of drones on demand and scalable drone design.
- Reusable, recyclable materials.
- Inexpensive tracking technologies.

AIR FORCE APPROACH

It is recommended that a BAA on the topic of autonomous swarms of thousands of UAVs with components in 1) technology development (e.g., inexpensive and small UAV technology, distributed networking and processing technology, sensor technology), and 2) theoretical advances (e.g., algorithms for autonomous swarms of inexpensive mobile devices, mathematical fundamentals to quantify the relationship between individual member goals/outcomes versu system level outcomes, statistical techniques to quantify reliability and accuracy of estimates based on inconsistent data). Fund multiple projects at universities, through SBIR/STTR's as well as a center.

It is recommended that open platforms (equivalent to GeniLab for networking) be provided where academic institutes can test algorithms without having to incur hardware cost at each institute. Such platforms will also have dual use in education.

Set up a national level competition (at X-Prize or DARPA Balloon Challenge level).

TIMELINE

5-15 years

SURVEY RISK

Not Available

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3.3 Advanced Manufacturing and Advanced Material Systems and Modeling

The Advanced Manufacturing and Advanced Materials and Modelling topic explores the next generation materials and manufacturing processes that will enable new technologies and advancements in existing technologies.

3.3.1 3D Freeform Additive Manufacturing

CONTRIBUTORS

Pierre Larochelle

OVERVIEW

In order to deploy advanced novel materials in the next generation aerospace platforms for the Air Force, full 3D freeform additive manufacturing systems are needed. Such systems would be capable of manufacturing optimized complex geometries using advanced materials. Examples where this would be required include airfoil shapes, turbine blades, and turbine inlets and exits.

Currently, most 3D printing additive manufacturing technologies, such as the commonly used fused deposition modeling (FDM), are normally limited to depositing material in parallel planes. This is done so that the process parameters can more easily be controlled and optimized for improved part quality. These process parameters include feed rate, print head speed, nozzle diameter, nozzle heating, filament cooling, filament deflection, and others. To deposit material in parallel planes, these systems utilize gantry style robot architectures that have three mutually orthogonal linear axes of motion. In such systems, the print head may not be rotated about any axis. The result is a three degree of freedom mechanical system that functions by positioning the print head. Because of the constrained motion of the print head, build planes are parallel and bulk material properties of the printed artifacts are significantly limited.

To realize the vision of truly freeform 3D additive manufacturing, a minimum of six degrees of freedom are needed to control the motion of the print head: three translational degrees of freedom and three rotational. Preliminary research in which an FDM system was tested by deploying a traditional PLA print head at the end of a six degree of freedom robot arm, revealed a plethora of research challenges that need to be addressed in order to successfully deploy 3D freeform additive manufacturing. These challenges include real-time control of filament feed rate, print head motion speeds, print head heating, and filament cooling to in order to produce part geometries that meet specifications in part geometry, part density, and bulk material mechanical properties. [1-20]

DETAILED DESCRIPTION AND ACTIONS

Specific research tasks include:

1. **High Fidelity Model Development:** Models are needed to predict the deflection of the printed filament that incorporate altitude and orientation of the print head within the earth's gravitational field, the printing path, the filament extrusion feed rate, the print head temperature profile, convective cooling of the printed filament, cooling of the filament after deposition on the printed part, relative humidity in the ambient environment, and print head nozzle shape. Multiple extrusion filament materials need to be addressed, e.g. from traditional polymers to exotic biomaterials and metal alloys.
2. **Algorithm Development for the Print Head**. There are two main areas in algorithm development:
    a. Motion of the Print Head and the Corresponding Build Platform: Current additive manufacturing processes typically begin by selecting a build direction (i.e. the direction in which the parallel slices are stacked), utilizing a build platform that is a flat plate orthogonal to the build direction, and then slicing the part geometry into parallel slices. The printer then, in sequence, prints each slice onto the build platform to yield the printed part. In 3D freeform additive manufacturing the "print in a single plan" constraint is removed thereby enabling printing in any direction. The challenge is to design a build platform and to plan the motion of the print head to avoid the physical collisions that may occur in the production process: print head/part collisions and print head/build-platform collisions.
    b. Motion of the Print Head Necessary to Achieve the Designed Bulk Material Mechanical Properties: It is well-known that the bulk mechanical material properties of the printed part are heavily dependent on the direction in which the part is sliced for traditional additive manufacturing fused deposition modeling. The research challenge here is to plan the motion of the print head to not only realize the desired part geometry but to also yield desired bulk material mechanical properties such as yield strength, tensile strength, or shear strength, in any of the six available directions.
3. **Integration of Models and Algorithms**. Integrate items 1 and 2 to yield a 3D freeform additive system.

AIR FORCE APPROACH

3D freeform additive manufacturing is inherently a multidisciplinary challenge requiring the expertise of multiple research communities including: robotics, materials, motion planning, process control, and others. In order to bring together the multidisciplinary teams that are needed to address these research challenges a workshop (e.g., Air Force Workshop in 3D Freeform Additive Manufacturing) should be organized to kick-off this effort. The workshop would provide a forum for sharing the research vision as well as the challenges that need to be addressed.

Following the Air Force workshop in 3D freeform additive manufacturing, the Air Force should solicit multi-institutional, collaborative proposals. The Air Force should fund –three to five teams for four years at ~$500 thousand per team to address research tasks 1 and 2a. Subsequently, the Air Force should fund three to five teams for four years at ~$500 thousand per team to address research tasks 2b and 3.

TIMELINE

7-10 Years

SURVEY RISK

	Low	Medium	High
Cost	0	15	3
Technical	1	11	6
Deployment	5	8	5
Defendable	4	11	3
Competitive	4	10	4

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3.3.2 Advanced Manufacturing for Microwave Vacuum Electron Devices

CONTRIBUTORS

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OVERVIEW

Advanced manufacturing techniques are needed to support production manufacturing of the complex structures necessary for high frequency (100-1000 GHz) microwave vacuum electron devices (MVEDs). MVEDs offer high-power density, high efficiency, and high-frequency capabilities. However, these structures are often fabricated using machining techniques that do not readily allow mass production. In particular, at high frequency (100 - 1000 GHz), Radio-Frequency (RF) support structures are difficult to manufacture, leading to specialized fabrication processes that do not support batch production [1]. Advanced manufacturing processes that could produce multiple 3D MVED circuit structures with high conductivity metal surfaces would enable lower cost MVEDs that could be mass produced and combined to generate high total output power.

DETAILED DESCRIPTION AND ACTIONS

Current generations of MVEDs are often fabricated in a one-off fashion, driven by a lack of batch fabrication processes in the scale of 100s of microns to millimeters. In particular, current generations of fabrication require machining of high quality copper for each device. Alternative routes using 3D printing and sintering approaches could be scalable, but fall short, resulting in metals of poor conductivities, that are driven by the nano-crystalline structure.

Recently, a technology has been explored that enables growth of crystalline materials without using an epitaxial substrate in arbitrary 3D geometries. While the growth of semiconductors has driven this technology, it is general and can be utilized to generate 3D metal structures with single crystalline or ultra-large grain polycrystalline structures. This would enable to the ability to first generate the desired structure using a non-ideal process that generates a low-conductivity metal, such as printing or electrodeposition, and then it would be possible to generate a final structure with cm-scale crystals and high-conductivity. These processes would also result in surface finishes with low roughness/asperities, which cause extremely large RF losses at high frequencies. New diagnostic techniques based on theoretical and numerical modeling [3] may also be developed to characterize the RF loss and ohmic heating in these new materials and devices, based on theoretical and numerical modeling [1,3].

High frequency MVEDs have been developed, including backward wave oscillators (BWOs) and traveling wave tubes (TWTs). While these devices have achieved [2] some success

(50 W TWT at 220 GHz), the fabrication processes are difficult, and a limited number of devices can be fabricated. Advanced manufacturing techniques for fabrication of the 3D slow wave circuit structures (folded waveguides, conductive posts) have greatly limited device availability at these frequencies. Advanced fabrication technology is currently evolving to the point that it could achieve methods to produce large numbers of MVEDs at low cost. With these developments, even very low power devices could be combined in single packages or multiple packages to generate high combined power. Theoretical understanding of these devices combined with modeling would allow development of fully integrated devices (electron source, circuit, collector, output structures). The new generation of cold cathodes (gated field emission arrays) have recently achieved 100 A/cm^2. This technology could be implemented with advanced manufacturing techniques directly into the structures. The resulting devices could be phase-locked and amplitude modulated for beam steering as well as higher power output. The nexus of advanced manufacturing techniques, MVEDs, and modelling represent a new opportunity for high frequency sources and amplifiers.

This research requires a convergence of new manufacturing technologies, device design and modeling, microfabrication of electron sources, and improved theoretical understanding of these devices. To achieve this research, the following actions are needed:

- Design and development of MVEDs that can be integrated with advanced manufacturing techniques allowing single substrate fabrication. This effort includes theoretical and modeling research for compatibility with manufacturing techniques and study of circuit losses at high frequency.
- Improved manufacturing of metallic structures, including waveguides and periodic circuits, that can achieve low losses at high frequency by using the advanced metal growth techniques. Research efforts should include extensive measurement of these structures and comparing these results with simulations.
- Development of full 3D fabrication of all structures (cathode, circuit, output port, and beam dump) on a single substrate by developing a design that allows total device integration. Device modeling should also study sensitivity.
- Fabrication of an entire device structure is needed for a proof of concept.

AIR FORCE APPROACH

This technology represents an ideal nexus of simulation, advanced manufacturing, cold cathodes, and MVEDs. Multidisciplinary research efforts would be needed to understand the device fabrication and integration requirements. Novel material and device characterization techniques need to be developed to complement the advanced manufacturing processes. It is proposed that the Air Force establish a workshop that brings together researchers in the area of MVEDs as well as materials scientists, computer scientists, and mechanical engineers to discuss the devices that need to be fabricated, identify the issues, and propose a solution path.

TIMELINE

7-10 Years

SURVEY RISK

	Low	Medium	High
Cost	3	8	7
Technical	1	10	7
Deployment	5	10	3
Defendable	8	10	0
Competitive	7	8	3

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3.3.3 Function Driven Materials Discovery

CONTRIBUTORS

Jayakanth Ravichandran

OVERVIEW

This area involves creation of integrated theoretical and experimental approaches to targeted materials discovery problems. Advances in electronics and photonics have unleashed great technological progress in the past half century. Sustained progress relies heavily on technological breakthroughs to overcome the impending limitations to the scaling of existing electronic and photonic devices. Similarly, several good technologies are underdeveloped due to the inability to discover new materials or to process known materials into useful forms. One of the key bottlenecks to these technologies is the development of functional materials and structures.

Current approaches to materials discovery are typically Edisonian in nature, and recently, descriptor and data driven materials genome type initiatives have been developed as an alternative. Most reductionist approaches to materials discovery often fail due to the complexities in determining the exact function-structure-chemistry relationships in materials. Function driven materials discovery can provide a rational path to the discovery and development of specific high performance materials. The proposed research effort will leverage scientists and engineers working on a theoretical basis for materials discovery to experimental studies ranging from materials synthesis to system level development. The key outcome of this effort will be in developing a direct relationship between the performance metrics and the structure and chemistry of materials or their assemblies.

Function driven materials discovery will be a collaborative effort between scientists and engineers focusing on theoretical and experimental materials science and engineering in collaboration with experts with device or system level analysis to define the material requirements. Theoretical studies will include atomistic to macroscopic modeling approaches such as density functional studies, phase field modeling, mathematical methods to handle large data, and machine learning approaches. Experimental studies will span materials synthesis and processing, characterization, property measurements, and device studies. The system level experts will define the requirements for the materials or devices using one or more figure of merits or metrics, which can be fully related to the structural and chemical descriptors through the theoretical modeling studies. [1-8]

DETAILED DESCRIPTION AND ACTIONS

Several technologies have been identified that have fundamental limitations in processes and/or materials and can leverage the proposed function driven materials discovery approach. These include:

Seeing the Invisible. The development of next generation thermographic systems will enable revolutionary applications in imaging, remote sensing, night vision, process monitoring and control. The fundamental limitation to these systems has been in realizing materials and structures that can act as wavelength, phase, and polarization sensitive detectors, as well as linear and non-linear optical elements. Specifically developing materials for mid-wave and long-wave infrared regimes that are tolerant to defects and are sensitive for the specific thermal radiations can revolutionize future autonomous technologies such as driverless cars and autonomous sensors for the internet of things.

Going Quantum. Next-generation energy-efficient technologies, such as topological quantum computing, quantum sensing, and neuromorphic computing could revolutionize future technologies. To realize the full potential of quantum phenomena, we must drastically advance our ability to synthesize, characterize, and control quantum materials at the atomic scale. This grand challenge must be met through a tight integration of novel synthetic methods, transformative experimental tools, and advanced theory/data analytics. Particularly compelling are hybrid quantum materials, wherein reduced dimensionality, new crystalline symmetries, and strong interfacial couplings between atomically-thin constituents and novel substrates can realize unique quantum phenomena such as new forms of electronic order, dissipation-less charge transport, and quasiparticle excitations with unusual quantum statistics.

Closing the THz Gap. The terahertz frequency regime is perhaps the most scientifically useful, yet technologically challenging, region of the electromagnetic spectrum. Scientific breakthroughs in materials and devices that enable efficient sources, detectors, and optical elements that modulate the THz waves could lead to game-changing capabilities in RF sensing and amplification, transmit/receive functions, wideband operation, reconfigurability, and novel functionality. One of the primary obstacles in realizing a practical device, albeit the decades of concerted effort, lies in the challenges of fabricating uniform, ultrathin tunnel barriers with sub-nanometer accuracy. Thus, traditional semiconducting materials fall short of achieving 1 THz operating frequency at useful power levels (> 10 mW). Other approaches include establishing new device geometries and integrating materials to improve the power handling without significant losses; transmitting over long distances is necessary to enable THz based technologies.

Living Materials. Living materials combines two emerging classes of materials 1) self-healing materials and 2) stimuli-responsive materials. Self-healing materials are designed to repair damage inflicted upon them in order to maintain the original properties of the material (e.g. mechanical, thermal, optical, etc.). Stimuli-responsive materials sense a change, typically in local fields (e.g. electromagnetic and thermal), in order to perform a specific function. In order to enable a new paradigm of living materials, these two classes should be combined in order to enable materials that respond to their environment and can heal themselves in such a manner that they retain their responsive properties. One of the grand challenges in this area is embedding sensing elements in living materials that can communicate with the material system and enable a healing or functional response with high enough temporal resolution to avoid system failure. For example, we envision embedding directed energy weapon countermeasure responsive within material coatings.

AIR FORCE APPROACH

- Host a workshop on Function Driven Materials Discovery with emphasis on specific properties and functionalities of materials, devices, and systems that provide >10x improvement in performance and functionality.
- Establish AFRL/academic partnerships via AFRL summer faculty fellowships to develop seed-level collaborations based on workshop outcomes.
- Identify infrastructure needs for rapidly advancing materials discovery and fabrication that can be utilized as a national resource or via DURIP type mechanisms.
- Provide dedicated programmatic funding focused on teaming AFRL with leading academic and industrial institutions at the level of two MURIs (5 years, ~$3 million per year).
- Recruit, co-locate, and enable a unique talent pool of researchers dedicated to solving fundamental and applied challenges related to function driven material design and synthesis..

TIMELINE

5-10 Years

SURVEY RISK

	Low	Medium	High
Cost	1	10	4
Technical	0	10	5
Deployment	3	9	3
Defendable	6	8	1
Competitive	1	12	2

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3.3.4 Multidimensional Hybrid Materials

CONTRIBUTORS

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OVERVIEW

Moving beyond current state-of-the-art technologies requires material solutions beyond a single component. Multidimensional hybrid materials (MHMs) constitutes a new paradigm in "all dimension (0,1,2,3D) integration" where each dimension plays a key role in the summed function. MHMs are poised to enable the dramatic advancements in device and system performance required to achieve next generation technologies. For this research area, we present examples of how multidimensional hybrid materials outperform their traditional counterparts as a means to motivate a concerted research effort in this area.

The rapid evolution of photonics, RF electronics, and related technologies, has allowed military defense systems to utilize such devices for advanced applications, such as multi-functional RF/microwave/millimeter wave antennas, LIDAR transmitters and detectors, and ultrahigh bandwidth communication systems. However, revolutionizing conventional systems can only be accomplished through innovative breakthroughs in multifunctional materials capable of going beyond what is possible with traditional materials. As current synthesis technologies mature for 0D to 3D materials, innovative processes to intentionally combine such synthesis techniques and leveraging the unique physical properties that arise from materials dimensions, atomic structure, and their interfaces remains elusive. Therefore, transformative design and synthesis of MHMs will enable novel functions for defense applications.

Quite often, technological advances follow material breakthroughs. While advances in individual materials systems continue to evolve, revolutionary changes are only possible when bridging material dimensions. The development of MHMs will bring a rich spectrum of new opportunities from novel quantum phenomena and electronic properties to unique hybridized biological functions.

DETAILED DESCRIPTION AND ACTIONS

Key open questions that form the nucleus of the proposed research include:

- What new/novel phenomena are possible with hybrid multidimensional materials;
- To what extent do interfaces control the properties of the hybrid structures;
- Which hybrid structures enable superior performance compared to their counterparts;
- How will the hybrid structures best be exploited at the device and circuit level to ensure superior performance; and

- To what extent does integration impact the physical properties of constituent materials, and can phenomena such as "proximity effects" be engineered to enable new functionality in hybrid materials?

The examples that follow highlight several fundamental avenues of investigation uniquely enabled by multidimensional hybrid materials.

