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Visiting Faculty Research Program

Summer Faculty Fellowship Program

Research Fellowship Program

2020 Research Topics
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2020 Research Topics
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Autonomy, C2, and Decision Support

Multi-Domain Mission Assurance

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In an effort to support the Air Force's mission to develop Adaptive Domain Control for increasingly integrated Mission Systems, we are interested in furthering the identification of problems, and development of solutions, in increasing Full-Spectrum Mission Assurance capabilities across joint air, space, and cyberspace operations. Modern multi-domain mission planning and execution integrates tightly with cyber and information infrastructure. To effectively direct and optimize complex operations, mission participants need timely and reliable decision support and an understanding of mission impacts that are represented and justified according to their own domain and mission context. We are interested in understanding, planning, and developing solutions for Mission Assurance that supports operations requiring Mission Context across multiple domains, and spans both Enterprise and constrained environments (processing, data, and bandwidth). The following topic areas are of interest as we seek to provide solutions that are domain adaptive, mission adaptive, and provide rich, critical situational awareness provisioning to Mission Commanders, Operators, and technologies that support autonomous Mission Assurance.

- Summary, Representation, and Translation of Multi-Domain Metrics of Mission Health - Expansive Mission Assurance requires adequate mechanisms to describe, characterize, and meaningfully translate mission success criteria, mission prioritization, information requirements, and operational dependencies from one domain to another in order to react to events, deliver them appropriately to mission participants, and thereby increase the agility, responsiveness, and resiliency of ongoing missions.

- Multi-Domain Command and Control information Optimization - Currently, information can be disseminated and retrieved by mission participants through various means. Increasingly, mission participants will face choices of what, how, and where information will reach them or be pushed back to the Enterprise. Deciding between C2 alternatives in critical situations requires increased autonomy, deconfliction, qualitative C2 mission
requirements, and policy differentials. We are seeking representations, services, configuration management, and policy approaches towards solving multi-domain multi-C2 operations.

- **Complex Event Processing for Multi-Domain Missions** - The ability to better support future missions will require increased responsiveness to cyber, information, and multi-domain mission dynamics. We are seeking mission assurance solutions that process information event logs, kinetic operation event data, and cyber situational awareness in order to take data-driven approaches to validating threats across the full-spectrum of mission awareness, and justify decisions for posturing, resource and information management, and operational adjustments for mission assurance.

- **Machine Learning for Mission Support** - Decreasing the cost and time resource burdens for mission supporting technologies is critical to supporting transitioning to relevant domains and decreasing solution rigidity. To do this requires advanced approaches to zero shot learning in attempts to understand mission processes, algorithms to align active missions with disparate archival and streaming information resources, analysis of Mission SA to determine cross-domain applicability, and autonomous recognition of mission essential functions and mission relevant events. Additionally, ontologies and semantic algorithms that can provide mission context, critical mission analytics relationships, mission assurance provenance and response justifications, as well as mission authority de-confliction for intra-mission processes and role-based operational decisions, are topics that would support advanced capabilities for advanced mission monitoring, awareness, and assurance decisions.

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**Learning an Algorithm with Provable Guarantees**

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The purpose of this research is to address some theoretical issues related to learning algorithms with provable guarantees for problem-solving and decision-making. In practice, machine learning techniques are often optimized over families of parameterized algorithms. The parameters are tuned based on "typical" domain-specific problem instances. However, the selected algorithm seldom yields a performance guarantee (based on some metric). We wish to explore the notion of casting the algorithm selection problem as a learning problem. Our goal is to reason appropriately, develop new paradigms, move theory towards the state-of-the-art, and to solve computationally challenging problems that frequently arise in tactical environments.

Some research areas of interest include computational complexity, algorithms, artificial intelligence, machine learning, combinatorics and discrete mathematics, information theory, and statistical learning theory.
Persistent Sensor Coverage for Swarms of UAVs

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The deployment of many airborne wireless sensors is being made easier due to technological advances in networking, smaller flight systems, and miniaturization of electromechanical systems. Mobile wireless sensors can be utilized to provide remote, persistent surveillance coverage over regions of interest, where the quality is measured as the sum of coverage and resolution of surveillance that the network can provide. The purpose of this research is to provide efficient allocation of mobile wireless sensors across a region to maintain continuous coverage under constraints of flight speed and platform endurance. We seek methods for the structuring constraint optimization problems to develop insightful solutions that will maximize persistent coverage and provide analytical bounds on performance for a variety of platform configurations.

Characterizing Swarm Systems Capabilities

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Large collectives of coordinating robotic systems require new methods for characterizing expected behavior and communicating that capability to human users. Interactions between platform capability, hardware configuration, and software algorithms yield a mean and variance of expected performance for a given mission. Characterizing these interactions and resulting performance requires new analytical methods that can scale to hundreds or thousands of entities and can map a manifold of performance to specific mission objectives. We seek new methods for characterizing expected swarm performance, with tools that can help a human operator to explore the trade-off space of number of platforms, configuration, and software algorithms. Areas of interest include Operations Research, Statistical Analysis, Multi-Robot Task Assignment, Modeling and Simulation, and Dynamical Systems.
Machine Learning with Structured Knowledge

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State of the art supervised machine learning models have yielded impressive results on a wide variety of problems. These models are commonly learned via training algorithms that rely exclusively on training data, i.e., example inputs and outputs from some domain of interest. Yet for many domains, additional knowledge has been collected or constructed to provide useful information about the concepts therein. We seek to develop means of exploiting the presence of such knowledge, particularly when it appears in a form that precisely defines concepts and their relationships. Given data for a particular supervised learning task, and a collection of structured knowledge, our research investigates how to use said knowledge to make learning more tractable, improve predictive performance, or facilitate explanation and understanding of learned models. Broadly, we are interested in machine learning and/or knowledge representation and reasoning expertise. More specific technologies of interest include (but are not limited to) techniques for learning predictions from graphs (such as graph neural networks), knowledge graph embeddings, knowledge graph search algorithms, etc.