Closing the THz Gap. The terahertz frequency regime is perhaps the most scientifically useful, yet technologically challenging, region of the electromagnetic spectrum. Scientific breakthroughs in materials and devices that enable efficient operation in this region could lead to game-changing capabilities in RF sensing and amplification, transmit/receive functions, wideband operation, reconfigurability, and novel functionality. One of the primary obstacles in realizing a practical device, albeit the decades of concerted effort, lies in the challenges of fabricating uniform, ultrathin tunnel barriers with sub-nanometer accuracy. Thus, traditional semiconducting materials fall short of achieving 1 THz operating frequency at useful power levels (> 10 mW). Importantly, there are opportunities that exist to establish the foundational knowledge in hybridizing next generation 2D layers with traditional 3D materials (2D/3D hybrids) to achieve THz operation at milliwatt power ranges [1]. Such a breakthrough relies on developing vertical 2D/3D hybrids that are predicted to have inherent advantages in the ultrahigh-frequency performance due to the truly atomistic dimensions. Recent studies illustrate the potential promise of the concept while highlighting the need for significant further advances in interface control and structure optimization [1-5]. Therefore, investigations into 2D/3D hybrids will strongly impact THz technology not possible with traditional materials.

The Organic-Inorganic Hybrid Materials. Inorganic-organic hybrid materials or multidimensional materials with large repeating units with different chemical and structural characteristics can enable new functionalities beyond conventional inorganic or organic materials [6-8]. For example, recently, organic-inorganic hybrid perovskite halides have created a generation of defect-tolerant semiconductors. Metal-organic frameworks have shown as a versatile platform to achieve a broad range of physical and chemical properties. Recently, super-atom crystals of C60-metal-organic clusters combine molecular and nanoscale objects to achieve a new crystalline order that shows interesting magnetic or thermal properties. One can imagine that these materials could offer unique and original flexibility towards designing materials with unusual physical, chemical, and biological properties.

Bioinspired Function in Hybrid Materials. Nature provides a diverse set of biomolecular machines with unique functions derived from their structure. For example, within the body, proteins are responsible for repairing and generating tissue, producing energy at the cellular level, producing hormones, and producing immune response. Multidimensional hybrid materials, inspired by such biomolecular machines, may enable biointegration of electronics, optoelectronics, and energy harvesting/storage systems with unique functions that facilitate and enhance human-machine interfaces. Recent examples of multidimensional hybrid materials include microelectrode arrays for interfacing with the brain. Conductive polymer meshes contacted with carbon nanotubes have been used to map neuron activity in the mammalian brain [9], and graphene microelectrode arrays have leveraged the optical transparency of graphene and its high electrical conductivity to enable simultaneous two-photon microscopy imaging, optogenetic stimulation, and cortical signal recording [10]. However, these applications do not fully and intentionally combine biotic and abiotic materials of varying dimension to achieve particular function, e.g. self-healing, energy production, etc. To achieve such bioinspired function in these hybrid materials, investigations into the fundamental interactions between biomolecular and multidimensional materials must be undertaken. These investigations should combine computational and experimental approaches to expedite materials discovery and translation to practical application.

Nanobiocatalysis. The overall objective of this research is to develop a transformative design paradigm for next-generation, long-term stable, and electrochemically active enzyme electrodes by nano-confining enzymes in a mesoporous carbon matrix using the ship-in-a-bottle approach. Previous enzyme immobilization research has enabled the development of functional bioelectronics, including biosensors and biofuel cells for various health and portable electronic applications [11]. However, due to a poor electrochemical communication between the enzymes and electronic supports, the electrochemical activity of such bioelectronics is low. Furthermore, its state-of-the-art lifetime is limited to days due to enzyme denaturing and leaching. In this project, we will overcome these issues by nano-confining enzymes into an electronically conductive nanoscale environment. To demonstrate this novel nanoscale enzyme reactor (NER) concept, glucose oxidase (GOx) [12] and pyranose oxidase (POx) [13] have been successfully integrated into the nanocavity of mesoporous carbon foams. These GOx-based and POx-based NERs have shown high electrochemical performances with long-term stabilities for both biosensor and biofuel cell applications.

AIR FORCE APPROACH

- Host workshop on development of hybrid materials with “revolutionary” properties not possible in single material structures, with a recommendation report of the areas where hybrid materials will make the most impact.
- Establish AFRL/academic partnerships via AFRL summer faculty fellowships to develop seed-level collaborations based on workshop outcomes.
- Identify infrastructure needs for development of hybrid materials that can be utilized as a national resource.
- Provide dedicated programmatic funding focused on teaming AFRL with leading academic and industrial institutions at the level of two MURIs (5 years, ~$3M/year).
- Recruit, co-locate, and enable a unique talent pool of researchers dedicated to solving fundamental and applied challenges related to multidimensional hybrid materials.

TIMELINE

10-15 Years

SURVEY RISK

	Low	Medium	High
Cost	0	10	8
Technical	0	9	9
Deployment	2	11	5
Defendable	5	11	2
Competitive	4	12	2

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3.3.5 Multiscale Materials Manufacturing

CONTRIBUTORS

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OVERVIEW

In order to produce advanced materials for 2030, the capability to simultaneously manufacture materials at multiple length scales will be necessary. The research challenge is to apply multiscale modeling and design techniques to yield an integrated system capable of manufacturing materials with specifications and processes done at the nano through milli length scales. We envision a manufacturing process that produces materials at the milli length scale while processing them to milli, micro, and nano scale specifications. The result is the capability to produce novel materials to desired nano, micro, and milli scale specifications and mechanical properties.

Current manufacturing techniques are often highly siloed, separated by length scales and materials, enabling highly optimized processes for a specific product. Currently, there are no materials processing techniques that enable creation of multiscale materials with reasonable time and cost. If developed, a manufacturing process that spans these scales would enable new active and passive materials for electronic warfare, sensing networks, and camouflage.

DETAILED DESCRIPTION AND ACTIONS

Multiscale Materials Manufacturing: Addressing this challenge requires using deposition approaches that are general for a wide class of materials and enable control over lateral dimensions in-situ without the need for expensive and complex lithography. Five areas of development are required to realize this vision.

- Catalog established growth techniques and miniaturize these approaches to enable compatibility with a local growth probe.
- Develop novel growth approaches that utilize high local electric fields and optical excitation.
- Integrate these processes into a single tool to understand the interdependencies between different materials and material classes.
- Demonstrate micro and milli scales together with a set of processes, and nano and micro scales together using another set of processes.
- Demonstrate multi-scale materials fabrication with multiple materials across the nano, micro, and milli scale.

Print Head-Processing Manufacturing: When multi-scale material processing is required today, we often rely on either thermodynamic or kinetic processes to achieve nanoscale features embedded in a larger, macroscale material. However, this imposes a significant challenge, limiting the obtainable nano- and micro-scale structures to those nature allows. To go beyond material thermodynamics and kinetics, we have developed a variety of additive and subtractive processing techniques such as inkjet printing, 3D printing, and patterning coupled with etching. However, both additive manufacturing and subtractive manufacturing do not currently exhibit the characteristics required for next generation materials that require integrated sensing, simple information processing, and active responses to external stimuli.

Specifically, present day additive manufacturing often creates materials with undesirable nanocrystalline microstructures, resulting in poor performance materials, both in terms of optoelectronic and mechanical properties. Thus, despite the advances in printed electronics and 3D material printing, the resulting materials cannot achieve the necessary performance.

Alternately, lithography and etching based processes enable the machining of ultra-high quality materials such as single crystalline semiconductors. However, the throughput and cost of these approaches make it prohibitively expensive per unit amount of material produced.

Current materials manufacturing processes are designed and optimized for specific length scales. When systems bridging multiple length scales are required, often no fabrication approaches exist that satisfy the manufacturing needs. Some of the reasons for such systems to be focused on specific length scales are the controlled environmental conditions that the nominal processes require. For example, at the shorter length scales, manufacturing processes typically require clean room environments meeting dust particle, humidity, and other specifications. A “print on a chip” manufacturing processes is envisioned that yields milli scale material production by utilizing print head localized micro and nano scale controlled environmental conditions at the print head.

This envisioned solution involves local control over growth using a print head type approach. This print head would allow local deposition of precursors with controlled temperature/energy on a substrate held at a desired growth temperature. Additionally due to the proximity of this fixture to the growth surface, the application of both intense electric fields and optical excitation is possible.

AIR FORCE APPROACH

The Air Force should utilize a phased approach with milestones for achieving the vision of multiscale materials manufacturing. Four phases are suggested with each having two research milestones to be achieved before moving on to the next phase of the research.

Phase 1

- Miniaturization of current state of the art growth processes for integration with local print-head growth approach.
- Development of in-situ optical sensing for real-time feedback during growth.

Phase 2

- Development of novel local growth modes utilizing intense electric fields or optical stimuli.
- Processes for real-time, closed-loop feedback of local materials growth processes using in-situ monitoring techniques.

Phase 3

- Single process which generates materials with a combination of micrometer and millimeter scale features.
- A separate process, which generates materials with nanometer and micrometer scale features.

Phase 4

- Demonstration of a tool, which enables nano to milli scale growth with in-situ monitoring and real-time closed loop control.

In order to increase the probability of successfully achieving the vision of multiscale materials manufacturing, the Air Force should fund five research teams for three years to work to address the research challenges of Phases 1 and 2. Estimated cost is $700 thousand per team for a total of $3.5 million. Upon establishing the foundation by successfully completing Phases 1 and 2, the 3 research teams should be funded for 3 years to address Phases 3 - 4. Estimated cost is $700 thousand per team for a total of $2.1 million.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	0	10	8
Technical	0	8	10
Deployment	1	8	9
Defendable	5	9	4
Competitive	2	11	5

3.3.6 Using Ultrafast, High-Electric Field Pulses to Catalyze Fuel Conversion Processes

CONTRIBUTORS

Peng Zhang, Su Ha

OVERVIEW

This research proposes to develop the use of high pulsed power systems to enhance a conventional fuel catalysis for improving gas-to-liquid conversion efficiency. Synthetic jet fuels can be produced by converting methane from shale gas and biogas using an F-T based fuel reforming process. However, this conventional process requires a high operating temperature (> 800 °C) to activate the stable methane (the main component of shale gas and biogas). If one can activate methane (CH4) at lower temperatures, the overall conversion cost for synthetic jet fuel productions can be significantly reduced. The ultrafast and high-electric field pulse-based reforming process can allow efficient conversion of the gases into liquid fuels at lower operating temperatures.

The combination of high voltage pulsed power and traditional methods of catalysis could be an important interdisciplinary approach to the problem of fuel production, involving electrical and chemical engineering, modeling, and experimental development. Catalysis is a mature field, where breakthroughs are difficult to come by, but the potential payoff of an advance in producing fuels from biogas or shale gas could be extremely important to extend current global availability of liquid fuels. A focused program of study on the feasibility and impact of pulsed electric fields and non-thermal discharges on traditional catalysis is proposed.

DETAILED DESCRIPTION AND ACTIONS

Recent studies have aimed at producing streamers in organic liquids, or liquids contaminated with organic material, with an aim to decontaminate water or reform hydrocarbons into hydrogen rich gas [1]. Fast pulse produced streamers have also been extensively studied to enhance combustion [2]. These studies have explored the production of streamers in liquids with varying concentrations of hydrocarbons and in liquids containing hydrocarbon molecules of various sizes. Streamer discharges were shown to produce varying amounts of free radicals depending on discharge size and length, indicating some promise in employing the method to decontaminate.

While streamer production might be a desirable feature in some applications, another promising path is the production of high-pulsed electric fields without producing significant amounts of volumetric discharge. Fast pulsed electric fields are potential means of producing high local voltages without transition to arcing. This high-pulsed electric field over the catalytic surfaces can also be used to activate the strong C-H bond of CH_4 at the low reaction temperatures [3]. The conventional plasma-assisted reforming process creates the hot plasma gas, or cool but energetic streamers, to activate the chemical bonds that typically lead to low reaction selectivity. Unlike this conventional process, the electric field-based reforming process can selectively activate the desired chemical bonds of reactive species, which allow it to possess the high reaction selectivity for producing the desired fuel products while keeping the overall conversion high. This high-pulse electric field-assisted chemical reaction technology can also be used in different chemical transformation processes to generate the value-added products from low value carbon sources.

Production of high-pulsed fields without significant discharge is a challenging direction for pulsed power research that will need to combine modeling and experimental thrusts. Work in High Power Microwave (HPM) circles to understand and mitigate window discharge and pulse shortening, for instance, could be an important part of developing high rep rate, high electric field, discharge free systems. Theoretical and computational modeling on the effects of surface structures (intrinsic surface roughness or intentionally grown sharp needles or nanoparticles) on local field enhancement and distribution, coupled electrical-thermal conduction, joule heating, electrical contacts between different structures, space charge [4], and mitigation of potential multipactor and discharges need to be studied.

This research can be achieved through the following actions:

- Develop models to study field enhancement, electron emission, and ultrafast response of the circuit.
- Develop models to study the effect of high-pulse surface electric field on the CH_4 reforming reactions as well as other important C1 chemistry reactions.
- Fabricate the power source with an appropriate circuit design to generate the ultrafast pulse power based on the model results.
- Construct the capacitor-typed reactors with an optimum catalytic surface structure that can generate the high surface electric field without the discharge.
- Using the capacitor-typed reactors, investigate the high surface electric field effect on the fuel reforming reactions and compare these experimental results with the theory and model results.

AIR FORCE APPROACH

The Air Force should support the basic science where fast-pulsed electric field technology from the electric engineering field is combined with catalysis science from the chemical engineering field to experimentally and computationally demonstrate the fast pulse electric field-assisted reforming process. From this basic science research, we can gain a fundamental understanding of how the high electric field influences the nature of the chemical reaction (e.g., reaction elementary steps). Based on this fundamental understanding, we can design efficient electric field-assisted fuel reforming systems to address our energy challenges.

TIMELINE

5-15 Years

SURVEY RISK

	Low	Medium	High
Cost	1	13	1
Technical	1	6	8
Deployment	3	9	3
Defendable	4	8	3
Competitive	3	9	3

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3.3.7 Embedding Sensors into Aircraft Components for Damage Detection

CONTRIBUTORS

Firas A. Khasawneh

OVERVIEW

Modern aircraft manufacturing is seeing an increased use of composites such as carbon fiber reinforced polymer (CFRP). While CFRP, for example, offers several advantages because it is strong and light weight, one of the challenges is the damage that may occur due to impact with hostile objects in-flight as well as non-hostile objects during takeoff and landing. The damage from these impact events can be localized, and therefore difficult to detect using global damage detection methods, such as modal tests. Therefore, there is a need for researching embedded sensors at a larger scale for performing both localized and aggregated damage detection and structural health monitoring of aircrafts. The application to CFRP, however, is only one example; a methodology for sensor embedding can also benefit parts manufacturing using other materials. However, an embedding strategy for metal parts will need to accommodate the high temperatures often associated with the manufacturing process given that many sensors are destroyed at temperatures near 150 °C.

While recently there has been some efforts to embed sensors, such as Fiber Bragg Grating optical sensors, into polymers, there remains several challenges for large-scale sensor embedding for structural health monitoring. Some of these challenges include studying the effect of embedding sensors on the structure’s integrity, methods for seamless integration of sensor during aircraft manufacturing, signal telemetry, and developing analysis tools for large sets of time series.

Current technology focuses on surface sensors, which include sensors embedded on the surface of the material or in shallow trenches near the material surface. However, surface sensing is inapplicable when the instrumented element functions in a harsh environment where the sensor cannot function. Further, damage may occur inside the material, and surface sensors may not be able to detect it. For example, defects exist in all manufactured parts because of the imperfections in the material and in the manufacturing processes. These defects can be solid inclusions or voids, but in either case, they can serve as nuclei for damage initiation and propagation. Without information from sensors embedded inside the part, obtaining information about this damage is difficult or impossible, especially at the early stages of damage development.

Therefore, the interest in deeply embedded sensors can provide new insight into the condition of the structures and components and provide early warnings that can help prevent disastrous failures. There are two practical methods for embedding sensors into the material: 1) a hybrid approach in which the sensors are produced and then embedded by interrupting the manufacturing process, or 2) a local growth approach in which the sensors are produced in-situ as part of the part manufacturing process. The hybrid approach is more time consuming and introduces more variability in the manufacturing process due to the repeated heating/cooling cycles associated with pausing the manufacturing process in order to embed the sensors.

The local growth approach, on the other hand, is a future direction of research that can advance the goals of Air Force research. In this approach, the manufacturing center is equipped with multi-material printing capabilities that allow it to 3D print sensors quickly and accurately as part of the manufacturing process. There is very recent (and growing) research on 3D printing sensors. Technologies, such as aerosol jet printing and inkjet printing, have recently been used successfully to print sensors and electronic components. The advantage of this method for producing sensors is that it does not require the costs and the infrastructure needed for traditional methods that utilize lithography and need expensive clean room facilities. Further, if these manufacturing systems are mobile, then the Air Force can have mobile printing technology for fixing equipment and/or printing parts deployable in remote locations.

DETAILED DESCRIPTION AND ACTIONS

Integration of sensors into the material matrix involves several challenges that span multiple disciplines. These challenges include development of technologies for embedding the sensors during the manufacturing process, miniaturization of sensors for minimal material flow interruption, designing communication protocols that minimize the required telemetry, and data analysis methods for analyzing localized (individual/neighborhood data) as well as the aggregated data over the whole structure. The following discusses each point in more detail.

Sensor Embedding. Sensors within the material matrix can be viewed as contaminants that can weaken the structure. Therefore, there is a balance that needs to be found between sufficient distribution of sensors and maintaining the material integrity. Further, there is a need for researching a robust approach for embedding the sensors. This might require using robotic arms and adaptive fixtures that can hold and place the sensor into the desired location with minimal errors.

Sensor Miniaturization. Since the introduction of sensors can weaken the material matrix, their footprint must be reduced to a minimum. If the sensors are produced in a cleanroom with sub-millimeter size, then there is a need for a method for storing and dispensing the sensors (as well as the needed telemetry) during the manufacturing process. On the other hand, if the sensors are produced during the manufacturing process, then there is a need for more research on 3D printing of sensors. The latter is an especially promising approach because it can additively manufacture sensors on complicated geometries during the manufacturing process.

One of the big challenges for embedding sensors within materials other than polymers, such as metals and metal alloys, is the high heat associated with manufacturing. It would be beneficial to research new manufacturing methods or new sensing elements technologies that will allow sensors to be embedded into metal parts.

Telemetry. Even with successful sensory embedding, it is important to establish communication pathways that will carry the information from the sensors and allow further data processing. The main methods for telemetry in structural health monitoring are: wireless such as WiFi communication (typically through fluid media) or ultrasonic communication (typically through solid media), and wired such as conductive wires or fiber optics.

In some situations, such as when the sensors are aerially deployed into the ocean, wireless communication may be the only available method for data transmission, but utilizing this approach for structural health monitoring can be challenging. Specifically, wireless communication is strongly related to power consumption since it can require much more energy than computing and sensing. Further, if sensors are embedded in metallic materials or reinforced concrete, wireless communication may not be a viable option.

Therefore, at least for structural health monitoring and especially for sensors embedded within the material, it would seem that sensor networks need to be wired either mechanically or by using optical fibers. Admittedly, upscaling the sensor embedding into 3D printed parts, from a few dozens/hundreds to thousands/ten-thousands, can create challenges with connecting the leads to the multiplexer for data processing. Therefore, it is beneficial to research methods for reducing the number of wires using techniques such as analog time division multiplexing (TDM).

Data Analysis. The collection of data generated from the sensors will include information about the health of the structure’s local neighborhoods, and when combined, can give information about the overall health. The challenge is that we do not know the space spanned by this large number of time series. This necessitates creating tools for visualizing the (coarse) level structure of the data, learning the space of signals, which might be a stratified space consisting of several pieces ‘nicely’ glued together, and providing a summary representation of the signals. The latter point requires developing an understanding of how the signals from the different sensors align or diverge. In order to analyze the complex signals resulting from the embedded networks, we turn to the new field of topological signal processing, which combines methods from topological data analysis (TDA) with tools from time series analysis to analyze streams of data. One of the useful topological tools, the persistence diagram, comes from persistent homology.

AIR FORCE APPROACH

On the high level, one research approach could consider that given a single time series f output by a sensor within a fixed range of time, we first map it to a set of point clouds P_f in the space of signals X. We then compute the persistent diagram summary of this point clouds P_f. Given a collection of signals, we then obtain a collection of persistence summaries D_f s in the space of persistence diagrams. We then develop unsupervised machine learning frameworks for such collection of persistence summaries to detect damage, and use supervised machine learning frameworks to predict the likelihood of damage/cracks, as well as to characterize the damage.

The resources needed include technologies for 3D printing of sensors, machines for manufacturing aerospace components including polymers and composites, and testing facilities to simulate dynamic and possibly thermal loading on the manufactured parts.

TIMELINE

15 Years

SURVEY RISK

Not Available

REFERENCES

3.3.8 Transforming Materials Discovery Through Computational Science and Engineering Innovation

CONTRIBUTORS

Lan Li, Yan Wang

OVERVIEW

The goal of this research area is to seek universal, high-throughput, multiscale and computationally efficient approaches by: 1) Developing new predictive tools and relevant theories; 2) Enhancing multiscale modeling with artificial intelligence; and 3) Designing novel computing architectures to enhance the performance of the modeling tools.

By 2030, the demand for the materials that are multi-functional, tough, self-healing, cost-effective, environmental friendly, energy-efficient, extreme-environment-resistant, and readily manufacturable will be increase to meet U.S. Air Force operational needs and to strengthen air, space, and cyber power. Thus, powerful and effective computational modeling techniques are required to discover capable materials and develop the corresponding manufacturing processes. Existing modeling techniques suffer many challenges and limitations, such as different length- and time-scale coupling issue, size effect, accuracy, and high computational cost. In addition, existing modeling tools/methods cannot be universally applied to different materials, systems or problems. The goal of this research area is to seek for universal, high-throughput, multiscale and computationally efficient approaches. The approaches should consist of, but not limited to, at least the three mechanisms described below:

1. Develop new predictive tools and relevant theories or optimize existing tools and theories to accelerate materials discovery for Air Force-related applications.
2. Enhance multiscale modeling with artificial intelligence to accelerate or enable materials discovery and manufacturing process development
3. Design novel computing architectures to enhance the performance of the modeling tools developed and used to fulfill the program goal.

DETAILED DESCRIPTION AND ACTIONS

This research area proposes to solve materials problems using advancements in both hardware and software. It targets solving the challenges and limitations of existing modeling techniques (discussed in the previous section), including coupling, accuracy, and computational time issues as well as the limited applicability of existing modeling tools and methods. The research area would develop effective predictive tools and relevant theories (such as physics- or chemistry-based models and computational algorithms [1-3]) to solve the length-scale, time-scale and multiphysics coupling problems. The tools developed should be capable of modeling different physical and/or chemical processes/properties in various systems. It would explore artificial intelligence [1] to enhance modeling techniques for improved accuracy and reduced computational cost. The research would design novel computer architectures (such as quantum computing [4] and special-purpose hardware [5]) to accelerate and optimize the performance of the developed tools.

This research area is inherently multidisciplinary and its success relies on advancements in several research areas, such as material science and engineering, computer science and engineering, physics, chemistry, and mathematics. The newly developed universal tools, models and theories should be able to support a broad range of research areas, meet various technology needs, and facilitate the development of new materials and manufacturing processes for Air Force applications.

AIR FORCE APPROACH

University, national labs, and industry should collaborate to leverage each other's capabilities in modeling, artificial intelligence, and cyberinfrastructure. The program should support center-level efforts (such as MURI programs) and AFRL/university/industry collaboration and parallelize with student and faculty summer fellowships to encourage the researchers involved in the awarded project to engage in training and use the facilities at the AFRL. Awarded projects should have the promise for transformative innovations in at least two of the following aspects: development of novel computer architectures (e.g., special-purpose computers or hardware dedicated for modeling), computing mechanisms (e.g., quantum computing), and algorithms (e.g., machine learning). The program should also encourage strengthened collaboration between theorists and experimentalists for validation and verification.

TIMELINE

5-15 Years

SURVEY RISK

	Low	Medium	High
Cost	5	7	6
Technical	1	6	11
Deployment	4	9	4
Defendable	6	10	2
Competitive	1	13	4

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3.4 Space Vehicle Systems, Metamaterials & Metastructures, and Passive & Active Stealth

3.4.1 Rapid Response Space Systems

CONTRIBUTORS

Ryan McBride, Uri Shumlak, Jean-Sabin McEwen

OVERVIEW

High powered, advanced space propulsion methods and systems have the potential to rapidly reposition spacecraft. Requirements include compact, low-mass, high-power supplies, e.g., fusion energy, tethers. The propulsion methods can serve multiple functions such as powerful sources of electromagnetic (EM) or neutron radiation for active interrogation or asset denial.

Space propulsion concepts with high propellant exhaust velocity and high thrust provide the ability to rapidly move spacecraft assets. High exhaust velocities reduce the required amount of onboard propellant and ultimately increase the lifetime of the spacecraft. Many electric plasma thrusters exist that produce high propellant exhaust velocities, but they are generally limited to low thrusts. High thrusts are necessary for rapid repositioning of spacecraft. The U.S. maintaining leadership in this area is critical to national defense and avoiding technological surprise from adversaries. The same propulsion devices with high exhaust velocity and high thrust are applicable to asteroid deflection missions and to manned missions for deep space exploration.

DETAILED DESCRIPTION AND ACTIONS

In order to develop rapid response systems, technologies that need to be investigated include:

- Compact, powerful radiation (e.g. EM, neutron) sources for satellite defenses and interrogative probes. These sources could include compact plasma radiation sources (e.g., z-pinch driven [1,2] and/or laser driven neutron, x-ray, and/or gamma ray sources) as well as compact high-power microwave sources (magnetrons, MILOs, etc.) [3]. The challenges will be to make the sources/payloads compact and powerful.
- Detectors and imaging techniques for active interrogation, where the developed technology is radiation hardened against the harsh space environment of EMP defenses.
- High power, pulsed devices.
- High power, low mass power supplies.
- Electrodynamic tethers as a source of electric power for propulsion.
- Compact fusion energy concepts [4].
- Simulations, at an atomistic level, the effect of fields on the formation of Taylor cones [5] and make connections to the large number of experimental and theoretical works on

the effect of electric fields on field emitter tips [6]. Specifically, try to better understand the formation of a Taylor cone in the presence of a high electric field. Here, it would be of interest to predict the necessary field strength for field-induced ionization when positive and negative electric fields are applied, since it is important to consider the interaction of the cation and the anion when it interacts with an external electric field [7]. The ionic liquid could be equilibrated using ab initio molecular dynamics or by classical molecular dynamics simulations [8]. This would be followed by DFT-based calculations to accurately quantify the interaction of an external electric field with the ionic liquid under consideration.

- High power plasma propulsion devices have the potential for multiple functions, such as radiation production for active interrogation of other satellites and EMP/HPM sources for disarming other satellites.

AIR FORCE APPROACH

A combined experimental and theoretical approach would be necessary to make progress in this research field. It is recommended that the Air Force sponsor a workshop that brings together researchers from within these areas to look at the interfaces and overlaps between existing thruster, radiation, and power source research programs to find new ways to combine these technologies and foster new collaborations among these areas.

TIMELINE

7-12 Y

SURVEY RISK

	Low	Medium	High
Cost	0	3	8
Technical	0	4	7
Deployment	0	5	6
Defendable	3	4	4
Competitive	3	5	3

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3.4.2 Large-Scale, Adaptive Metamaterials and Smart Skins

CONTRIBUTORS

Nader Behdad, Majid Manteghi

OVERVIEW

The aim of this research area is to develop large-scale surface coatings with electrical/optical properties (e.g., conductivity, dielectric permittivity, magnetic permeability, refraction index, loss, etc.) that can be changed dynamically and in a non-homogeneous fashion. This is envisioned as a large-scale, adaptive metamaterial/metasurface that can cover the entire surface of a large object (e.g., an aircraft) and adaptively change its electrical/optical properties in a non-homogeneous way and with a sub-wavelength resolution. This can be thought of as smart skin where based on the desired functionality, a given surface pattern of electrical/optical properties can be generated on demand. This concept has been researched in laboratory experiments but the challenge is to develop technologies that can be implemented on a large scale.

DETAILED DESCRIPTION AND ACTIONS

A reconfigurable/adaptive metamaterial will use an external stimuli (e.g., electric, thermal, acoustic, optical) to control certain electrical/optical properties (e.g., electric conductivity, dielectric constant, magnetic permeability) of the material. Metamaterials are generally formed using periodic structures with sub-wavelength dimensions. Moreover, many of the interesting properties that adaptive metamaterials can provide require having control over the properties of the metamaterial at the unit cell level. For example, to dynamically reduce the radar cross section of an object that is covered with an adaptive metamaterial, a given pattern of conductivity/dielectric constant can be created over the metamaterial cover. The pattern will need to have variations in the sub-wavelength scale.

The combination of needing large-scale metamaterials (e.g., to cover the surface of an aircraft) and the need to have control at the unit cell or microscopic level (e.g., to provide gradient or non-homogeneous type properties) makes the task of implementation of large-scale adaptive metamaterials extremely challenging.

Metamaterial designs and actuation techniques that allow for projecting/creating a given pattern (of conductivity, dielectric constant, etc.) over a large surface area of a reconfigurable metamaterial are needed. For example, a metasurface with a surface area of $1m^2$ may have anywhere from 10,000 to 1,000,000 individual elements (depending on the wavelength) that need to be controlled individually to get the desired functionality. Individually controlling and addressing these elements is a major challenge.

The realization of such metamaterials will require a multidisciplinary approach. For example, an adaptive metamaterial implemented as a periodic structure can be generated or controlled using acoustic standing waves applied to a compressible material (e.g., it could be an acoustic cavity filled with floating dielectric dust which can shape by acoustic wave). The cavity can be conformal and the periodicity can be controlled by the acoustic wave. This allows control of the structure by changing the frequency and shape of the acoustic wave dynamically.

To support this research, the following actions are proposed:

- Investigate various techniques including mechanical, electrical, chemical, or a hybrid (for example electromechanical, electrochemical, magneto-mechanical, etc.) to modulate a large-scale medium to achieve metamaterial like properties.
- After identifying possible research areas, theoretical investigation is required to study the feasibility and required scientific capability to develop each technique.

AIR FORCE APPROACH

Realization of this concept requires collaboration among different disciplines including electrical engineering, mechanical engineering, materials science, and chemical engineering, as well as close collaboration between academia and industry. Industry can serve a critical role in such a project, for example, by providing input regarding large-scale manufacturability. A workshop to bring together and initiate these collaborations is recommended.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	0	10	8
Technical	0	6	12
Deployment	2	10	6
Defendable	4	12	2
Competitive	4	12	2

3.4.3 Counter-Stealth Technologies

CONTRIBUTORS

Nader Behdad, Firas A. Khasawneh, Majid Manteghi

OVERVIEW

The U.S. is the leading country in developing stealth technology. However, other countries and potential adversaries are in the process of developing stealth technologies or have already developed stealth platforms. The development and widespread deployment of small, medium, and large-size stealth platforms in the future is expected. Therefore, techniques for reliably detecting such platforms are needed. In principle, one can envision performing this using a passive radar system that uses signals from a wide range of existing non-military emitters (e.g., cell phone base stations) to detect stealth platforms.

Detailed Description and Actions

Most stealth platforms operate by minimizing the backscattering radar cross section (RCS) of the target using a combination of shaping the object and using radar absorbing materials. However, it is extremely challenging to reduce the backscattering RCS of the target from all directions. Moreover, reducing the bistatic RCS of a stealth platform for all given illumination and observation angles is next to impossible. Therefore, in principle, bistatic radar systems have a better chance of detecting stealth platforms. Such radar systems use a transmitter and receiver that are not co-located. The idea here is to use the existing non-military transmitters (e.g., cell phone base stations) as transmitters of a multi-static radar system and one or more receivers that can be ground-based, airborne, or space-borne, as the receiver of this system. Such a system acts as a passive radar system in the sense that the transmitters are known, non-military sources. Therefore, a potential adversary's stealth platform will not be alerted by receiving such signals. Moreover, any given target is illuminated by many different transmitters from a multitude of locations and angles. A single receiver or multiple receivers can be used as part of the receiving system of these multi-static radar systems and can detect the stealth platform.

In another context, one can envision the problem of stealth platforms in a space environment. For example, one can envision a swarm of small space-borne drones (or mini-satellites) launched by an adversary to attack communications or intelligence, surveillance, and reconnaissance (ISR) satellites. Such drones can attach themselves to these satellites and be used for eavesdropping or for damaging the C/ISR satellites as needed. In such situations, it is important to detect these objects either from ground-based stations or using on-board sensors in the satellite.

To support this research, the following actions are proposed:

- Use vibration signatures to detect changes due to the attachment of a foreign element such as a stealth cube to the body of the satellite. Two different broad approaches can be used here:
    a. detections of shifts in the satellite natural modes, or
    b. detection of changes in the elastic waves that travel through the surface of the satellite (Lamb waves).

Both ideas rely on equipping the satellite with (piezoelectric) actuators that can excite the structure and sensors that can measure the resulting response. The resulting signals are then utilized to detect any shifts in the natural frequencies of the satellite from their original state.

- Excite different points on the satellite and measure the resulting response using attached sensors. If a foreign object is in the way of the waves that resulted from the excitation, then the response received by the sensors that are located between the excitation source and the foreign object will change their signature. It is then necessary to evaluate different tools and possibly develop new ones to detect these differences. Some of the tools to research include similarity measures in the time domain such as dynamic time warping and discrete Frechet distance, or similarity measures from topological data analysis (after extracting the topological features of the signal) such as bottleneck or Wasserstein distances.
- Investigate scattering patterns using image processing combined with machine learning. Specifically, while the stealth technology is impervious to radar's electromagnetic waves, stealth objects can still be visually detected. Therefore, by equipping the satellite or a neighboring satellite with cameras, it may be possible to detect approaching adversaries. If the satellite is behind earth, or if the stealth object is approaching the dark side of the satellite, it can still be possible to detect it using infrared cameras, which do not require sunlight.

AIR FORCE APPROACH

TIMELINE

10 years

SURVEY RISK

	Low	Medium	High
Cost	1	5	0
Technical	1	4	0
Deployment	2	5	0
Defendable	4	4	0
Competitive	2	6	0

3.4.4 Ephemeral Antennas and Electromagnetic Structures

CONTRIBUTORS

Majid Manteghi, Nader Behdad

OVERVIEW

This research idea proposes creating large electromagnetic structures (such as high gain antennas for high power applications) by temporarily using environmental manipulations (e.g., acoustic, material deposition, air turbulences). This concept is expected to be particularly useful for low-frequency applications.One of the major challenges in low-frequency communications and sensing is the large sizes of the antennas needed to generate/detect electromagnetic waves at these wavelengths. This is the case if high gain or directivity is needed from the antenna, which results in a very large physical dimension. One way to have a high-gain antenna is to use tapered travelling wave structures. These structures are usually multiple wavelengths long and have diameters less than a wavelength. At lower frequencies, these lengths can be in the order of meters to kilometers. This is the reason that most low frequency systems cannot take advantage of directive antennas.

DETAILED DESCRIPTION AND ACTIONS

VLF and LF radios are required for communications in challenging environments. Examples include underwater or underground communications systems, communications between underwater platforms and airborne platforms, sensing of underground tunnels from an airborne platform, sensing of underwater objects from airborne platforms, etc. Ferrite core loop antennas, with doughnut shaped radiation patterns, have been used at these frequency bands. In terms of implementation, designing a high gain, low frequency antenna is not practical due to their gigantic size.

One class of travelling wave antennas (tapered dielectric rod antenna) can be realized without deploying the antenna in its static physical structure, which requires very sophisticated technology and occupies a large space. Alternatively, this antenna can be realized by temporarily disturbing the environment to behave as a dielectric rod or corrugated rod antenna. There are various ways to realize the required disturbance: pump a stream of high-density particles to mimic a dielectric rod, use acoustic waves to create required corrugation, create a plasma stream in air, use the interface as a conductive path to direct the currents along, etc. The feed can be a conventional ferrite core loop and the proposed ephemeral (i.e., vanishing) structure can direct the wave a desired direction. Due to the transient nature of the environment supporting the flow of the RF currents, these antennas are referred to as ephemeral antennas (i.e., an antenna that exists in a short period of time and physically disappears).Ephemeral antennas may also be created using the wake turbulence of aircrafts. The small variations created in the index of refraction of air in the vicinity of the wave turbulence may be exploited to temporarily form an antenna (or other electromagnetic structures) as the plane flies.