Decentralized Planning for Command and Control

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In an effort to support the Air Force’s mission to develop robust autonomous Command and Control (C2) systems in contested environments, we are interested in furthering the identification of problems, and development of solutions, in decentralized planning for C2. We are interested in planning solutions in resource-constrained environments (processing power, data, and communication restrictions) with time-sensitive goals. The following topic areas are of interest as we seek to provide a decentralized C2, collaborative planning capability to enable continued execution of plans in a contested environment.

- Mixed-Initiative Plan Adaptation – When communications with a centralized planning authority are compromised, the challenge becomes the continuity of operations at decentralized locations can become difficult. Capabilities of interest include effective methods of plan adaptation that don’t require a complete re-planning phase in a centralized planning environment, and mixed-initiative plan adaptation solutions in a resource-constrained environment.

- Plan Deconfliction – As plans are successfully adapted to ensure mission continuity, how is re-synchronization effected when communications between distributed/decentralized C2 components are lost or compromised, and then restored – if at all. Local planning by distributed agents may be locally effective, but often leads to the need for later plan deconfliction and negotiation once communications resume and partial plans and plan fragments are aggregated. Finding effective ways to reduce the occurrence of initial plan
conflicts as well as to minimize the amount of time required to de-conflict a set of partial plans is critical to time sensitive mission requirements. We are interested in plan de-confliction and synchronization solutions enabling inter-plan collaboration, efficient deconfliction, and plan (re)synchronization for autonomous/decentralized C2.

Graph Theoretical Approaches to Explore Mission Impact Analysis

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In complex enterprise networks, graph/network analysis enables the exploration of dependencies and critical nodes. This research explores the application of graph theory and network analysis to mission threads (represented as a directed graph) to enable the analysis of mission impact on a set of mission threads. This work will also consider the application of constrained optimization problems on the representative directed graph to quantify and evaluate concepts such as robustness of mission threads.

Response-based Adaptive Sampling Techniques

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Standard design of experiments work well with a small number of controllable input parameters. As the number of input parameters grows, static experimental designs begin to fail. In the cyber domain, online control of experimentation is required in order to produce only valuable experimental data. This research seeks to explore the application of response-based adaptive sampling (active learning) algorithms to complex experimental data (to include multiple outputs of interest). These algorithms have typically been explored only in a theoretical setting and we look to apply them to real world data sets (or representative data sets). This research is looking to explore a wide range of these algorithms, to potentially include bandit problems and other machine learning approaches for real-time experimental design.
Mathematical Theory for Advances in Machine Learning and Pattern Recognition

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To alleviate the effects of the so-called ‘curse of dimensionality’, researchers have developed sparse, hierarchical and distributed computing techniques to allow timely and meaningful extraction of intelligence from large amounts of data. As the amount of data available to analysts continues to grow, a strong mathematical foundation for new techniques is required. This research topic is focused on the development of theoretical mathematics with applications to machine learning and pattern recognition with a special emphasis techniques that admit sparse, low-rank, overcomplete, or hierarchical methods on multimodal data. Research may be performed in, but not limited to: sparse PCA, generalized Fourier series, low-rank approximation, tensor decompositions, and compressed sensing. Proposals with a strong mathematical foundation will receive special consideration.

Data-Efficient Machine Learning

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Many recent efforts in machine learning have focused on learning from massive amounts of data resulting in large advancements in machine learning capabilities and applications. However, many domains lack access to the large, high-quality, supervised data that is required and therefore are unable to fully take advantage of these data-intense learning techniques. This necessitates new data-efficient learning techniques that can learn in complex domains without the need for large quantities of supervised data. This topic focuses on the investigation and development of data-efficient machine learning methods that are able to leverage knowledge from external/existing data sources, exploit the structure of unsupervised data, and combine the tasks of efficiently obtaining labels and training a supervised model. Areas of interest include, but are not limited to: Active learning, Semi-supervised learning, Learning from "weak" labels/supervision, One/Zero-shot learning, Transfer learning-domain adaptation, Generative (Adversarial) Models, as well as methods that exploit structural or domain knowledge.

Furthermore, while fundamental machine learning work is of interest, so are principled data-efficient applications in, but not limited to: Computer vision (image/video categorization, object detection, visual question answering, etc.), Social and computational networks and time-series analysis, and Recommender systems.
The problem of designing decision-making agents which satisfy formal behavioral properties is an important challenge to overcome in an increasingly automated and autonomous world. We seek novel methods for establishing verifiable behavior in agents which must simultaneously maximize a reward signal. By verifiable behavior, we refer to the problem of finding optimal decision-making policies for agents in a known environment subject to constraints on the behavior of the agent. The proposed approaches should not merely attempt to verify an existing decision-making agent, but rather design the agent from scratch by utilizing the additional information provided by given complex behavioral specifications and other constraints. These specifications can take on mathematically rigorous representations in the form of temporal logics and the automata used to model them, but they can be stated in plain English. Examples include “the agent must eventually reach a state of sufficient resources and only visit such states thereafter” or “every time a hostile state is visited, the agent will eventually end up in a safe state for a specified amount of time”. This is a particularly relevant problem for Air Force operations. For example, an Air Tasking Order (ATO) used for operational decision-making entails complex specifications as determined by the commander’s intent and SPINS (SPeCIAL INStructions) provided by the Joint Force Air Component Commander (JFACC).
Connectivity and Dissemination

Blockchain-based Information Dissemination across Network Domains

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While crypto currency research has been around for decades, Bitcoin has gained a significant adaptation in recent years. Besides being an electronic payment mechanism, Bitcoin’s underlying building blocks known as blockchain, has profound implications for many other computer security problems beyond cryptocurrencies such as a Domain Name System, Public Key Infrastructure, file storage and secure document time stamping.

The purpose of this topic is to investigate blockchain technologies, and develop decentralized highly efficient information dissemination methods and techniques for sharing and archiving information across network domains via untrusted/insecure networks (internet) and devices. Areas of consideration include but are not limited to: security design and analysis of the state of the art open source blockchain implementations (e.g., bitcoin), developing the theoretical foundation of blockchain-based techniques on different application domains, quantifying block mining efficiencies, block editing, and smart contracts in such domains.

Dynamic Resource Allocation in Airborne Networks

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From the Air Force perspective, a new research and development paradigm supporting dynamic airborne networking parameter selection is of paramount importance to the next-generation warfighter. Constraints related to platform velocity, rapidly-changing topologies, mission priorities, power, bandwidth, latency, security, and covertness must be considered. By developing a dynamically reconfigurable network communications fabric that allocates and manages communications system resources, airborne networks can better satisfy and assure multiple, often conflicting, mission-dependent design constraints. Special consideration will be given to topics that address cross-layer optimization methods that focus on improving the performance at the application layer (i.e. video or audio), spectral-aware and/or priority-aware routing and scheduling, and spectral utilization problems in cognitive networks.
Cognitive RF Spectrum Mutability

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When considering operations across terrestrial, aerial, and space domains, effective use of the limited Electromagnetic Spectrum (EMS) for a multitude of purposes is critical. The combined pressures of increasing demand for services and less available bandwidth for all make it imperative to develop capabilities for more integrated, flexible and efficient use of available spectrum for all functions (communications, radar, sensors, electronic warfare, etc.) across all domains (terrestrial, aerial, and space). In recognition of the need for affordable, multi-functional software-defined radios with spectrum agility and survivability in contested environments, this research effort seeks lightweight Next-Generation Software Defined Radio (SDR++) architectures and advanced waveform components for affordable solutions based on COTS and non-development items (NDI), relevant operational security, and appropriate trades in levels of software & hardware roots-of-trust. This will create an innovative high-performance flexible radio platform developed to explore the use of next-gen cognitive, smart-radio concepts for advanced connectivity needs across heterogeneous waveform standards and multiple EMS use-cases; while meeting tighter cost budgets and shorter time-to-fielding. The technology developments will support global connectivity and interoperability via multi-frequency/band/waveform reprogrammable radios for networked, multi-node aerial layer connectivity & spectrum mutability, providing system composability and engineered resilience.

Wireless Sensor Networks in Contested Environments

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Sensor networks are particularly versatile for a wide variety of detection and estimation tasks. Due to the nature of communication in a shared wireless medium, these sensors must operate in the presence of other co-located networks which may have competing, conflicting, and even adversarial objectives. This effort focuses on the development of the fundamental mathematics necessary to analyze the behavior of networks in contested environments. Security, fault tolerance, and methods for handling corrupted data in dynamically changing networks are of interest.

Research areas include but are not limited to optimization theory, information theory, detection/estimation theory, quickest detection, and game theory.

Development of new cryptographic techniques is not of interest under this research opportunity.
Digitizing the Air Force for Multi-Domain Command and Control (MDC2)

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This in-house research effort focuses on working on the Android Tactical Assault Kit (ATAK), which is an extensible, network-centric Moving Map display with an open Application Programming Interface (API) for Android devices developed by Air Force Research Laboratory (AFRL). ATAK provides a mobile application environment where warfighters can seamlessly exchange relevant Command and Control (C2), Intelligence Surveillance and Reconnaissance (ISR), and Situational Awareness (SA) information for domestic and international operations. This capability is key to the Department of Defense’s (DoDs) goal of digitizing the Air Force for MDC2 efforts, because it serves as the backbone for connecting numerous platforms, people, and information sources.

Wireless Optical Communications

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Quantum communications research involves theoretical and experimental work from diverse fields such as physics, electrical engineering and computer science, and from pure and applied mathematics. Objectives include investigations into integrating quantum data encryption with a QKD protocol, such as BB84, and characterizing its performance over a free space stationary link. The analysis of the secrecy of the data is extremely important. Quantum-based encryption systems that use the phase of the signal as the information carrier impose aggressive requirements on the accuracy of the measurements when an unauthorized party attempts intercepting the data stream.

Free Space Optical Communication Links: Laser beams propagating through the atmosphere are affected by turbulence. The resulting wave front distortions lead to performance degradation in the form of reduced signal power and increased bit-error-rates (BER), even in short links. Objectives include the development of the relationship between expected system performance and specific factors responsible for wave front distortions, which are typically linked to some weather variables, such as the air temperature, pressure, wind speed, etc. Additional goals are an assessment of potential vulnerability of the quantum data encryption.

Associated with the foregoing interests are the design and analysis of simple to complex quantum optical circuitry for quantum operations. Characterization of entanglement in states propagating through such circuits in terms of measures such as PPT, CSHS inequalities, and entropic techniques are of interest.
Airborne Networking and Communications Links
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This research effort focuses on the examination of enabling techniques supporting potential and future highly mobile Airborne Networking and Communications Link capabilities and high-data-rate requirements as well as the exploration of research challenges therein. Special consideration will be given to topics that address the potential impact of cross-layer design and optimization among the physical, data link, and networking layers, to support heterogeneous information flows and differentiated quality of service over wireless networks including, but not limited to:

- Physical and MAC layer design considerations for efficient networking of airborne, terrestrial, and space platforms;
- Methods by which nodes will communicate across dynamic heterogeneous sub-networks with rapidly changing topologies and signaling environments, e.g., friendly/hostile links/nodes entering/leaving the grid;
- Techniques to optimize the use of limited physical resources under rigorous Quality of Service
- (QoS) and data prioritization constraints;
- Mechanisms to handle the security and information assurance problems associated with using new high-bandwidth, high-quality, communications links; and
- Antenna designs and advanced coding for improved performance on airborne platforms.