The design of such structures will most likely require expertise from electrical engineering, mechanical engineering, materials science, and plasma science. Current technology allows testing this idea as a proof of concept. The challenge would be to get adequate control over the temporary phenomenon exploited (e.g., turbulence, plasma discharge, etc.) and get a predictable and repeatable performance.

To support this research, the following actions are proposed:

- Identify the possible applications, and for each application, identify the required electromagnetic structures, which are required to exist for a short period of time.
- Investigate the theoretical foundation and required techniques in all the involved disciplines
- Study the integration techniques required to simultaneously design the desired structures in all the involved disciplines.
- Investigate the possibility of extending the resulting technology to areas as large as space infrastructures or as small as nanostructures for applications in drug delivery or cancer treatment.

AIR FORCE APPROACH

This is a multidisciplinary research area that involves electromagnetics, mechanical engineering, plasma science, and material science. Preliminary results can be generated through simulation, and small-scale models can be created for higher frequencies as a proof of concept. The idea might be of interest to the DoD in general (Air Force, Navy, DARPA) and NASA as well. Due to the need for collaborative efforts, this research area could also be a subject for a MURI effort.

TIMELINE

>5 Years

SURVEY RISK

	Low	Medium	High
Cost	4	10	4
Technical	2	7	9
Deployment	5	8	5
Defendable	3	14	1
Competitive	3	13	2

3.4.5 AI Driven Materials Discovery Processes

CONTRIBUTORS

Patrick Johnson

OVERVIEW

Artificial intelligence (AI) can be used to improve and speed up the design and modeling of new materials. In particular, machine-learning techniques can replace expensive and time-consuming laboratory processes and computational simulations to quickly and reliably predict how to create materials with desired properties and how materials will behave in specific circumstances. [1,2]

DETAILED DESCRIPTION AND ACTIONS

Materials discovery and optimization is often laborious and time intensive. Integrating AI into the materials synthesis process can provide a means to accelerate new materials discovery. Utilizing AI algorithms can help probe larger parameter spaces more efficiently as well as mitigate investigator bias. Integrating computational modeling efforts in this effort would provide insight into the fundamental processes involved in materials and structures formation.

So-called surrogate models leverage experimental results to learn how properties of materials and experimental parameters relate to them.

Actions for supporting this research endeavor include the following:

- Algorithms that can handle high data sizes and rates.
- Just-in time spectral and physical property analysis coordinated with AI driven experimental automation.
- Platforms for high throughput synthesis and analysis specific to the type of material.
- Leveraging the learned AI models to understand fundamental processes.

AIR FORCE APPROACH

An integrated AI/computational/experimental approach necessitates a collaborative effort across multiple disciplines, including computer science, materials science and chemical/physics computational modeling. Programs could include MURI level efforts and AFRL/university collaborations.

TIMELINE

5-10 Years

SURVEY RISK

	Low	Medium	High
Cost	3	8	7
Technical	2	6	10
Deployment	5	6	7
Defendable	5	7	6
Competitive	4	6	7

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3.4.6 Realization of Metamaterials/Metasurfaces for Active/Passive Devices Applicable to Smart Emitters and Detectors

CONTRIBUTORS

Charles E. Hunt, Nader Behdad

OVERVIEW

Devices using nano-scale metamaterials have been modeled, but few have been experimentally demonstrated due to a) the lack of guidance about what the most-critical Air Force needs are with these materials, b) lack of materials synthesis methods for realizing the materials systems, and c) a lack of new device-fabrication techniques which make realizing these devices possible. This arena needs new approaches to materials synthesis and device fabrication outside of the mature IC fabrication technology methods that exist for the electronics industry. [1-4]

DETAILED DESCRIPTION AND ACTIONS

The Air Force has, and will continue to have, significant need to send and collect signals. Applications include communications, intelligence gathering, stealth, guidance and protection. Certain portions of the EM spectrum are already well exploited, but some (notably THz and hard/soft xray) are not. This is predominantly due to a lack of active and passive emitter and detector devices, which operate effectively in these bands.

At present, virtually all smart metamaterial solutions involve materials combinations, which either cannot be made, or can only be made in a manner which is insufficient to the requirement (e.g., impure, defective, incorrect size in one or more dimensions). If the models demonstrate which materials are needed, new chemical synthesis methods, beyond the constraints of current nano-scale IC fabrication techniques need to be discovered. Most likely, the solution to realizing metamaterials lies in going outside the established “box” which has been generated by Moore’s Law and the roadmap of the IC industry. Research needs to explore entirely new techniques.

Presuming new materials synthesis methods emerge, device fabrication techniques that exploit these methods need to be explored with the objective of fabricating the modeled metamaterials/surfaces. This research should also aim to realize devices that employ these materials/surfaces. The challenge is significant; but the benefit is enormous in that it opens an entirely new arena of active and passive devices.

This research program would also identify applications that might benefit from active and passive devices using parts of the EM spectrum presently underutilized. For example, a) Communications: encrypted smart systems which extend locally to distances beyond those associated with MM waves, b) Intelligence: both radiative devices and sensors coupled to them can be used in information gathering. Many hybrid options exist here, such as combining information gathering with communications, or with AI processors for high-speed response. c) Stealth: metasurfaces can be used to conceal devices on virtually any scale (macro systems up to aircraft), with the advantage that the materials can be adaptive on multiple levels (electrical, optical, thermal, chemical, etc.). d) Guidance: Systems which communicate with command units could be useful in ranges not currently possible. Metamaterials, which can adapt, can be incorporated as part of the encryption in two-way communications between master-slave systems. e) Protection: Metamaterials/surfaces can be active or passive in deflecting or absorbing radiation. They can be incorporated over a broad range of areas, from micro-size up to large-scale (clothing, equipment cases, even aircraft surfaces.) What constitute "best" areas to explore is not dictated by the researchers but rather by the Air Force customers.

Once identified, the "best" need areas can be examined with the objective to find specifications for the active or passive devices which are perceived to solve the problem. This set of specifications become the focal point for the theorist/modeler who is designing a metamaterial/surface. The resulting models will guide exploration of specific materials to be used.

Upon identifying a materials set to be incorporated in a smart metamaterial, both the synthesis method and fabrication technology needs to be developed. In most cases, this is likely the greatest challenge. For example, if the 3D metamaterial which has been modeled is found to be a nano-scale periodic matrix of crystalline gold interspersed with TiN and covering a 10 sq. ft. area, how is it fabricated? Although this might be viewed as a simple binary combination of materials, the realization of this could be both a materials synthesis and device fabrication challenge.

AIR FORCE APPROACH

The Air Force should define its needs so that the theory/modeling teams can project best solutions. Then, workshops should bring both materials synthesis and fabrication teams together to brainstorm the best approaches for realizing the solutions. Research RFPs and BAAs can be generated as a result of these workshops.

TIMELINE

10-15 Years

SURVEY RISK

	Low	Medium	High
Cost	1	15	2
Technical	0	13	5
Deployment	2	13	3
Defendable	1	15	2
Competitive	0	15	3

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3.4.7 Satellite Defense for Orbital Kinetic Objects (Incidental or Malicious) Using Electrostatic Deflection

CONTRIBUTORS

John Verboncoeur, Jim Browning

OVERVIEW

Kinetic objects in space, whether incidental debris or launched in a malicious attack, can pose a significant threat to satellites in the same orbital track. Many of these objects naturally become negatively charged from ambient plasma, and additional negative charge could be introduced in their path very rapidly upon demand. Local application of an electrostatic lens could deflect these objects and can be redirected to a lower orbit in the fractional obit transit. Depending on collisionality and other conditions, simple redirection may result in an elliptical orbit, so orientation of field may be necessary to both redirect and reduce the energy to move to a less hazardous orbit, or deorbit completely.

Consider a number of high value satellite assets placed in an orbit. Kinetic objects in this orbit with differential velocities pose impact and damage threats to these satellite assets. While neutral objects cannot be steered at a distance, charged objects can be steered using electric fields. Only a small perturbation of the trajectory is needed in order to accomplish this steering. Many of these kinetic objects have a net charge, making them steerable with an electrostatic lens. Additional charge could also be injected into their path, resulting in an increased charge to mass ratio. Alternative mitigation methods, to the extent they exist, might include ballistic interception. Given the typically small size of these objects, that becomes challenging, and interceptors which miss their target may themselves become a threat.

DETAILED DESCRIPTION AND ACTIONS

Development of a wide area orbital electrostatic lens of perhaps >1 m^2 , which is capable of providing a small deflection to charged orbital objects, will result in a minor change in energy and direction; this deflection could move the kinetic object to a harmless orbit, or deorbit it completely. The orbital lens may consist of a modest to high voltage plate pair whose field vector has components normal to the propagation direct to reduce the energy, and perpendicular to alter the trajectory. Note that the lens can be activated only when a threat is detected, and further would draw little dark current depending on the ambient plasma density.

Depending on the mass of objects and ambient plasma density, additional charge could be inserted in to the path using electron sources similar to the neutralizers in an ion thruster. The sources would require simultaneous emission of positive charge in order to remain neutral.

As objects pass through the charge cloud, they would become increasingly negatively charged, to an extent dependent upon the electron temperature and density of the cloud. The electron cloud can be placed just in front of the orbital electrostatic lens.

The orbital lens '+' charge injector system can be placed in periodic positions in orbit to eliminate kinetic objects. Research challenges/risks include kinetic object detection for activation of the system, powering the lens and charge injectors, providing the right impulse to the lens to obtain a safe orbit, and orbit station keeping for the system. One might imagine the latter might be possible using ion thrusters which are themselves part of the neutralization system. This would require capabilities in orbital mechanics, orbital object detection, orbital station keeping, orbital power, charged particle physics, and plasmas.

AIR FORCE APPROACH

The development steps to support the R&D leverage significant elements in existing or proposed programs. An excellent first step might be a rapid study to determine technical and economic feasibility of the proposed system, followed by component development via incremental R&D programs:

- Orbital station keeping of microsats.
- On-demand volume injection of charge along with neutralization. These components looks similar to an ion thruster with electron neutralization.
- Electrostatic lens: ability to project two components of electric field, along and perpendicular to the object trajectory. Here the challenge is limiting dark current.
- Power supply for the charge source and lens may require solar + storage, or remote power transfer technology.

Object sensing and warning used to activate the charge and lens components. This may leveraging existing capabilities.

TIMELINE

>10 Years

SURVEY RISK

Not Available

3.5 *Cybersecurity*

3.5.1 Vulnerability and Countermeasures of Embedded Systems

CONTRIBUTORS

Steven F. Barrett, Cameron H.G. Wright

OVERVIEW

The purpose of this research effort is to explore and catalog the vulnerabilities of microcontroller, DSP, and FPGA processors; develop design practices to counter these vulnerabilities; and publish results in appropriate professional literature. The purpose of this research effort is to explore the vulnerabilities of microcontrollers and digital signal processors (DSPs) within an embedded system. Within the last decade, considerable effort has been expended in identifying the vulnerabilities in a wide variety of embedded systems employing programmable logic controllers and embedded systems connected to the internet. There is not much information in the literature concerning microcontroller, DSP and FPGA based systems.

DETAILED DESCRIPTIONS AND ACTIONS

Embedded systems are ubiquitous—they are everywhere! They are present in many commercial, educational, and military based systems. The broad term embedded systems include microcontrollers, digital signal processors, programmable logic controllers, field programmable gates arrays, and devices connected to the internet. The rapid development of internet connected embedded systems has been placed under the broad umbrella term of the “Internet of Things.”

In the last decade there have been many instances of these systems being exploited and causing damage to the system under control. For example, in 2010, Stuxnet was developed by an unknown source to target and disrupt the Iran nuclear program. Stuxnet was developed to exploit vulnerabilities within the Supervisory Control and Data Acquisition (SCADA) system for the programmable logic controllers (PLCs) within Iran’s nuclear program [1].

Schneier [2] reports on system vulnerabilities within the internet. That is, the common hardware use to connect devices to the internet including routers, servers, and modems. Schneier describes how the integrated circuits (ICs) controlling these products are mass produced by a small number of manufacturers on slim profit margins. When device vulnerabilities are detected there is little incentive to correct or “patch” the device. Furthermore, if patches are developed, they are difficult to deploy and users typically do not apply the patch [2]. For example, in 2016, Mirai a botnet, was deployed throughout the internet. The botnet contained 68 known, default user name pairs common throughout the IoT industry. Basically, the IoT industry includes any device with internet connectivity. The botnet scanned for devices that had a default user name and password in place. This allowed the botnet access to the device. The overall result was a massive, distributed denial-of-service (DDoS) attack on IoT devices. Some devices had the capability to allow the user to change to a different user name password pair. Interestingly, many of the devices attacked did not have this feature [3].

Considerable literature exists on the vulnerability and countermeasures for PLC and IoT based systems. However, the literature is conspicuously quiet on microcontroller, DSP, and FPGA based system vulnerabilities and countermeasures. The proposed research effort will explore and catalog the vulnerabilities of the microcontroller, DSP, and FPGA based processors; develop design practices to counter these vulnerabilities; and publish results in appropriate professional literature.

AIR FORCE APPROACH

Fund research team to investigate vulnerabilities and countermeasures in embedded systems technology.

TIMELINE

5-10 Years

SURVEY RISK

	Low	Medium	High
Cost	10	8	0
Technical	3	15	0
Deployment	8	7	3
Defendable	3	9	6
Competitive	2	11	5

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3.5.2 Cyber Resilient Systems-on Chip Designs

CONTRIBUTORS

Nader Rafla

OVERVIEW

Any System-on-Chip (SoC) may contain intentionally inserted vulnerable and malicious cores (Hardware Trojan) that can look benign at the time of design, manufacturing, and testing but turn into active threats at a later point of time during a normal operation. Additional major security issues, for SoCs may include piracy IP evaluation, reverse engineering, cloning, and counterfeiting. SoC systems usually contain millions of logic cells, megabytes of memory, high-speed transceivers, analog interfaces, multicore processors and a communication network. In addition, they might include an embedded Field Programmable Gate Array (FPGA) that can be reconfigured at run time and may self-evolve to adapt to the environment.

DETAILED DESCRIPTION AND ACTIONS

Applications running on SoCs may include communication infrastructures, sensitive data access, critical industrial control, and high-performance signal processing. SoCs are used by the Air Force in new weapons systems and platforms which must be cyber resilient and which are expected to be in every system. There is an urgent need to design new low-cost robust security measures during the design and test phase to cover most aspects of security threats before the SoC is deployed into the field. Most of the cyber-research currently done in this area focuses on securing the interfaces to the SoC in an attempt of protecting the SoC not to develop cyber-resilient hardware.

AIR FORCE APPROACH

TIMELINE

3-5 years

SURVEY RISK

	Low	Medium	High
Cost	2	9	1
Technical	2	8	2
Deployment	2	9	1
Defendable	1	10	1
Competitive	2	8	2

3.6 Modelling and Computational Approaches

3.6.1 Advanced Embedded Boundary Methods for Modeling of Electromagnetics and Charged Particles

CONTRIBUTORS

John Cary

OVERVIEW

Embedded boundary methods allow second-order accuracy while still primarily computing on structured grids, which are computationally efficient. However, there are a number of advances to make, including going to a higher order; developing efficient representations of smoother particles, especially near physical boundaries; and addressing treatment of high-contrast dielectric interfaces. [1-6]

DETAILED DESCRIPTION AND ACTIONS

Computational dynamics on structured grids is highly performant as the data structures are accessed regularly. Moreover, for electromagnetic particle-in-cell simulation it is practically a necessity; as without it, naturally charge conserving current algorithms are unwieldy or unavailable. However, structured grids by themselves cannot represent boundaries except by stair-stepping, which reduces the order of accuracy. This can be overcome by use of embedded boundary methods, which change the method of updating field values in the cells cut by the boundary only. The resulting computations can be highly performant on modern architectures, as the aligned data can make effective use of vector instructions.

Unfortunately, there are no published methods for taking such methods to higher order. In part this is due to the lack of a rigorous mathematical foundation, in part it may be related to the requirement of larger stencils for associated higher-order field advances, with such stencils reaching beyond the cut cells/embedded boundaries. In addition, there are problems for charged particle emission into a system and absorption, with the associated charge entering or leaving the system. Methods for doing this have been published, but questions about whether there are more efficient methods remain. Methods for working with “larger” (smoother) particles have not been published, but they are needed for simulations with less Monte Carlo noise.

AIR FORCE APPROACH

An initial workshop could be organized to understand the state of the art of embedded boundary methods across Electromagnetics (both conductors and dielectrics), Fluid Dynamics, and Charged Particle motion. Such a workshop could have presentations on what is being done along with observed accuracy and any limitations (which are often difficult to obtain from publications). One goal of the workshop would be to identify fruitful areas for cross pollination, e.g., where might the fundamentals of EM embedded boundary methods be useful in Fluid Dynamics and vice versa?

Ultimately one would have a broad call for developing advanced approaches to kinetic modeling that would bring together universities, labs, and industry to propose new approaches or modifications of existing approaches. There should be a target of performance, working code, in either source or binary form, so that users apply any codes to those benchmarks.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	10	6	2
Technical	2	9	7
Deployment	7	9	2
Defendable	9	5	4
Competitive	6	7	5

REFERENCES

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3.6.2 Methods for Computational Application Development with Varied and Changing Computational Platforms

CONTRIBUTORS

John Cary, Uri Shumlak

OVERVIEW

There is already a large variation in the compute devices (GPU, many-core, multi-core) that a computational application developer must consider in current development. Given that each year, more device types are being developed and proposed, methods/abstractions for development across multiple devices must be found. [1-2]

DETAILED DESCRIPTION AND ACTIONS

Computational capability has been instrumental in the development of Air Force needed items. For example, electromagnetic (EM) computation is needed for the development of antennas of particular characteristics, and EM computation in the presence of charged particles is important for radars and plasma environments. The hardware for doing such computations has been rapidly changing in the last decade. The use of GPUs for computations has become common, but there are many ways of writing code for them, including OpenCL, OpenACC, and CUDA. Many-core processors are quickly evolving; for example, Knights Corner with cores on the order of 60, had only a two-generation lifespan. There are multiple performance-related instruction sets (SSE, AVX2, AVX512) with more on the horizon. There are also new (quantum computing) and resurfacing (analog computing) computing devices envisioned.