THz Communication – Materials and Mechanisms
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THz communication holds promise to increase wireless data rates over short distances. This may be achieved using emerging technologies based on nanostructured materials. Potential material candidates may include carbon based nanomaterials or other plasmonic materials. This research effort focuses on understanding the materials and mechanisms which allow for the transmission of THz frequency signals. Topics of interest include theoretical examination of the physical mechanisms responsible for propagating the THz signals from source to receiver; design and fabrication strategies for component development (transmitters or receivers) capable of supporting THz frequencies; and analytical exploration of component efficiencies to minimize free space loss.
In order to transfer information between disjointed networks, various domains, or disseminate to coalition partners, Cross Domain Solutions (CDS) exist to examine and filter information that ensures only appropriate data is released or transferred. Due to the ever-increasing amount of data needing to be transferred and newer, more complex data format or protocols created by different applications, the current CDSs are not keeping up with the current cross domain transfer demands. As a result, critical information is not being delivered to the decision makers in a timely manner, or sometimes, not at all. In order to meet today’s cross domain transfer needs, CDSs are looking to employ newly emerging technologies to better understand the information that they use to process and adapt to large workloads. These emerging technologies include, but are not limited to, machine learning based content analysis, information sharing across mobile and Internet of Things (IoT) based devices, cloud based cross domain filtering systems, passing information across nonhierarchical classifications and processing of complex data such as voice and video. While adding these new technologies enhance CDSs’ capabilities, they also add a substantial complexity and vulnerabilities to the systems. Some common attacks may come from a less critical network trying to gain critical network access, or malware on the critical-side trying to send data to the less critical side. Research should investigate and examine methods to efficiently secure emerging technologies beneficial to CDSs. Researchers will collaborate heavily with the AFRL’s cross domain research group for better understanding of cross domain systems as they apply their specific areas of emerging technology expertise to these problems. The expected outcome may include a design and/or a proof of concept prototype to incorporate emerging technologies into CDSs. It may also include vulnerability analysis and risk mitigation for those emerging technologies operated in a critical environment.

Mission Driven Enterprise to Tactical Information Sharing

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Forward deployed sensors, communication, and processing resources increase footprint, segregate data, decrease agility, slow the speed of command, and hamper synchronized operations. Required is the capability to dynamically discover information assets and utilize them to disseminate information across globally distributed federations of consumers spread across both forward-deployed tactical data links and backbone enterprise networks. The challenges of securely discovering, connecting to, and coordinating interactions between federation members and transient information assets resident on intermittent, low bandwidth networks need to be addressed. Mission prioritized information sharing over large-scale, distributed, heterogeneous networks for shared situational awareness is non-trivial. The problem space requires investigation, potential solutions and technologies need to be identified, and technical approaches need to be
articulated which will lead to capabilities that enable forward deployed personnel to reach back to enterprise information assets, and allow rear deployed operators the reciprocal opportunity to reach forward to tactical assets that can address their information needs.

- Anticipating versus Reacting - Conditions in real-world environments are dynamic - threats emerge and may be neutralized, opportunities appear without warning, etc. - and robust autonomous agents must be able to act appropriately despite these changing conditions. To this end, we are interested in identifying events which signal that a change must be made in one agent’s behavior by mining past data from a variety of sources, such as its own history, messages from other autonomous agents, or other environmental sensors. This capability would allow agents to learn to anticipate and plan for scenario altering events rather than reacting to them after they have already occurred.

Reactive Service Migration

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Reactive service migration involves service fault detection and fail-over mechanisms, information service workload migration strategies to relieve overloaded network resources, and pre-positioning of information and services by recognizing the usage patterns of information consumers to anticipate their needs ahead of time. Reactive service migration fail-over mechanisms might make use of workflow compensation, service redundancy, or other exception handling techniques. Workload migration may involve the use of load balancing techniques to achieve optimal resource utilization, maximize throughput, minimize response time, and avoid overload. Pre-positioning of information and services might require the tracking and detection of events or changes in state which indicate an impending user need. In all cases, reactive service migration is concerned with optimizing the quality and availability of information management system services.

Next-generation Aerial Directional Data Link & Networking (NADDLN)

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Given the scarcity of spectrum, there is a desire to develop self-forming, self-managing directional tactical data links operating at higher frequencies. Directional networking provides an opportunity to increase spectral efficiency, support ad-hoc aerial connectivity, improve resistance to intended/unintended interference, and increase the potential capacity of the link. However, complexity is added to the pointing, acquisition and tracking (PAT) required to establish and maintain a network of directional links over omnidirectional systems. Research interests reside in (1) the ability to make real-time content/context-aware trades involving capacity, latency, and interference tolerance; (2) mission-aware link and network topology control; and (3) affordable
apertures and PAT systems; ultimately, to deliver new capabilities for next-generation aerial directional data link & networking (NADDLN).

Advanced High Speed Data Links

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This in-house research effort focuses on very high speed data links (multi-gigabits) built on commercial standards such as IEEE std. 802.16. We are exploring the advantages of using orthogonal frequency division multiplexing and multi-access (OFDM, and OFDMA). In order to achieve multi-gigabit performance, we are investigating the use of an ultra wide band communication scheme with high order modulation techniques. Several challenge topics need to be investigated in this project. These topics include, but are not limited to:

- Doppler Frequency spread for ultra wide band communication systems using OFDM/OFDMA in high mobility airborne environment
- Peak-to-Average Power Ratio (PAPR) mitigation in OFDM communication system
- Clock and Carrier recovery techniques in very high speed communication systems
- Time and Frequency synchronization in OFDM/OFDMA communication systems
- Real-time high efficiency Forward Error Correction (FEC) techniques using state-of-the-art FPGA design

Complex Network and Information Modeling & Inference

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Recent advances in sensing technology have enabled the capture of dynamic heterogeneous network and information system data. However, due to limited resources it is not practical to measure a complete snapshot of the network or system at any given time. This topic is focused on inferring the full system or a close approximation from a minimal set of measurements. Relevant areas of interest include matrix completion, low-rank modeling, online subspace tracking, classification, clustering, and ranking of single and multi-modal data, all in the context of active learning and sampling of very large and dynamic systems. Applications areas of interest include, but are not limited to communication, social, and computational network analysis, system monitoring, anomaly detection, video processing. Also of interest are topological methods such
as robust geometric inference, statistical topological data analysis, and computational homology and persistence. The exploration of new techniques and efficient algorithms for topological data analysis of time-varying and dynamic systems is of particular interest. Candidates should have a strong research record in these areas.

**Quantum Networking with Atom-based Quantum Repeaters**

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A key step towards realizing a quantum network is the demonstration of long distance quantum communication. Thus far, using photons for long distance communication has proven challenging due to the absorption and other losses encountered when transmitting photons through optical fibers over long distances. An alternative, promising approach is to use atom-based quantum repeaters combined with purification/distillation techniques to transmit information over longer distances. This in-house research program will focus on trapped-ion based quantum repeaters featuring small arrays of trapped-ion qubits connected through photonic qubits. These techniques can be used to either transmit information between a single beginning and end point, or extended to create small networks with many users.

**Agile Networking for the Aerial Layer**

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The characteristics of today's aerial layer networks are limiting effective information sharing and distributed command & control (C2), especially in contested, degraded, operationally limited environments, where the lack of interoperability and pre-planned/static link configurations pose the greatest challenges. Advanced research in wireless networking is sought to support aerial information exchange capabilities in highly dynamic environments. This includes but is not limited to: disruption/delay tolerant networking; radio-to-router interface protocols; opportunistic transport protocols; resilient data/message protocols and on-demand prioritization; spectrum use; dynamic networks' topology management, infrastructure sharing and mesh networking.
Next Generation Wireless Networking: Network Slicing

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Network Slicing (NS) makes it possible in a single communication infrastructure to provide multiple customized networks that can meet specific requirements. It allows mission actors to have full control of the life cycle of a network slice, including its resources while providing software control of the behavior of its forming networks. It enables execution of high-level multi-mission policies and defining complex tasks to dynamically control networks and their resources to meet on-demand in-theater mission requirements while mitigating vulnerabilities and threats in cyber and Electro Magnetic (EM) domains.

The topic seeks highly motivated research on how NS and its enabling technologies, Software Defined Networking (SDN), Network Function Virtualization (NFV), cloud infrastructure along with network management and orchestration can support dynamic, resilient local and global command & control (C2) for joint tactical edge network (JTEN) operations. For example, high level network control makes it possible for operators to specify more complex tasks that involve integrating many disjoint network functions (e.g., security, resource management, and prioritization, etc.) into a single control framework, which enables: (1) mapping mission or application level requirements to a set of tangible network configurations; (2) robust and agile network reconfiguration and recovery; (3) flexible network management and planning; and, in turn, (4) improvements in network efficiency, controllability, and survivability.

Emerging 5G Technologies for Military Applications

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Emerging 5G communications and network technologies can be leveraged to enhance military communication capabilities. In particular, 5G enabling technologies are envisioned to provide higher data rates, lower latency, lower power consumption, security enhancements and ubiquitous access including non-terrestrial links. The three major use case domains of 5G—enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and massive machine type communications (mMTC)—provide the opportunity to harness commercial technology for future AF use cases such as smart bases, self-driving vehicles and augmented and virtual reality technologies for training. The 5G research areas of interests for this topic include but not limited to:

- Spectrum sharing with unlicensed and shared bands
Today’s increasing demand for higher data rates and congestion in conventional RF spectrum have motivated research and development in higher frequency bands such as millimeter-wave, terahertz band and beyond. New developments in device and physical layer technologies promise to relieve the overcrowded spectrum at lower frequencies as well as enable new high-bandwidth applications that are not feasible with current wireless technologies. The focus of this research is to develop novel networking solutions that will exploit the full potential of unprecedentedly large bandwidth offered by the recent developments in high-frequency bands.

Traditionally, wireless networks have been designed with the major constraint being available bandwidth. We are interested in new and novel protocols at higher layers that do not hold the same assumption but address the challenges stemming from the peculiarities of channel physics at high frequencies. For example, very high path loss caused by atmospheric and molecular absorption at these frequencies have effectively shorten the transmission range. This, in turn, calls for deployment of highly directional antennas and massive-MIMO arrays as well as relaying and multi-hop communication schemes. In this new paradigm, our research areas of interest includes but are not limited to:

- Link layer protocols where nodes do not need to aggressively contend for the channel but have to consider challenges stemming from channel characteristics and use of directional antennas.
- Transport and network layer protocols that can support very high data arrival rates without data loss or queueing issues.
- Topology control of ultra-dense networks consisting of active and passive relay nodes and nodes using directional and massive-MIMO antenna arrays.
- Synchronization and medium access strategies that consider the effect of very high-speed data rates (Tbps or at least multi-Gbps) in high-speed airborne networks.
• Compatibility with legacy frequency band access to provide spectrum diversity to the system.
• Cross-layer protocols that take into account of challenges and opportunities at higher frequency bands.