This makes developing new computational capabilities daunting. Because it takes multiple years to develop a new computational capability, with computational devices having a sub-half-decade lifetime, coding can be obsolete at or before the time it is completed. The result is that only the simplest computational applications can be developed. Moreover, with the risk of rapid obsolescence, developing computational capability can be a risk to one’s career, which can discourage this kind of work.

Research is needed to mitigate this situation. For example, at present, code development should be able to take advantage of vector, thread, multi-device (CPU, GPU, other), and multiple node (network interface card) parallelism. Moreover, it should be able to break up the problem in different ways, with different granularity, or with different data structures. Thus, even at present, the development of highly flexible coding methodologies is needed.

Looking ahead one could study the proposed computational device ideas, and begin asking how one might develop new approaches in a way that insulates applications from change.

- Coding languages with high level abstractions that facilitate code reuse for evolving computing hardware.

AIR FORCE APPROACH

A workshop on computing with current and emerging devices could be organized to understand the scope of the problem. The workshop elements would include a) presentations on current research in device development; b) current approaches at handling the wide arrays of current devices; and c) presentations on the array of algorithms that must be considered, including explicit field updates, particle-in-cell, molecular dynamics, etc. A report might address the challenges of developing emerging architectures and report on progress in this area. The workshop report could provide a basis for a research program in this area. The research program would cover the full range of the problem from development of methods through their implementation, testing, and evaluation.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	5	8	4
Technical	4	5	8
Deployment	6	6	5
Defendable	4	8	5
Competitive	4	9	4

REFERENCES

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3.6.3 Improving the Kinetic Modeling of Plasmas

CONTRIBUTORS

John Cary

OVERVIEW

The kinetic plasma modeling methods, continuum/Vlasov and particle-in-cell (PIC), each have drawbacks—memory usage in the former and Monte Carlo noise in the latter. Totally new approaches or modifications of existing approaches are needed to enable large plasma systems simulation [1-5].

DETAILED DESCRIPTION AND ACTION

There are two widely used approaches to the kinetic modeling of plasmas, the continuum approach and the PIC approach. The continuum approach has the advantage of not having Monte Carlo noise. However, it requires much more memory, both because the discretization of velocity makes this 6-dimensional, and generally one must maintain memory for plasma particles in regions where plasma particles might show up but are perhaps insignificantly present for most of the computation. PIC methods have reduced memory requirements but are accompanied by both higher noise, as noted above, and grid instabilities when the Debye (plasma shielding) length is not resolved, even in regions where such shielding is not present. The latter can be mitigated by implicit particle methods, but current implementations are slow and not well adapted to the most recent and emerging computing devices (GPUs and CPUs with advanced instructions). Furthermore, implicit particle methods lack mature high fidelity boundary conditions, particularly for particle-surface interactions.

Approaches in this research area could consider new algorithms orthogonal to existing algorithms or could improve existing algorithms. Examples include reducing the memory requirement of continuum approaches, improving the convergence or speed by other means of implicit PIC methods, and reducing PIC noise beyond smoothing or extended particle shapes. Advanced hybrid models may be capable of combining the best features of both approaches.

AIR FORCE APPROACH

An initial workshop could be organized to understand the full range of limitations of present approaches and the consequences of such limitations, e.g., exemplar problems that cannot be computed today. The exemplar problems should be defined to the point where they can act as benchmarks for implementations. The resulting document could provide background to a broad call for developing advanced approaches to kinetic modeling that would bring together universities, lab, and industry to propose new approaches to or modifications of existing approaches. There should be a target of performant, working code, in either source or binary form but in any case having been set up to address those problems, so that users apply any codes to those benchmarks.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	5	9	3
Technical	3	7	7
Deployment	6	9	2
Defendable	6	7	4
Competitive	2	12	3

REFERENCES

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3.6.4 Developing Predictive Models for Plasma-Surface Interactions

CONTRIBUTORS

John Cary, Ryan McBride, Jean-Sabin McEwen, Uri Shumlak

OVERVIEW

There are many cases where plasmas and/or intense electric and magnetic fields interacting with surfaces have a significant effect on overall system dynamics. Research is needed to understand how to describe the interactions and on-surface behavior in and away from thermodynamic equilibrium. Do particles move due to near-surface fields? What are the equations describing the dynamics, including adsorption, interaction, movement, and desorption? Interactions of surface and near-surface particles with boundary plasmas can dramatically affect the plasma dynamics.

DETAILED DESCRIPTION AND ACTION

In many cases plasmas and/or intense electric and magnetic fields interacting with surfaces have a significant effect on overall system dynamics. Such interactions can take the form of particles adhering to the surface, particles migrating while on the surface, particles interacting while on the surface, particle desorption, defect migration below the surface, field emission, explosive emission, thermionic emission, photoelectric emission, etc. Applications include spacecraft charging in the space plasma environment; plasma interaction with walls in low-temperature plasmas, such as plasma thrusters and microelectronics processing; laser-plasma interactions in inertial confinement fusion; power flow in pulsed power systems used for radiation generation (x-rays, neutrons, and high-power microwaves); multipactor; and divertor-wall interactions in magnetic confinement fusion plasmas.

There have been several approaches that could be used to describe the interaction of an electric field and/or plasmas with surfaces. On the one hand, a mean field type description could be used for the interaction of a surface with an electric field and/or a plasma. For example, literature shows that a computationally tractable fluid model can capture the effects of neutral particles in a plasma [1]. The effects of oscillating electric fields are also being actively investigated by solving the time-dependent Schrödinger equation [2]. Although such an approach can give considerable insights, it is not computationally tractable to go beyond such a mean field approach for such a model. On the other hand, the interaction of adsorbates with a metal surface in the presence of a constant electric field have been recently characterized using a non-mean field approach [3]. As such, a natural question arises: can such non-mean field models be extended to incorporate some of the complexities of a computationally tractable fluid model. For example, one could develop a non-mean field model where an oscillating electric field is applied when a metal surface is exposed to hydrogen. This problem is of interest to the semiconductor industry since metal surfaces, such as tin, are often exposed to a laser which induces a plasma at the gas-solid interface. We also note that, in the past, such non-mean field models were also applied when a lattice gas model was developed to obtain an equation of state in a plasma environment [4]. However, the effect of electric fields on the underlying dynamics, to the author's knowledge, has not yet been developed.

Development of new experimental platforms and new diagnostic techniques will be required. The measurement of very low-density plasmas, close to surfaces, and often fully enclosed in metal structures is challenging. Simplified, exemplar platforms could be developed, which include open diagnostic access with minimal structural perturbations. These platforms should be designed to collect experimental data while maintaining apples-to-apples correspondence to simulated problems. Diagnostic techniques could include advances in laser-resonant diagnostics (for measuring very low plasma densities), laser-induced fluorescence (for tracking plasma migration), Faraday rotation (for magnetic fields), polarized Zeeman and Stark spectroscopy (for electric and magnetic fields), dopant tracking (to understand where desorbed constituents migrate to within the system), etc.

The following actions support this research effort:

- Development of higher-fidelity models for plasmas interacting with surfaces.
- Development of higher-fidelity models for intense electric and magnetic fields in vacuum interacting with surfaces when no plasmas are present (at least initially, to better understand plasma formation and mitigation of plasma formation for certain applications).
- Development of well-controlled and well-characterized experimental platforms for model validation. These can be surrogate platforms designed solely for model validation.
- Physical models at the PDE level that transition based on local parameters to maintain formal validity.
- Neutral densities increase near surfaces due to recombination/ionization, outgassing. Plasma-neutral and multi-species interactions must be modeled in a tractable manner.
- Programs/efforts to implement the developed models into full-scale design software.

AIR FORCE APPROACH

With the relative paucity of knowledge in this area, the Air Force should undertake a combined theoretical-experimental approach, with multiple groups involved. Ideally, there would be two or more theoretical research groups proposing modeling ideas that are validated (or not) by experimental research groups. Industry involvement could lead to hardened software available to designers of spacecraft, thrusters, and other plasma devices.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	7	7	3
Technical	2	7	8
Deployment	5	7	5
Defendable	4	9	4
Competitive	1	14	2

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3.6.5 Quantum Mechanisms Modeling in Beams and Plasmas

CONTRIBUTORS

Peng Zhang

OVERVIEW

As device miniaturization and hybridization progress, the generation and manipulation of charge particles and plasmas in nanometer scale gaps and structures are becoming ubiquitous. Recent advances in lasers and optics also provide the opportunity to access and control such nanoscale beams and plasmas at ultrafast time scale. Quantum mechanisms would become increasingly important and perhaps even dominant in future ultrafast and nanoscale plasmas and vacuum devices.

On the other hand, there is continuous demand on pushing the limit of existing high power, high frequency devices and systems. Examples include increasing the maximum output power of high power microwave sources, such as magnetrons and back wave oscillators, and maximizing the gain of traveling wave tubes. High fidelity modeling of plasmas-surface interactions (e.g., near cathodes) is crucial to further increase the current level and quality of the driving electron beams to these devices. Since electron emission processes (e.g., field emission, thermionic emission, and photoemission) and plasma breakdown are intrinsically quantum mechanical phenomena, it is essential to provide quantum mechanism modeling to critically understand these important issues.

DETAILED DESCRIPTION AND ACTION

There has been recent efforts to develop quantum mechanical models on the physics of diodes and electron emission. A unified theory for the current transport in a nano- and sub nano-diode was recently developed [1], which encompasses the Simmons' direct tunneling law, Fowler-Nordheim law, the classical Child-Langmuir law, and the quantum Child-Langmuir law in various limits, including their transition. The unified scaling law is valid for various insulating materials (including vacuum) sandwiched between the cathode and anode. An analytical solution is constructed for ultrafast strong field electron emission from a metal surface that is subjected to an arbitrary combination of dc bias and laser field, by solving the time-dependent Schrodinger equation exactly [2]. It is found that ultrashort electron bunches may be generated with a moderately low intensity laser in combination with a strong bias dc electric field. Novel concepts on geometrical diodes [3] and micro-discharges in asymmetric geometrical gaps [4] wre studied. Recent advances in diodes [5], electron emission [6], and solved and unsolved problems [7], were reviewed.

These studies are still in their infancy. Quantum physics in plasmas and beams are poorly understood. Issues on electron emission, secondary electron yield, ionization, surface roughness and termination, space charge, heating phenomena, thermal conduction, collisions and scattering, electrical contacts, etc. under the context of ultrafast and nanometer scales require new models to understand the basic physics.

The following actions are needed:

- Develop quantum models to explore the largely untouched quantum world of plasmas and beams
- Theoretical models may be used to benchmark/verify the large scale computational tools and guide experiments.
- Theory and analytical solutions may also be embedded in the multiscale computational modeling to provide physics-based, high fidelity simulation tools with accelerated time performance.

AIR FORCE APPROACH

Interdisciplinary approaches are needed to address the physics at different levels of complexity. It would be greatly beneficial to integrate with experimental efforts (groups at universities, labs, and industry) to validate the developed models, which in turn provide predictions to the experimental outcome.

TIMELINE

5-10 Yrs

SURVEY RISK

	Low	Medium	High
Cost	2	13	2
Technical	1	7	9
Deployment	2	13	2
Defendable	4	10	3
Competitive	2	9	6

REFERENCES

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3.6.6 Virtual Prototyping

CONTRIBUTORS

John Cary, Jean-Sabin McEwen, Uri Shumlak

OVERVIEW

Accurate simulation of plasma devices requires modeling the plasma with sufficient physical fidelity as well as modeling the surrounding containment vessels, electrodes, and dielectrics. Topics include quantifying plasma model uncertainty, physics-based coupling between models, and improved algorithms that exploit new compute platforms and hardware.

DETAILED DESCRIPTION AND ACTION

Plasmas enable new technologies by providing a means to apply large forces at a distance and by interacting with intense electromagnetic radiation using a state of matter that is immune to further breakdown. Plasma configurations are formed by external and internal electromagnetic fields and by the surrounding containment vessels, electrodes, and dielectrics.

The magnitude of internal electric fields can be quantified within classical and quantum mechanical-based models [1,2]. However, quantum-based calculations of internal electric fields differ significantly from the classical-based calculations. As such, a quantum-mechanical-based quantification of internal electric fields is necessary to accurately quantify the strength of internal electric fields [2]. Experimental prototyping is a critical step for testing and proving these technologies; however, it is an expensive and slow process that impedes technology development. As such, virtual prototyping of plasma technologies, using quantum-based and classical-based simulations, can greatly speed the development process and its ultimate implementation in the field. Effective virtual prototyping must capture the relevant physics associated with the plasma dynamics, with the solid surface response, and with the plasma-surface interactions.

These are recommended outcomes for advancing this research:

- High-fidelity plasma physics models coupled to surface models
- Quantified model uncertainty that permits selection of the simplest physical models (and the minimum computational effort) to provide uniform fidelity necessary to locally satisfy formal validity limits.
- Self-adjusting software that transitions between physical models in space and time as needed to maintain a uniform uncertainty throughout the simulation.
- Numerical algorithms that solve high-dimensionality PDEs and exploit new compute platforms, e.g., many-core, GPUs, accelerators, quantum computers.

- Complementary quantum mechanical calculations to accurately quantify the strength of internal electric fields.

AIR FORCE APPROACH

It is recommended that the Air Force conduct a code framework workshop that brings together domain specialists in theoretical/computational plasma models, surface models, and computational mathematics. This workshop should be followed by a validation workshop between plasma technology experimentalists and computationalists. Calls for proposals should include those for quantifying model uncertainty, facilitating collaborations among the domain specialists, and short-term proposals (i.e. one year) that assess the feasibility of a virtual prototyping approach. It is recommended that researchers have access to DoD cluster resources so as to effectively perform the required calculations

TIMELINE

12 Years

SURVEY RISK

	Low	Medium	High
Cost	4	11	3
Technical	3	6	9
Deployment	3	8	6
Defendable	2	12	4
Competitive	2	12	4

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3.7 Blue Sky Areas

This topical classification was used to capture those topics sufficiently diverse that they did not fit easily into the remaining categories. The goal was also to encourage more unusual topic discussions across a range of disciplines.

3.7.1. An Adaptive Framework for UltraHuman Information Response

CONTRIBUTORS

Allison Anderson, Andy Kliskey, Marco Rolandi

OVERVIEW

The objective of this topic is to create an UltraHuman Information Response by compiling physiological, behavioral, and environmental data to assess warfighter state. This information is communicated to the individual, the machine with whom he or she is interacting, and mission control. These actuators then make decisions to optimize the human response to the situation, for example via an electroceutical stimulus, a behavioral correction, or a change in instructions from command to optimize the task allocation (See Figure 2 below). [1,2]

DETAILED DESCRIPTION AND ACTIONS

The modern combat environment requires UltraHuman adaptability with an intimate link between warfighter and technology. Recent advances in sensors, neural stimulation, and electroceuticals are able to link specific biomarkers to situational stress and correct the potential for error in the warfighter decision-making process. At the same time, external interventions may not always correct for the warfighter state. In this case, an internal correction or adaptation of the mission instructions from the command to the troops may be required. The adaptive framework for UltraHuman Information Response collects and compiles physiological, behavioral, and environmental data to assess warfighter state and communicates the state to the external actuators, the individual, and mission control. The internal, artificial, and command controller then compile their decision to optimize the human response to the current warfighter state.

The Air Force has made pivotal investments in breakthrough technologies for national security. Through the rapid increase in scientific knowledge spanning hardware, software and miniaturization, technology is becoming a pervasive component of the individual experience. Nowhere is this infusion more pronounced than in a military context where Air Force personnel are tasked not only with incorporating a stream of new technologies into their active workflows, but to integrate disparate technologies that may compete with one another for a critical slice of mental bandwidth.

A key premise is that there is a human saturation threshold, beyond which the tax on mental processing degrades critical survival and operational factors, such as situational awareness or physical performance. This is not to suggest a limit to the advancement of technology but rather to illuminate the need for a transformational way in which we view the extent to which the human can absorb external inputs and so improve the science of the human-machine interface. In defining the limits of current user interfaces, we can consider the profound adaptation of voice-control, augmented reality, and neural interface alternatives that will pave the way for tomorrow's warfighters to successfully embrace the growing wealth of tactical and strategic data that will be at their disposal. Among of the issues to consider and address is technology induced environmental distancing whereby over reliance on digital technology potentially inhibits situational awareness and human performance.

The proposed framework begins by extracting information from the human and environment as shown below in Figure 2. This is accomplished through sensory information from a variety of sources. Biomarkers are objective measures of the body’s status using chemical, hormonal, and biological characteristics. These are typically discrete, invasive measures, but may also be collected by implanted means. Biosignals are also objective human measures that can be continuously monitored noninvasively and are a measure of the gross response of the body. External cues are data collected from the environment, machine, or system with which the human is interacting. To properly aggregate the information, data fusion algorithms incorporating advanced statistical methods and signal processing should be used to provide a measure of the psychological and physiological status of the person. This information can then be fed to the relevant actuators in the system. These actuators include those in the person’s chain of command, the machine with which the person is working, and the person him/herself. Each of the actuators then uses this information to make decisions about how performance may be augmented. As such, each of these actuators may have different information needs. Command can use the information to make decisions regarding tasking or assistance assignments. The machine may use this input to change how information is displayed to the person or transition between levels of autonomy. The person can use this self-status information to regulate stress levels, seek assistance, or motivate performance. In addition to these system-level performance enhancements, augmentation may also be enacted at the cellular level where embedded biological technologies could be used to enable performance enhancement.

We have identified three technical challenges on the path to enabling this framework and suggest actions taken in this research area aim to overcome these challenges:

1) Development of sensors and stimulation with fast response and precise spatiotemporal control that overcome the tradeoff between accuracy and encumbrance in an operational environment.