Verification-Guided Reinforcement Learning in Unknown Environments

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Reinforcement learning and sequential decision-making have been revolutionized in recent years thanks to advancements in deep neural networks. Recent breakthroughs include DeepMind’s AlphaStar and its victories over world champions in StarCraft II and OpenAI’s DOTA player. Another noteworthy breakthrough was accomplished by the AlphaGo system and its victory over the world Go champion. However, even in this impressive system, the learned agent performed sub-optimal actions that puzzled both the Go and the reinforcement learning communities. Such failures in decision-making motivate the need for methods that can provide (statistical) guarantees on the actions performed by an agent. While the AlphaGo system serves as an interesting and relevant example, the true testament to the need for such methods comes from potential safety-critical applications of reinforcement learning. Such is the case with autonomous driving and military recommender systems.

We are interested in establishing such guarantees in both discrete and continuous systems where agents learn policies, or action plans, through experience by interacting with their unknown environment. To this end, we seek specialists from areas such as optimal control, game theory, hybrid automata, formal methods, machine learning, and multi-objective optimization. Some problems of interest in this domain include, but are not limited to the following:

• Decision-making in partially observable Markov Decision Processes.
• Satisfying probabilistic guarantees on the behavior of a learned agent when approximate value functions (i.e. neural networks) are used to measure utility.
• Control of hybrid systems resulting from the discretization of continuous space induced by a given set of behavioral specifications. Such specifications are typically defined by a temporal logic such as computation tree logic and linear temporal logic.
• Decision-making in adversarial stochastic games.
• Reinforcement learning as a constrained optimization problem wherein expected long-term rewards are to be maximized while satisfying bounds on the probabilities of satisfying various behavioral specifications.
Research opportunities are available for T model-based design, development and demonstration of foundations of resilient and trustworthy computing, including technology, components and methods supporting a wide range of requirements for improving the resiliency and trustworthiness of computing systems via multiple resilience and trust anchors throughout the system life cycle including design, specification and verification of cyber-physical systems. Research supports security, resiliency, reliability, privacy and usability leading to high levels of availability, dependability, confidentiality and manageability. Thrusts include hardware, middleware and software theories, methodologies, techniques and tools for resilient and trusted, correct-by-construction, composable software and system development. Specific areas of interest include: Automated discovery of relationships between computations and the resources they utilize along with techniques to safely and dynamically incorporate optimized, tailored algorithms and implementations constructed in response to ecosystem changes; Theories and application of scalable formal models, automated abstraction, reachability analysis, and synthesis; Perpetual model validation (both of the system interacting with the environment and the model itself); Trusted resiliency and evolvability; Compositional verification techniques for resiliency and adaptation to evolving ecosystem conditions; Reduced complexity of autonomous systems; Effective resilient and trusted real-time multi-core exploitation; Architectural security, resiliency and trust; Provably correct complex software and systems; Composability and predictability of complex real-time systems; Resiliency and trustworthiness of open source software; Scalable formal methods for verification and validation to prove trust in complex systems; Novel methodologies and techniques which overcome the expense of current evidence generation/collection techniques for certification and accreditation; and A calculus of resilience and trust allowing resilient and trusted systems to be composed from untrusted components.

Cyber Defense through Dynamic Analyses

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Modern systems are generally a tailored and complex integration of software, firmware and hardware. Additional complexity arises when these systems are further characterized by machine learning algorithms, with recent emphasis on deep learning methods. Couple this with the limited but “sufficient” testing in the development phases of the system and the end result is all too often an incompletely characterized set of system response to stimuli not of concern in the original tests.
We are interested in new approaches to system testing for security and vulnerabilities that would otherwise go undetected. In particular, modern test methods such as fuzz testing (or fuzzing) can cover more scenario boundaries using data considered to be otherwise invalid from network protocols, application programming interface calls, files, etc. These invalid data better ensure that a proper set of vulnerability analyses is performed to prevent exploits.

Further, we are interested in leveraging AI and machine learning techniques combined with these modern methods such as fuzzing, to more completely perform system tests and vulnerability analyses.

Exploring Relationships Among Ethical Decision Making, Computer Science, and Autonomous Systems

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The increased reliance on human-computer interactions, coupled with dynamic environments where outcomes and choice are ambiguous, creates opportunities for ethical decision making situations with serious consequences where errors could cost loss of life. We are developing approaches that make autonomous system decisions more apparent to its users, and capabilities for a system to tailor the amount of automation based on the situation and input from the decision maker. This allows for dynamically adjustable human/machine teaming addressing C2 challenges of Autonomous Systems, Manned/Unmanned Teaming, and Human Machine Interface and Trust. The work focuses on developing a system for modeling and supporting human decision making during critical situations, providing a mechanism for narrowing choice options for ethical decisions faced by military personnel in combat/non-combative environments.

We propose developing software (an “ethical advisor”) to identify and provide interventions in situations where ethical dilemmas arise and quick, reliable decision making is efficacious. Our unique approach combines behavioral data and model simulation in the development of an interactive model of decision making that emphasizes the human element of the decision process. In the long term, understanding the fundamental aspects of human ethical decision making will provide key insights in designing fully autonomous computational systems with decision processes that consider ethics. As autonomous systems emerge and military applications are identified, we will work to provide verifiable assurance that our autonomous systems are making decisions that reflect USAF moral and ethical values. The first step towards realizing this vision is focusing on human decision processes and clarifying those values in a quantifiable model. The team has developed an ethical framework and preliminary model of ethical decision making that will be more fully developed with the Air Force Academy (AFA) and Air University (AU). In Year 1, we will articulate the individual psychological characteristic and situational factors impacting ethical dilemmas and develop realistic ethical dilemmas and situations. These scenarios will use computational agents employing AI and military personnel, requiring ethical decisions to be made by personnel in combat and non-combative environments. In year 2, we will develop the Ethical Advisor prototype, test the individual psychological characteristics and situational factors, refine the scenarios, and establish and implement collaborations across different commands/services. In
year 3, we will test and integrate the model and Ethical Advisor into a mission system, and conduct joint war game testing.