2) Development of an algorithm and communication strategies that translates the data gathered from the sensors into an actionable response.

3) A strategy to optimize human response to different levels of external feedback.

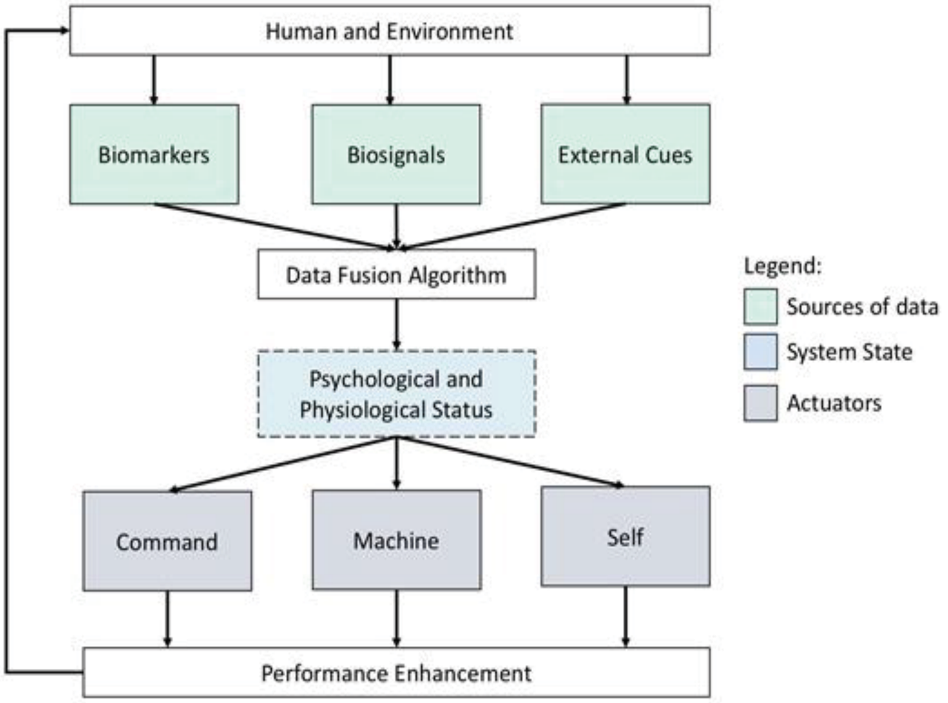

Figure 2: Framework for UltraHuman Information Response.

AIR FORCE APPROACH

In order to overcome the challenges described above, we suggest a holistic approach in which scientists, engineers, and physicians come together and establish a timeline with a granular approach. We envision these three thematic programs to run in parallel with close cross-program communication in order to adapt and correct the path of each program in response to the global findings. We foresee this effort to last 10 years from 2020-2030 in 2 phases. Each phase will cost $20 million per year. Phase 1 would include 10 multidisciplinary and multi-university teams, and Phase 2 will down select to the top 5 performing teams doubling their yearly budget.

TIMELINE

10 Years

SURVEY RISK

	Low	Medium	High
Cost	1	7	7
Technical	0	5	10
Deployment	1	10	4
Defendable	3	9	3
Competitive	3	8	4

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3.7.2 Numerical Model for Planetary Information Response

CONTRIBUTORS

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OVERVIEW

The objective of this topic is to develop a global monitoring model with predictive ability to measure the state of the planet. It identifies how human, ecologic, and environmental system interactions shift to identify global threats. These shifts can be countered through economic, socio-political, or environmental means (See Figure 3). In the modern globalized world, local events have global impacts. Current data gathering and data sharing technologies allow for planetary monitoring of humans, ecological life, and geophysical events. This collective data provides an unparalleled opportunity to develop a global monitoring system with predictive ability in order to measure the state of the planet. The objective of such a model is to identify how threats to these interacting systems can be countered. Alternatively, the model could be used to identify how these interventions then impact the human, ecologic, and environmental players. Here, we propose an adaptive framework for planetary information response. This framework monitors changes in the state of the planet to predict threatening events and correct for these events via economic, socio-political, and environmental interventions.

Existing monitoring and sensor systems for detecting perturbations, changes, and events at broad global scales are well developed and implemented for satellite, airborne, terrestrial, and oceanic sensors. However, the ability to seamlessly integrate multiple sensor inputs and make sense of the resulting complex array of observations and data is less developed. There are also additional sensor inputs that can enhance an integrated observing and detection system. These could include plants as sensors of change or high-fidelity human observers of change. New research should contribute to exploring expanded and integrated detection systems, data fusion algorithms for integration of diverse data sources and pattern recognition, and translating observations and detection of change for interventions that are part of an integrated response. [1,2]

DETAILED DESCRIPTION AND ACTIONS

The objective of this model is to develop an integrated bidirectional model to monitor global status and identify risks and threats in order to enact global change with local and global interventions. The framework is shown in Figure 3. Threats may be varied, but by integrating the response from multiple subsystems, precursors to instability and global trajectories may be identified and then altered to prevent negative outcomes. The status of the planet can be monitored by measuring a) human trends in migration, reproduction, consumption, and labor; b) the ecological status of plants, animals, and other living entities; and c) the geophysical change of the environment through measuring atmospheric composition, geologic shifts, oceanic trends, and ice sheets. These data may be collected through satellite reconnaissance, individual monitoring (i.e., through wearables, social media, etc.), globally derived reports (i.e. from the UN, the World Bank, etc.), numerical models (i.e., weather, ocean temperature, etc.), or in-situ reports from intelligence assets. Then, this information can be integrated through advanced machine learning algorithms and signal processing to determine the global status and shifts from historically derived states. From these risks, subsequent interventions may be achieved through economic, socio-political, or environmental means. The developed global status model could also be used in reverse to predict the impact that a chosen economic, socio-political, or environmental intervention may have on humans, ecological life, and geophysical systems.

We have identified three technical challenges on the path to enabling this framework and suggest actions taken in this research area aim to overcome these challenges:

1) development of strategies to collect large amounts of data from distributed sensor systems monitoring human, animal and plants, and geophysical phenomena;

2) the development of a global status model and communication strategies that translates the data gathered from the sensors into an actionable response; and

3) a strategy to optimize response to changes in global status.

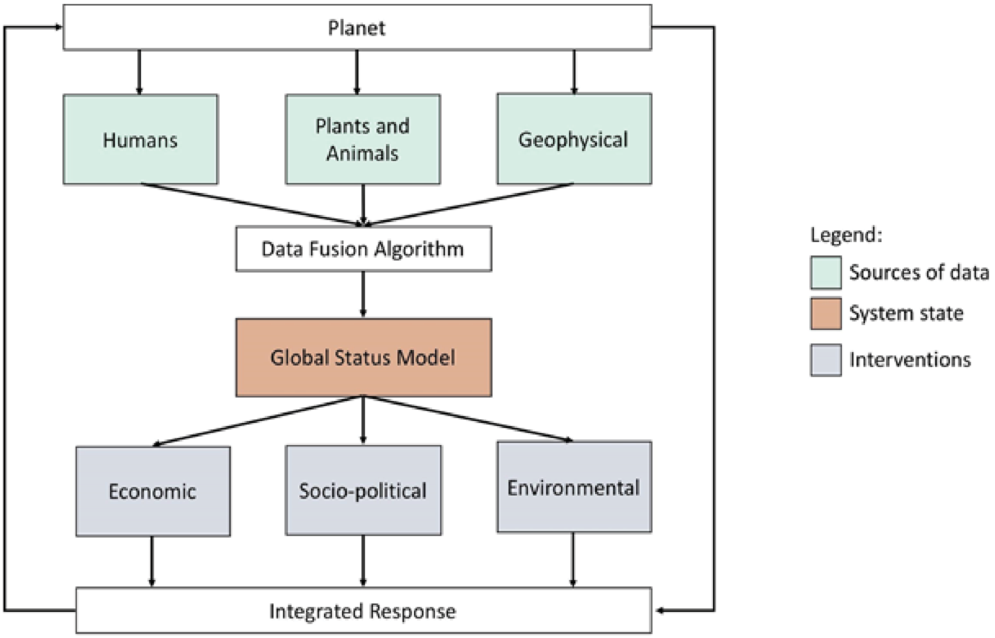

Figure 3: Framework for the Global Status Model.

AIR FORCE APPROACH

In order to overcome the challenges described above, we suggest a holistic approach in which scientists, engineers, and social scientists come together and develop a timeline with a granular approach. We envision these three thematic programs to run in parallel with close cross-program communication in order to adapt and correct the path of each program in response to the global findings. We foresee this effort to last ten years from 2020-2030 in 2 phases. Each phase will cost $20 million per year. Phase 1 would include ten multidisciplinary and multi university teams and Phase 2 will down select to the top five performing teams doubling their yearly budget.

TIMELINE

5-10 years

SURVEY RISK

	Low	Medium	High
Cost	3	5	8
Technical	1	2	13
Deployment	2	5	9
Defendable	7	4	5
Competitive	6	6	4

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3.7.3 Biomimetic Hyperacuity Sensor for Monitoring Structures

CONTRIBUTORS

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OVERVIEW

A wide variety of civil and mechanical systems such as bridges, dams, historical buildings, communication towers, cooling towers, and chimneys require monitoring continuously over a long period of time [4]. These systems are monitored for load effects, deflection, stress, strain, bending components and vibration [5]. There is a wide variety of sensors currently available to monitor these parameters, including strain gages, deflection gages, accelerometers, interferometers, tiltmeters, inclinometers, and plumbline telecoordinometers. Although these sensors provide the required data, most require physical contact with the monitored structure or are quite complex. We propose an optically based, non-contact sensor capable of measuring many of the desired parameters such as object horizontal and vertical movement, rotation, and vibration from a nearby but remote location. This sensor is based on the compound vision system of the common housefly. Other vision-based technologies exist.

DETAILED DESCRIPTION AND ACTIONS

A modular, analog-based, smart sensor with demonstrated hyperacuity inspired by the compound eye of the common housefly, Musca domestica has been developed. We propose to demonstrate the feasibility of using a cooperative network of these sensors to acquire information about civil and mechanical systems (e.g., bridges, dams, historical edifices, communication antenna, etc.) over a sustained monitoring period. This information is vital for alerting responsible parties to safety, maintenance, or repair issues for these systems.

The sensor, coupled with analog preprocessing hardware, extracts edge information quickly and in parallel. The design is motivated by the parallel nature of the fly's vision system and its demonstrated hyperacuity or precision of visual localization beyond the conventional resolution limit. The sensor is optical, non-contact, easily aligned and installed, modular and can be easily adapted in scale or dimension for a wide variety of sensing applications. We have modeled the capability of the sensor to provide accurate data under a wide variety of lighting and noise conditions and have developed the capability to easily manufacture the sensor housing, optics, and electronics using standard, low cost procedures [1-4]. This allows for the rapid prototyping of sensors for research purposes.

- Develop a robust, modular, “plug and play” sensor to be used for civil and mechanical systems long term monitoring inspired by the visual system of the common housefly.

- Develop sensor information processing algorithms to precisely localize the position of a spot, line, or bar stimulus in the sensor field of view. Render the information processing algorithms in low cost, fast, analog hardware.
- Demonstrate the sensor's capability to remotely monitor the movement, deflection, etc. of civil and mechanical structures under various lighting and weather conditions.
- Develop a cooperative network of sensors to monitor a structure using commercially available off the shelf network technology (e.g., Zigbee IEEE 802.15.4) such that unsafe or undesirable movements or deflections can be easily detected.

AIR FORCE APPROACH

Fund research team to develop and test prototype sensors.

TIMELINE

3-5 years

SURVEY RISK

	Low	Medium	High
Cost	2	9	3
Technical	4	6	4
Deployment	6	5	2
Defendable	3	9	2
Competitive	4	7	3

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3.7.4 Compact Modular Pulsed Power Development for Flexible Application Support

CONTRIBUTORS

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OVERVIEW

Many applications in defense (e.g., HPM, plasma radiation source development, high-power/high-energy lasers, pulsed electric space propulsion, etc.) require pulsed-power drivers. Advancing pulsed-power systems from the present state of the art will likely involve precise control over pulse shape, flexible driver impedance, flexible power output, lightweight systems, system modularity, system compactness, system portability, and knowledge of the fundamental plasma physics occurring within vacuum cavities and near surfaces.

DETAILED DESCRIPTION AND ACTIONS

This research could help the development of new design procedures for flexible pulsed-power systems. One example is the use of small, highly parallelized and serialized systems that can be rapidly assembled and reconfigured to service various applications and experimental platforms in a “plug-and-play” fashion. Small power units (consisting of small and fast capacitors and switches) make up the fundamental building blocks in these systems. These small units are sometimes called “bricks”. These bricks can be triggered in various timing sequences, and the brick output pulses can be combined to generate both fast and custom pulse shapes. The brick outputs can be thought of as basis functions that are combined together to generate a high-amplitude power pulse and/or a custom pulse shape. Dedicated studies are needed to understand the advantages and limitations of this approach. Sandia National Laboratories and the Institute for High Current Electronics in Tomsk, Russia, have embarked on research into brick-driven, pulse-shaped systems for high-pressure material properties applications [1-5], but these efforts could be expanded to generate custom pulse shapes for driving high power microwave sources, pulsed electric space propulsion systems, etc.

Additionally, technology development to further increase brick efficiency (i.e., making ever-smaller capacitors with ever-increasing charge storage) is needed. Advanced manufacturing and materials research for advanced capacitor development is needed. The development of high-power solid-state switches could also be useful (most high-power switching is still done with gas-filled spark-gap switches). Research into component lifetimes is also needed, especially when rep-rating is required for high-power pulsed systems

A significant drawback for high power electric or plasma space propulsion is the scaling of high voltage and pulsed power supply mass as thruster power increases. There have been significant advances in recent years in fast, high voltage switching (e.g. photoconductive switches) and in fast, compact capacitor development (e.g. capacitors employing nano-enhanced dielectrics) that could significantly reduce the mass of pulsed power supplies for high power space propulsion. An effort to survey the current state of pulsed power supply design with an aim to significantly decrease stored energy per kilogram could help to improve the viability of high-power space propulsion, and could have a positive impact on other application areas for pulsed power.

There is significant energy storage capability in ferroelectric/piezoelectric materials that should be studied comprehensively for compact production of pulsed power for applications ranging from high power microwaves to plasma sources. From piezoelectric transformers with extreme transformer ratios (10,000:1) and ferroelectric based nonlinear transmission lines to ferroelectric nanoparticles loaded into high energy density capacitor dielectrics, there are continuing efforts to exploit these materials for pulsed power. A concerted effort to develop these materials in their various embodiments could lead to significant improvements in high-energy density, compact pulsed power systems. A few potential ideas are listed below.

The following actions support this research area:

- Mechanically resonating high voltage pulse sources: One means of producing very compact high voltage pulsed power in one shot applications is inducing very large rates of strain in piezoelectric materials. These large strain rates can be produced by crushing under anvils or by means of high explosives. Piezoelectric materials can be used to store additional energy in resonant devices such as piezoelectric transformers. The energy stored in a resonating piezoelectric bar can be significantly larger than the electrical energy available to impulsive strain, since impulsive strains are inherently limited to thin layers and shock waves. It may be possible to significantly increase the energy available to convert into pulsed electrical energy by resonantly vibrating a piezoelectric material, and then rapidly stopping the vibration to convert that mechanical motion into electrical energy.
- Modular, self-charging pulse forming systems: Flexible, compact and power efficient pulsed power systems could find application in a variety of areas including high power microwaves, power beaming, remote radiography, and other areas. Highly compact pulsed power supplies in a brick format (as mentioned above) could be designed to incorporate high voltage charging systems, using piezoelectric transformer driven Cockcroft-Walton charging circuits. In this way, a low voltage, AC signal could be supplied to a modular circuit capable of HV, high current output. These modules could easily be voltage isolated from one another via high voltage isolation transformers, enabling floating configurations, and other flexible architectures.

AIR FORCE APPROACH

Encourage the Air Force Research Laboratory and Sandia National labs (both being national assets and resources) to engage with each other for compact, modular, pulsed power development activities (both labs are on Kirtland Air Force Base). Both labs could engage the academic community for R&D efforts with mutual benefit.

TIMELINE

10-15 Years

SURVEY RISK

	Low	Medium	High
Cost	1	13	1
Technical	3	8	4
Deployment	5	10	0
Defendable	6	9	0
Competitive	4	8	3

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3.7.5 Translation Process to Continue Development of Fundamental Research Results to Higher Technology Readiness Level via AFRL

CONTRIBUTORS

John Verboncoeur

OVERVIEW

While tremendous innovation exists in basic research supported by the Air Force, much of it is never translated. Obstacles to translation include:

- Lack of translation expertise among basic researchers
- Lack of funding pathways
- Lack of rewards for translation, particularly for university researchers.

As the rate at which threats are created and evolve continues to grow, the rate of translation of innovations must keep pace.

DETAILED DESCRIPTIONS AND ACTIONS

The present scheme for translating fundamental research innovations includes paths such as the SBIR/STTR. This is often inadequate for innovations that are sufficiently far from market or lack barriers to competition, rendering them less fiscally attractive. The current system also treats the translation activity as an entirely new proposal, with all of the inherent costs for the proposer and funding agency, and ultimately disconnecting the translation activity from the fundamental research by treating it as a new start.

We propose creating a set of standard translation funding mechanisms to ensure the translation process pairs university researchers with government labs (AFRLs). These mechanisms might be a set of supplement grants/contracts that follow a successful fundamental research project. These mechanisms may require that the fundamental research and AFRL teams need provide only a relatively light proposal that describes the justification and mission-case for the translation. Supplemental funding for this type of project could serve as a talent-development activity and might include using an IPA mechanism or an Air Force-funded postdoctoral fellowship as part of the translation.

Having one or more standard contracting vehicles in place and a fast pathway for stating the project, can be critical to keeping the team intact. For university researchers, even a semester break between the fundamental research and the translation can result in loss of key team members and loss of momentum. The ability to create the translation grant/contract as a supplemental to an existing project before the project end date can be crucial in ensuring continuity.

AIR FORCE APPROACH

Provide your thoughts on the approach the Air Force should take to develop this area and implement the technology. Include an estimate of resources needed, including potential government lab and/or industry capabilities needed for the R&D effort.

In order to execute this idea, the following actions could be taken by the Air Force:

- Develop a standard grant/contract vehicle for a translation supplement, including terms and conditions that flow down from the grant/contract being supplemented (this enables rapid approval without additional contract negotiations, reducing cost and ensuring continuity of support). Two years support would be a reasonable target. Teaming with an AFRL or private company should be required. The Air Force might request SBIR/STTR direct Phase II funding support for small company teams.
- Enable program managers to invite successful project PIs to submit the supplemental request at least six months prior to the project end date in order to facilitate personnel continuity planning. The assumption here is that the Air Force decision can be made rapidly - less than two months would be ideal.
- Some development for PIs and partners might be helpful.
- While this process should take research from a TRL2-3 level to perhaps 5-6, having a pathway from TRL5-6 to program of record might be interesting as well, such as an Air Force VC-like operation to make matches between AFRL/Industry efforts and major prime contractors.

TIMELINE

3-5 years

SURVEY RISK

Not Available

4.0 Recommendations for Science & Technology Implementation & University Research Support

Air Force sponsored university research through the Air Force Research Laboratories (AFRL) and the Air Force Office of Scientific Research (AFOSR) is intended to support the Air Force missions and themes which then narrowly defines the research areas compared to other non-DoD entities such as the National Science Foundation (NSF). The NSF supports a wide range of research over many topic areas making that research funding available to a very wide range of small to large research universities as well as a wide range of departments. By contrast, the Air Force research areas of interest often result in funding to engineering and specific physical science (math, physics) departments. In addition, relevant experimental research often requires substantial physical infrastructure including expensive instrumentation and fabrication capabilities. Hence, smaller research programs can have difficulty competing in these research areas. Collaborative programs such as Multidisciplinary University Research Initiatives (MURIs) are encouraged as a method of providing opportunities to smaller programs and increasing research diversity. Also, educational programs supporting undergraduate and graduate students in Air Force related research could also increase diversity in the program.

4.1 Science and Technology Implementation

A common concern regarding university-led research is the implementation of the basic research in Air Force related applications. Depending upon the technology readiness level (TRL), research capabilities may end up only in reports and publications. A method of recognizing important research results and advancing the TRL of that research is needed. We propose that the Air Force consider working with university researchers when an area of technological interest develops, and implementing a method for advancing this research through the Air Force Research Labs (AFRL). As a university research program advances, Air Force representatives could actively identify successful research projects and encourage follow-on collaborative research with AFRL. Then the university researchers could transfer the research and relevant “art” to AFRL researchers through a 1- 2 year program. Similar to the manner in which corporate R&D is transferred to manufacturing, university research often requires more in-depth transfer of the ideas and concepts so that new researchers can further develop the technology. In this effort, the AFRL would increase the TDL from universities. This discussion is also provided under **Topic 3.7.5** Translation Process to Continue Development of Fundamental Research Results to Higher TRL via AFRL.

4.2 University Research Support - Grants Process

University research efforts can be complicated and delayed by the timing of grant funding and the availability of researchers, particularly graduate students. In many cases, the start of grants is dependent upon grant negotiations, and when the contracting agency is ready, the grant must start. Unlike industry, universities work on academic year (AY) cycles. Often the researchers do not yet have students ready to begin research because they cannot commit to the students until funds are available. When grants start well after the beginning of an AY, researchers may have no students ready to work on the project. In addition, students already in the program may be funded by other research, and it may be impractical to move students to new projects. Therefore, time is often lost on these projects (1-5 months) as faculty recruit students or start new semesters with their students. Such delays are often detrimental to the research. While university researchers are sympathetic to the complex issues of contract deployment and the need to work through multiple research grants by contract staff, allowing some flexibility in grant start times, when needed, would improve research efforts and effectiveness. Specifically, start times corresponding to the beginning of the fall semester (nominally mid-Aug) are probably most efficient, followed by early spring.

4.3 Future Research Workshop Efforts

During the workshop for this project, participants were quite universal in their positive feedback regarding the opportunity to get together and meet with other university researchers for a pure “brainstorming” effort. A survey of participants was conducted electronically, and they were asked questions about their views on the workshop. They could rank the question from 0 to 100% or provide Yes/No answers to the questions. The results are presented in Table 2. As can be seen, all participants who answered the survey thought the workshop generated useful connection and new ideas. 87% of participants thought the workshop was valuable and would recommend it to colleagues.

Table 2: Workshop survey results

Survey Question	**Average**	**Std. Dev.**	**High**	**Low**
How likely would you be to recommend this workshop, or a workshop like this, to a colleague?	87.5%	14.2%	100%	48%
Do you feel the workshop was valuable?	87.8%	12.4%	100%	57%
Was the workshop helpful in creating connections for collaboration with colleagues? (Yes/No)	100%	0%	100%	100%
Did the workshop generate any new ideas for your future research? (Yes/No)	100%	0%	100%	100%

In particular, participants enjoyed talking with researchers from a number of different research areas. This opportunity is not common for most university researchers as they usually attend conferences or review meetings with people of similar research interests. We recommend that the Air Force consider similar periodic university research workshop events in the future. Participants could be chosen from a list of proposers, not just awardees, to AFOSR and AFRL programs. Multiple research programs could combine proposers to generate the list, and then AFOSR and/or a university could host a 2-day topical workshop in which 30-40 university researchers are invited to attend and discuss their research interests and brainstorm ideas They could then present these ideas to the relevant program divisions for consideration in future research calls. Some attendees commented that the approach of "university only" attendees also makes the workshop more dynamic as participants were not unintentionally biased to generate ideas for a specific program officer. Such workshops could be rotated through different groups and proposers so that the opportunity is spread among many different researchers, universities, and topics over a 5-8 year time frame. This approach might also enable collaborations beween smaller research programs and more established research programs.

5.0 Conclusions

A workshop was held in Boise, ID from May 30-June1, 2018. A group of 33 university researchers from 20 different universities met and discussed ideas for research topics for the Air Force in the year 2030. The workshop allowed participants to collaborate in a number of areas and develop research ideas individually or in groups. The participants captured their ideas electronically using a Digital Workspace template. Facilitators supported the process. At the end of the workshop, participants presented their ideas to the group, and feedback and suggestions were provided. A workshop risk survey was sent to the participants in which they could evaluate the risk of the research idea under 5 categories: cost, technical, deployment, defendable, and competitive. These responses were used to evaluate the risks of each topic. After the research topics were captured, the workshop organizers combined the topics into this report. Participants were then invited to contribute more details to their areas or to organize their ideas based on the finalized format. In addition to describing the technical areas, participants were asked to recommend the approach the Air Force should take in pursuing the research topics. Finally, the organizers summarized these results for this report. Participants generated 42 research ideas over a wide range of topics with most groups having 3-4 collaborators. Finally, recommendations for the Air Force support of university research were provided including Science and Technology Implementation, University Research—Grants Process, and Future Research Workshop Efforts. The overwhelming feedback was that such a workshop was very valuable to participants.

Acknowledgements

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Appendices

Appendix A. Online Workshop Resources

TRACKING AND ENGAGING THE FUTURE: US AIR FORCE RESEARCH IN 2030

Collaborative Research Innovation Workshop

May 30 through June 1 – Boise, Idaho

We're inviting university researchers from across the West to help us define a list of visionary research topics that the United States Air Force should be investigating by the year 2030. Read the call from the US Air Force for background detail.

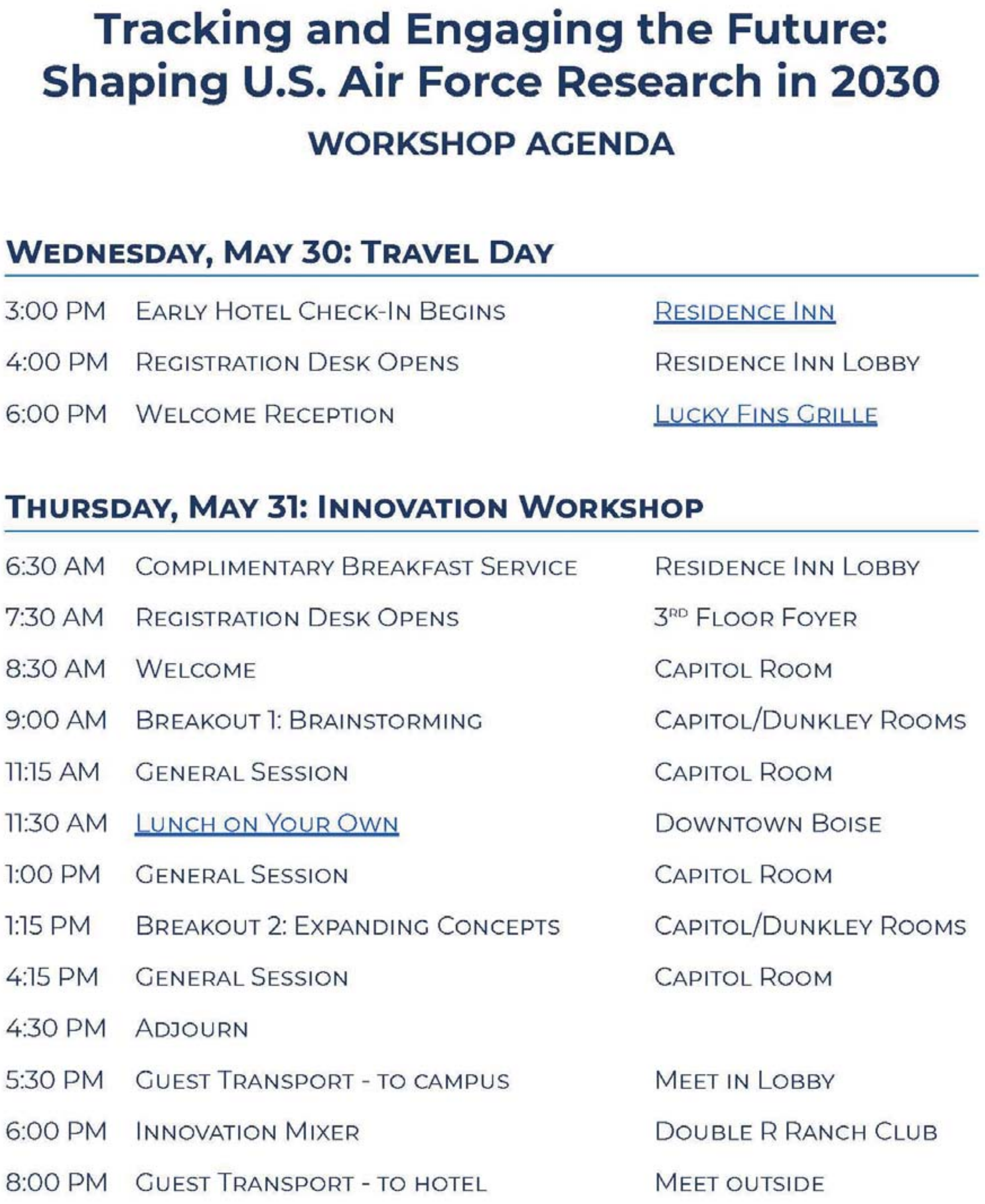
HELP SHAPE THE DIRECTION OF FUTURE RESEARCH

Our focus is on the key themes named by the US Air Force, which include their foundational mission, core functions, domain focus, a focus on airmen, and a call for innovation.

Preliminary focus areas include:

- advanced manufacturing
- advanced material systems and modeling
- application computing
- bio-integrated electronics
- communications, including covert communications in restrictive environments
- core computational technology
- cyber-security
- new electronic devices and approaches for harsh environments
- passive and active stealth
- resilience to electronic warfare attack and directed energy
- space system defenses for cyber, electronic, and kinetic threats
- space vehicle systems
- tracking technology (e.g. radar sources, distributed sensing)
- wireless power transmission (e.g. laser power beaming for cubesats, drones)

Figure A1. Science and Technology 2030 public website.



Tracking and Engaging the Future: Shaping U.S. Air Force Research in 2030

WORKSHOP AGENDA

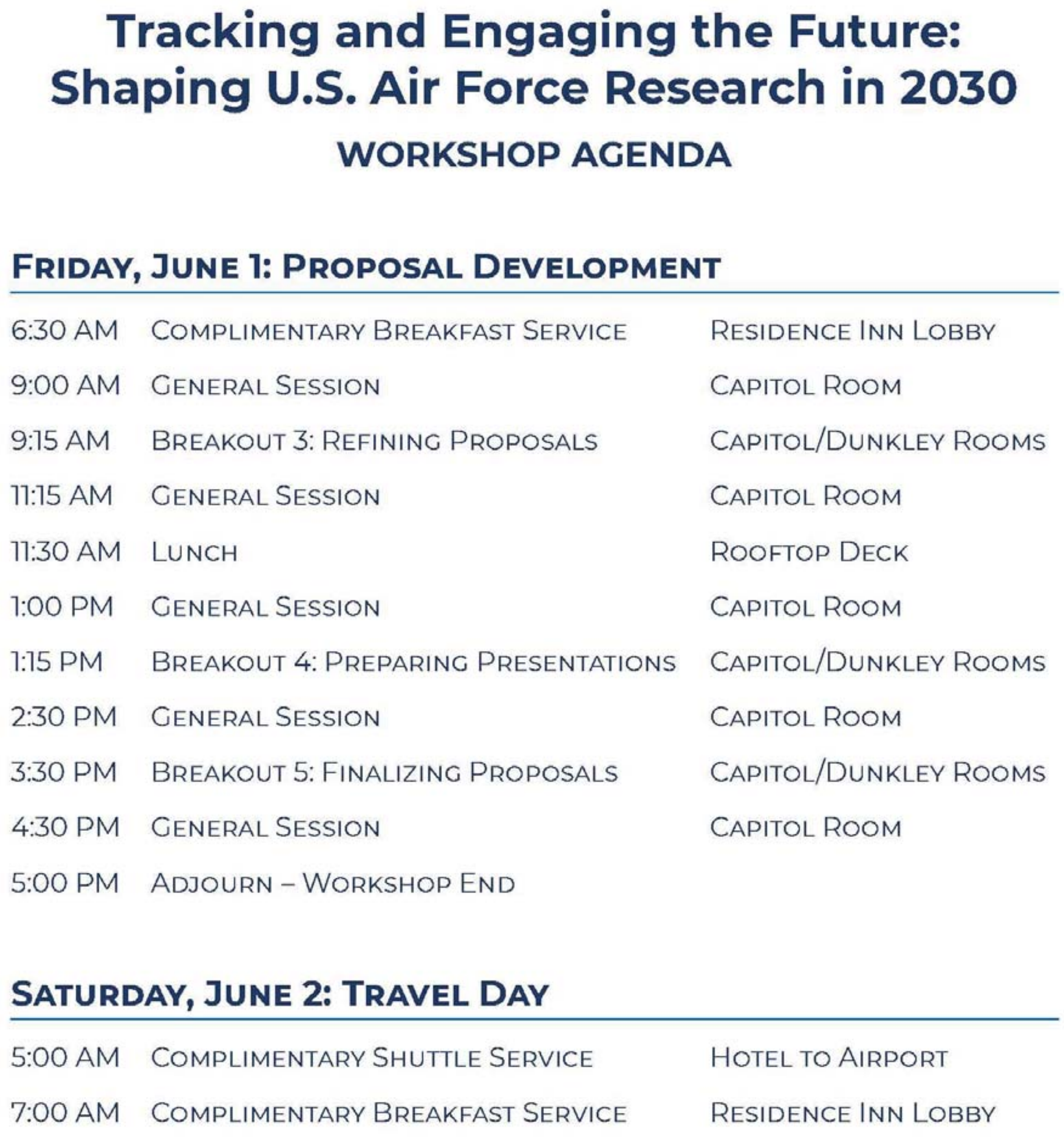
Wednesday, May 30: Travel Day

3:00 PM	Early Hotel Check-In Begins	Residence Inn
4:00 PM	Registration Desk Opens	Residence Inn Lobby
6:00 PM	Welcome Reception	Lucky Fins Grille

Thursday, May 31: Innovation Workshop

6:30 AM	Complimentary Breakfast Service	Residence Inn Lobby
7:30 AM	Registration Desk Opens	3rd Floor Foyer
8:30 AM	Welcome	Capitol Room
9:00 AM	Breakout 1: Brainstorming	Capitol/Dunkley Rooms
11:15 AM	General Session	Capitol Room
11:30 AM	Lunch on Your Own	Downtown Boise
1:00 PM	General Session	Capitol Room
1:15 PM	Breakout 2: Expanding Concepts	Capitol/Dunkley Rooms
4:15 PM	General Session	Capitol Room
4:30 PM	Adjourn	
5:30 PM	Guest Transport - to campus	Meet in Lobby
6:00 PM	Innovation Mixer	Double R Ranch Club
8:00 PM	Guest Transport - to hotel	Meet outside

Figure A2. Science and Technology 2030 Agenda, page 1.