We are seeking individuals from a variety of educational disciplines (Psychology, Philosophy, Computer Science) with experience in data gathering and summarization techniques, programming, and testing. The gathered data would be used for developing algorithms and programming to begin enabling software to mimic human decision making in complex ethics-laden situations.

**Trusted Software-Intensive Systems Engineering**

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Software is a prime enabler of complex weapons systems and its fungible nature is key to the development of next generation adaptive systems. Yet, software is the most problematic element of large scale systems, dominated by unmet requirements and leading to cost and schedule overruns. As the complexity of today's system lies in greater than $10^5$ requirements, $10^7$ lines of code, thousands of component interactions, 30 year product life cycles and stringent certification standards. The tools used to design, develop and test these complex systems do little to instill trust that the software is free from vulnerabilities, malicious code or that it will function correctly. Furthermore there is virtually no tool capable of detecting design flaws. The objective of the trusted software-intensive systems engineering topic is to develop techniques and tools to enable trust (with a focus on security and correctness) throughout the software lifecycle.

Areas of interest include: evidence-based software assurance; static analysis tools with a preference to analysis at the binary level; algorithm or design-level analysis; secure software development; model-based software engineering; correct-by-construction software generation.

**Application of Game Theory and Mechanism Design to Cyber Security**

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Cyber attacks pose a significant danger to our economic prosperity and national security whereas cyber security seeks to solidify a scientific basis. Cyber security is a challenging problem because of the interconnection of heterogeneous systems and the scale and complexity of cyberspace. This research opportunity is interested in theoretical models that can broaden the scientific foundations of cyber security and develop automated algorithms for making optimum decisions relevant to cyber security. Current approaches to cyber security that overly rely on heuristics have been demonstrated to have only limited success. Theoretical constructs or mathematical abstractions provide a rigorous scientific basis for cyber security because they allow for reasoning quantitatively about cyber attacks.
Cyber security can mathematically be modeled as a conflict between two types of agents: the attackers and the defenders. An attacker attempts to breach the system’s security while the defenders protect the system. In this strategic interaction, each agent’s action affects the goals and behaviors of others. Game theory provides a rich mathematical tool to analyze conflict in strategic interaction and thereby gain a deep understanding of cyber security issues. The Nash equilibrium analysis of the security games allows the defender to allocate cyber security resources, understand how to prioritize cyber defense activities, evaluate the potential security risks, and reliably predict the attacker’s behavior.

Securing cyberspace needs innovative game theoretic models that consider practical scenarios such as: incomplete information, imperfect information, repeated interaction and imperfect monitoring. Moreover, additional challenges such as node mobility, situation awareness, and computational complexity are critical to the success of wireless network security. Furthermore, for making decisions on security investments, special attention should be given to the accurate value-added quantification of network security. New computing paradigms, such as cloud computing, should also be investigated for security investments.

We also explore novel security protocols that are developed using a mechanism design principle. Mechanism design can be applied to cyber security by designing strategy-proof security protocols or developing systems that are resilient to cyber attacks. A network defender can use mechanism design to implement security policies or rules that channel the attackers toward behaviors that are defensible (i.e., the desired equilibrium for the defender).

**Cyber Security Research and Applications for Cyber Defense**

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The Air Force’s mission to fly and fight in Air, Space, and Cyberspace involve the technologies to provide information to warfighters anywhere, anytime, and for any mission. This far-reaching endeavor will necessarily span multiple networks and computing domains not exclusive to military. Cyberspace remains beneficial and a technological advantage when vulnerabilities are under control. Cyber defense is concerned with the protection and preservation of critical information infrastructures available in cyberspace, and has implications in air and space.

Economics, a study of resource allocation problems, has always been a factor in engineering, and promises to address many issues surrounding the management and operation of large-scale information systems. The introduction of mobile agents, autonomy, computational economy, pricing mechanisms, and game theory mechanisms in a virtual domain such as cyberspace may unveil the same set of phenomena as seen in real domains. Studying these from an economics perspective may provide insights related to cyberspace’s arbitrary scale, heterogeneity of resources, decentralized operation, and tolerance in presence of vulnerability.

This research topic seeks innovative approaches to: 1) protect our own resources through information assurance; 2) enable our systems to automatically interface with multi-domain systems through information sharing, while possessing the ability to operate correctly in unanticipated states
and environments; 3) provide the means to circumvent attacks by learning new configurations and understanding vulnerabilities before exploitation, and 4) reconstitute systems, data, and information from different domains rapidly to avoid disruptions.

Fundamental research areas of interest within this topic include:

- Design of systems composed of both trusted and untrusted hardware and software; study of virtualization of hardware components and platforms with configurability on-the-fly.
- Mathematical concepts and distinctive mechanisms that enable systems to automatically continue correct operation in the presence of unanticipated input or an undetected bug or vulnerability.
- Examination of assumptions, mechanisms, and implementations of security modules with capability to rewrite itself without human interactions in the presence of unwanted/unanticipated configurations.
- Information theory and category theory describing interactions of systems of systems that lead to better consideration of their emergent behaviors during attack and reconstitution; models used to predict system responses to malwares and coordinated attacks as well as analyses of self-healing systems.
- Study and application of emerging security technologies, such as blockchain.

Development of new cryptographic methods are not of interest under this topic.

**Assurance in Mixed-Trust Cyber Environments**

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Operations in and through cyberspace typically depend on many diverse components and systems that have a wide range of individual trust and assurance pedigrees. While some components and infrastructures are designed, built, owned and operated by trusted entities, others are leased, purchased off-the-shelf, outsourced, etc., and thus cannot be fully trusted. However, this heterogeneous collection of mixed-trust components and infrastructures must be composed in such a way as to provide measurable and dependable security guarantees for the information and missions that depend on them.