Tracking and Engaging the Future: Shaping U.S. Air Force Research in 2030

WORKSHOP AGENDA

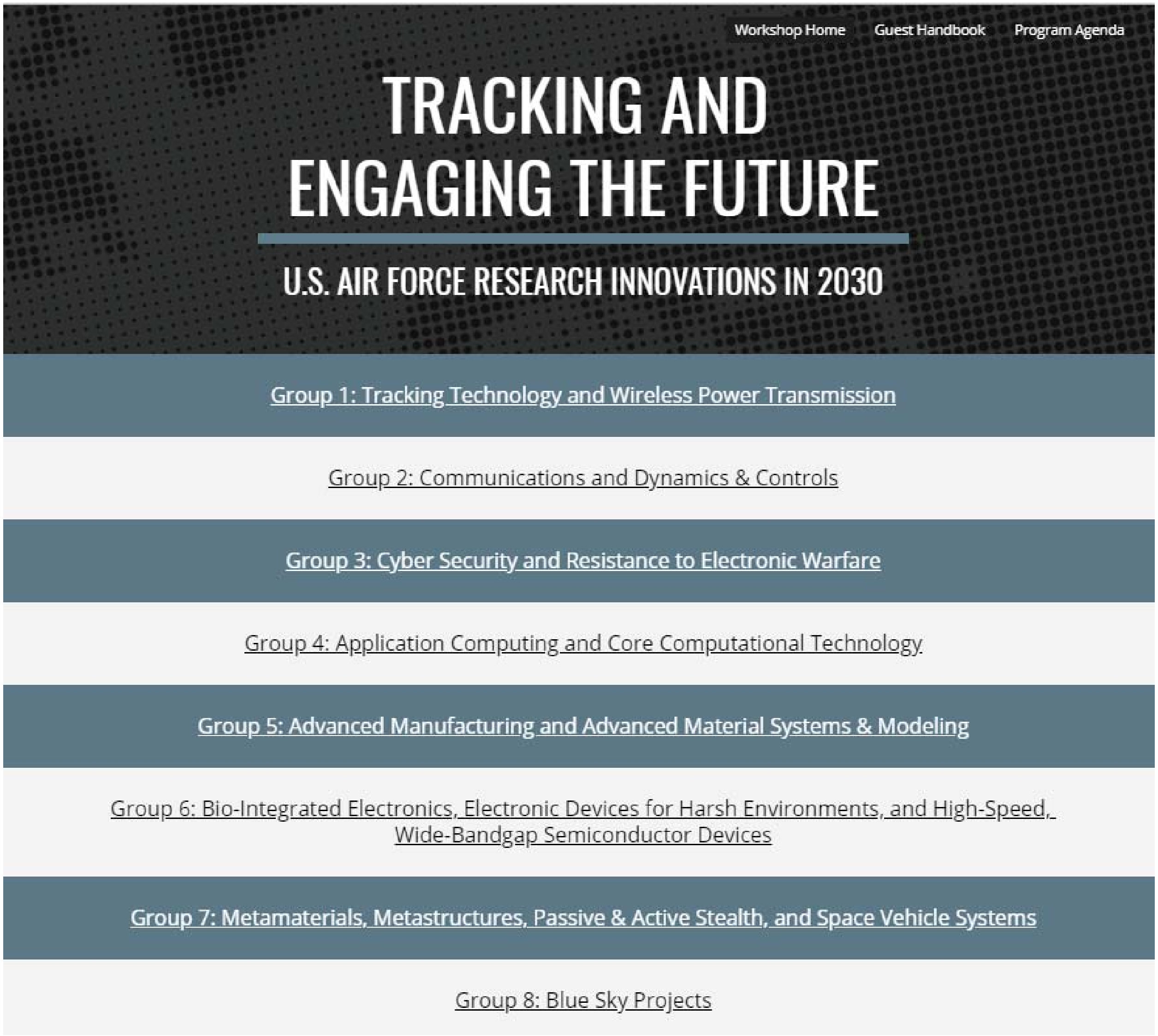
Friday, June 1: Proposal Development

6:30 AM	Complimentary Breakfast Service	Residence Inn Lobby
9:00 AM	General Session	Capitol Room
9:15 AM	Breakout 3: Refining Proposals	Capitol/Dunkley Rooms
11:15 AM	General Session	Capitol Room
11:30 AM	Lunch	Rooftop Deck
1:00 PM	General Session	Capitol Room
1:15 PM	Breakout 4: Preparing Presentations	Capitol/Dunkley Rooms
2:30 PM	General Session	Capitol Room
3:30 PM	Breakout 5: Finalizing Proposals	Capitol/Dunkley Rooms
4:30 PM	General Session	Capitol Room
5:00 PM	Adjourn – Workshop End	

Saturday, June 2: Travel Day

5:00 AM	Complimentary Shuttle Service	Hotel to Airport
7:00 AM	Complimentary Breakfast Service	Residence Inn Lobby

Figure A3. Science and Technology 2030 Agenda, page 2.



TRACKING AND ENGAGING THE FUTURE

U.S. AIR FORCE RESEARCH INNOVATIONS IN 2030

Group 1: Tracking Technology and Wireless Power Transmission

Group 2: Communications and Dynamics & Controls

Group 3: Cyber Security and Resistance to Electronic Warfare

Group 4: Application Computing and Core Computational Technology

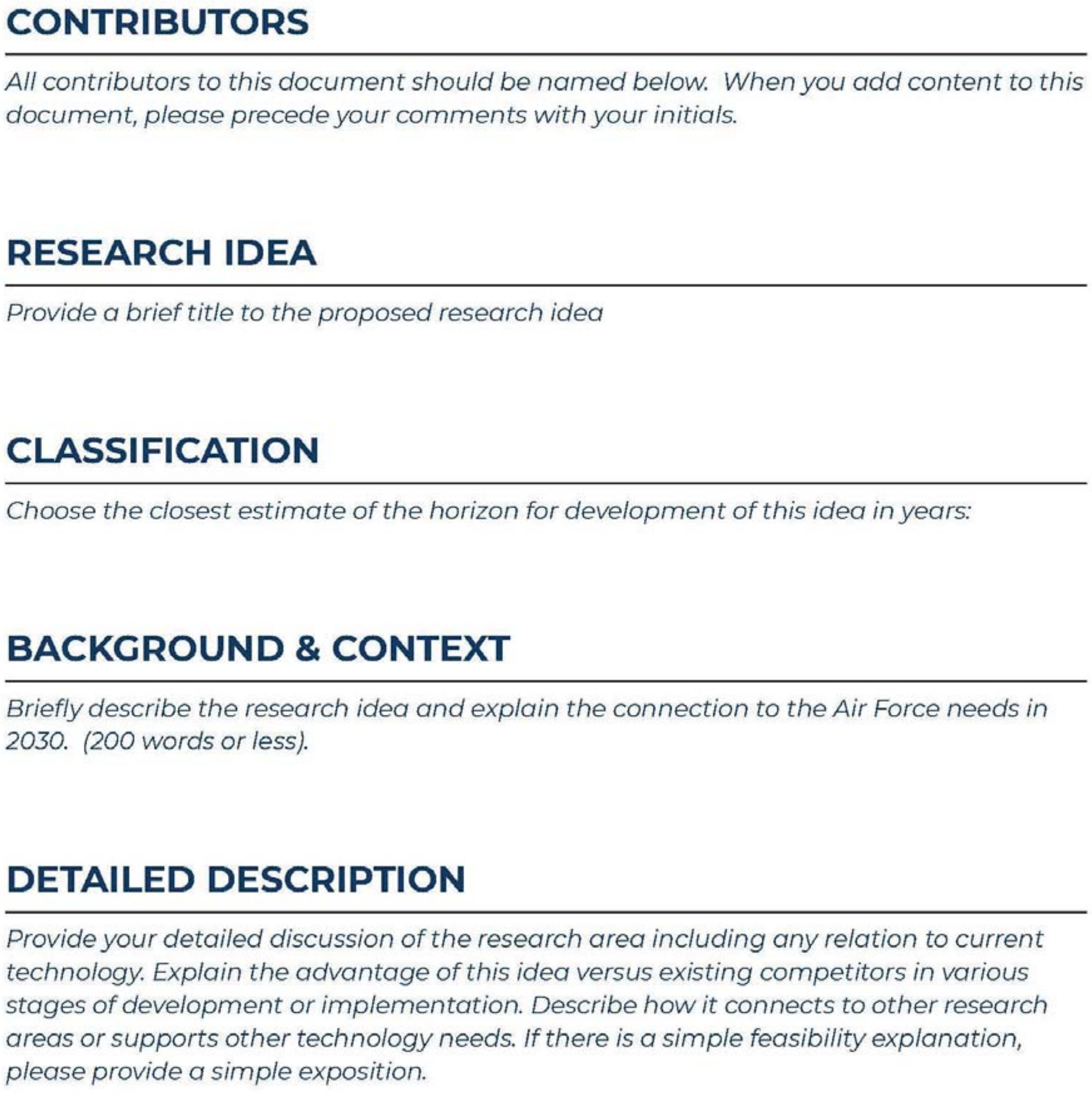
Group 5: Advanced Manufacturing and Advanced Material Systems & Modeling

Group 6: Bio-Integrated Electronics, Electronic Devices for Harsh Environments, and High-Speed, Wide-Bandgap Semiconductor Devices

Group 7: Metamaterials, Metastructures, Passive & Active Stealth, and Space Vehicle Systems

Group 8: Blue Sky Projects

Figure A4. Science and Technology 2030 digital workspace.



CONTRIBUTORS

All contributors to this document should be named below. When you add content to this document, please precede your comments with your initials.

RESEARCH IDEA

Provide a brief title to the proposed research idea

CLASSIFICATION

Choose the closest estimate of the horizon for development of this idea in years:

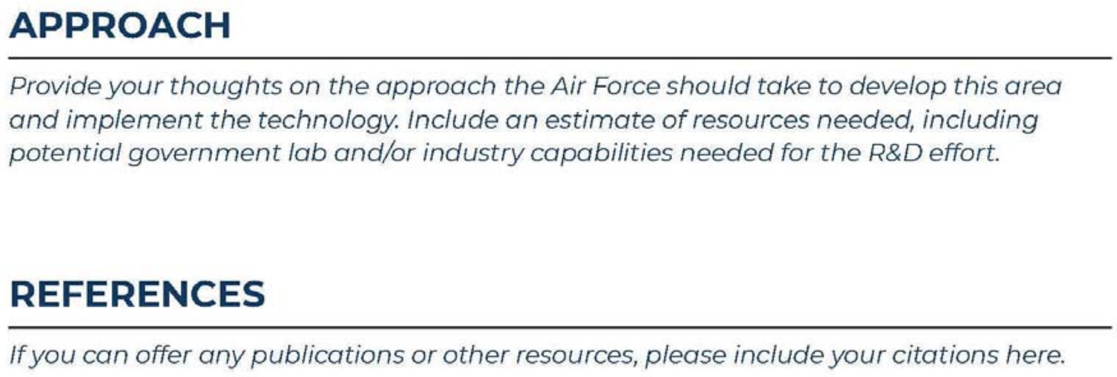
BACKGROUND & CONTEXT

Briefly describe the research idea and explain the connection to the Air Force needs in 2030. (200 words or less).

DETAILED DESCRIPTION

Provide your detailed discussion of the research area including any relation to current technology. Explain the advantage of this idea versus existing competitors in various stages of development or implementation. Describe how it connects to other research areas or supports other technology needs. If there is a simple feasibility explanation, please provide a simple exposition.

Figure A5. Science and Technology 2030 research idea template, page 1.



APPROACH

Provide your thoughts on the approach the Air Force should take to develop this area and implement the technology. Include an estimate of resources needed, including potential government lab and/or industry capabilities needed for the R&D effort.

REFERENCES

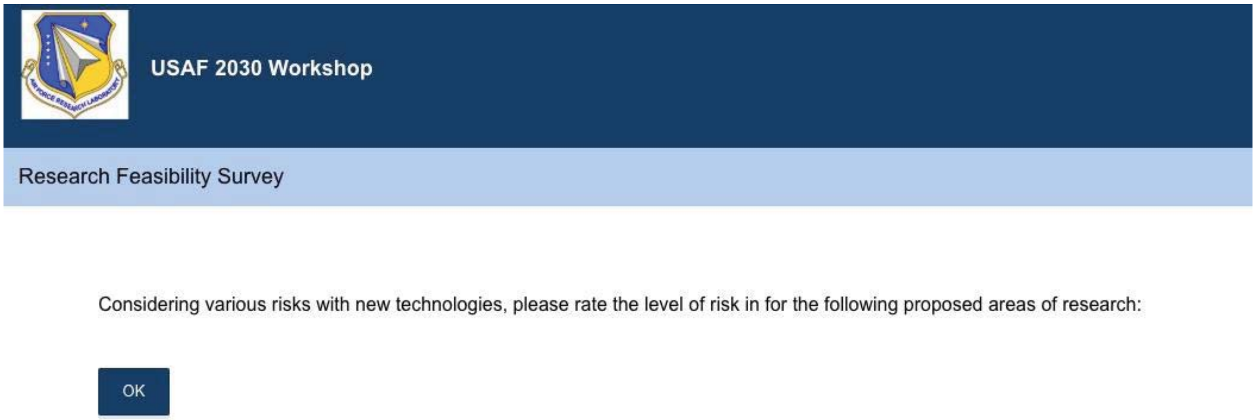
If you can offer any publications or other resources, please include your citations here.

Figure A6. Science and Technology 2030 research idea template, page 2.

Appendix B. Risk Analysis of Research Areas

Table B1. Risk categories and their descriptions.

Risks	Description
Cost	What is it likely to cost to complete the research phase of this technology? How many different parties are required to complete the work? What sort of equipment and infrastructure will be required? Does it require any materials from politically unstable or challenging countries? Yes=high, No=low risk
Technical	Consider whether or not this technology can be successfully developed. Does it require advancing just a few technologies, or multiple scientific breakthroughs? Is it likely to take a very long time to complete? Yes=high, No=low risk
Deployment	Will this be to transition from research to development? Will it require significantly new infrastructure, or at significantly larger scales than are expected to be available? What about the workforce? Yes=high, No=low risk
Defendable	Will it be difficult to protect this technology? Is it likely others could neutralize it, or render it ineffective? Consider whether or not other parties will be able to acquire it without authorization, or will be able to hack it. Yes=high, No=low risk
Competitive	Is it likely other countries or groups could develop this technology before the US? Could they then threaten the ability of the US to use it as intended? Yes=high, No=low risk

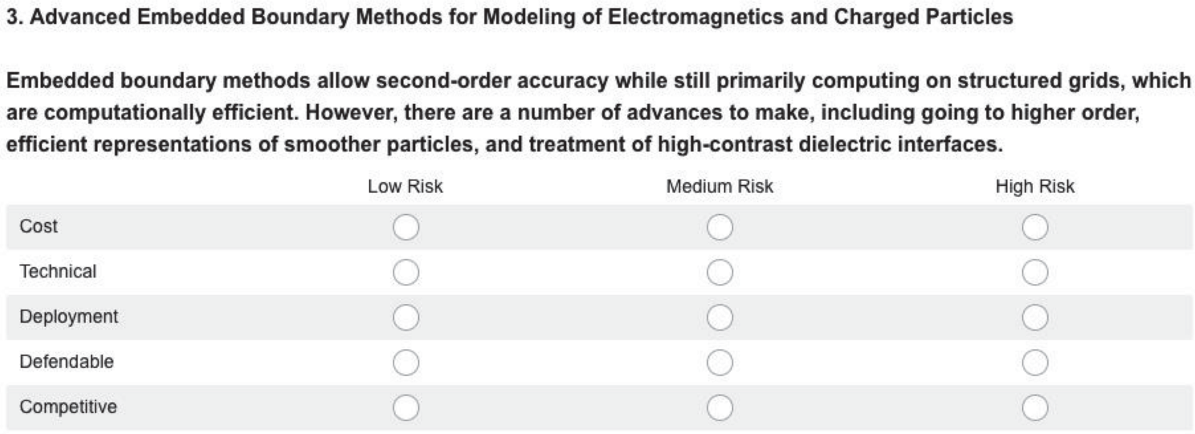


USAF 2030 Workshop

Research Feasibility Survey

Considering various risks with new technologies, please rate the level of risk in for the following proposed areas of research:

Figure B1.Online Workshop Risk Survey opening window. Clicking "OK" opened a series of windows for each Research Area, an example of which is in Figure A8.

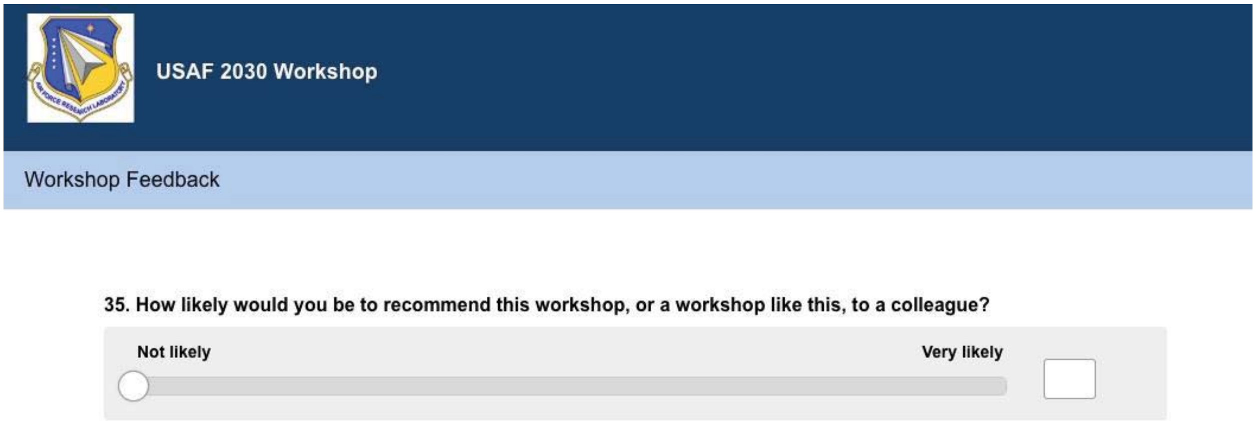


3. Advanced Embedded Boundary Methods for Modeling of Electromagnetics and Charged Particles

Embedded boundary methods allow second-order accuracy while still primarily computing on structured grids, which are computationally efficient. However, there are a number of advances to make, including going to higher order, efficient representations of smoother particles, and treatment of high-contrast dielectric interfaces.

	Low Risk	Medium Risk	High Risk
Cost	○	○	○
Technical	○	○	○
Deployment	○	○	○
Defendable	○	○	○
Competitive	○	○	○

Figure B2. Example online Workshop Risk Survey Question. Participants used the risk category descriptions in Table 1 to evaluate each Research Area.



USAF 2030 Workshop

Workshop Feedback

35. How likely would you be to recommend this workshop, or a workshop like this, to a colleague?

Figure B3.Example online Workshop Quality Survey Question. Participants use the slider to indicate their response from 0-100.