This research topic invites innovative research leading to the ability to conduct assured operations in and through a cyberspace composed of many diverse components with varying degrees of trust. Topics of interest include, but are not limited to:

- Novel identity and access control primitives, models, and mechanisms.
- Secure protocol development and protocol analysis.
- Research addressing unique concerns of cyber-physical and wireless systems.
- Security architectures, mechanisms and protocols applicable to private, proprietary, and Internet networks.
- Embedded system security, including secure microkernel (e.g., seL4) research and applications.
- Zero-trust computing paradigms and applications.
- Legacy and commercial system security enhancements that respect key constraints of the same, including cost and an inability to modify.
- Secure use of commercial cloud infrastructure in ways that leverage their inherent resilience and availability without vendor lock-in.
- Novel measurement algorithms and techniques that allow rapid and accurate assessment of operational security.
- Obfuscation, camouflage, and moving target defenses at all layers of networking and computer architecture.
- Attack- and degradation-recovery techniques that rapidly localize, isolate and repair vulnerabilities in hardware and software to ensure continuity of operations.
- Design of trustable systems composed of both trusted and untrusted hardware and software.
- Non-traditional approaches to maintaining the advantage in cyberspace, such as deception, confusion, dissuasion, and deterrence.

Formal Methods for Complex Systems

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Formal methods have supported the design and analysis of systems in various domains, yet they are not able to extend this success to many of the systems being developed today. To address the increasing complexity of systems, this research area seeks rigorous and formal approaches to the design, specification, and verification of complex systems. It seeks to support investigation on new powerful formal methods: formal models and abstractions that can perspicuously capture the complexity of modern systems and support their formal analysis, compositional verification techniques, and semantically sound integration of formal methods.
Secure Processing Systems

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The objective of the Secure Processing Systems topic is to develop hardware that supports maintaining control of our computing systems. Currently most commercial computing systems are built with the requirement to quickly and easily pick up new functionality. This also leaves the systems very vulnerable to picking up unwanted functionality. By adding specific features to microprocessors and limiting the software initially installed on the system we can obtain the needed functionality yet not be vulnerable to attacks which push new code to our system. Many of these techniques are known however there is little commercial demand for products that are difficult and time consuming to reprogram no matter how much security they provided. As a result the focus of this topic is selecting techniques and demonstrating them through the fabrication of a secure processor. Areas of interest include: 1) design, layout, timing and noise analysis of digital integrated circuits, 2) Implementing a trusted processor design and verifying that design, 3) Selection of security features for a microprocessor design, 4) verifying manufactured parts, and 5) demonstrations of the resulting hardware.

Microkernel Security and Usability

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Security for embedded (or SWaP-constrained) devices has come a long way; however only in certain application spaces. Both the Android and iOS kernels have built-in Mandatory Access Control functionality to enforce separation and isolation of apps and access to system services such as network or storage. In addition to being secure, both systems also have tremendous application ecosystems that rival the functionality of even desktop environments, all in a SWaP-constrained environment. Unfortunately, the same success cannot be found in other environments such as the IoT space. This is despite the fact that the underlying technologies behind Android and iOS (SELinux and TrustedBSD) are open source. It follows then that the issue of security is not the lack of technologies, but the lack of ease of adoption. The security adoption and integration problem is then exacerbated in traditional “embedded” spaces (such as avionics and automotive) where legacy software applications are prevalent and real-time guarantees are necessary.

This topic seeks innovative research in tools and techniques that will drastically reduce the cost of adopting new security paradigms for embedded systems as well as provide additional insights into the cost/benefits of security. For example, seL4 is a formally verified microkernel with strict enforcement of capabilities at the microkernel level. It was not only designed for security, but also performance, meaning it is capable of supporting real-time applications. Despite the existence of a US-based Community of Excellence, adopting seL4 into existing platforms is challenging. Interested embedded systems developers must first create an Architecture Support Package (ASP) as well as a Board Support Package (BSP) for each system board configuration. Additionally, these
ASP's and BSP's must be designed in such a way as to satisfy both the underlying assumptions made by the formal proof as well as abide by the security abstraction layer (seL4 capabilities). This can be a challenge to adoption unless clear evidence of the eventual benefits exist. In this example, both tools and techniques to automatically create ASP's and BSP's (perhaps by transforming/translating from existing non-seL4 implementations), as well as ones to project the security value of seL4’s microkernel as compared to the expected long term development and sustainment costs are of interest. Other topics of interest include, but are not limited to: ideas on automatically transforming virtual machine applications (legacy applications are often executed within seL4 Virtual Machines) into native seL4 applications; ideas on automatically separating complex applications into subcomponents (e.g., micro-services) that can each execute as its own native app; ideas on extending the formal proof of the microkernel down to applications; ideas on security abstraction layers (e.g., Android permissions) that enforce both security as well as real-time performance; etc. are all within scope.
Quantum Computing Theory and Simulation
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Quantum computing research involves interdisciplinary theoretical and experimental work from diverse fields such as physics, electrical and computer science, engineering and from pure and applied mathematics. Objectives of AFRL’s Emerging Computing Technology Branch include the development of quantum algorithms with an emphasis on large scale scientific computing and search/decision applications/optimization, implementations of quantum computational schemes with low error threshold rates, implementations of quantum error correction such as topological protection, and the simulation of quantum circuits/computers and quantum error correction schemes with an emphasis on modeling experiments. Topics of special interest include the cluster state quantum computing paradigm, quantum simulated annealing, the behavior of quantum information and entanglement under arbitrary motion of qubits, measures of quantum entanglement, and the distinction between quantum and classical information and its subsequent exploitation.

Advanced Event Detection and Specification in Streaming Video
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Focus area 1: graph analysis techniques applied to assessing the resilience of critical infrastructure systems (e.g. electric power grid, communications systems); to include sets of critical nodes and links, measures of centrality, dimensionality reduction, application of game theory, graph matching and alignment with large sparse graphs, and corresponding metrics to characterize assessments and data fitness, and related areas.

Focus area 2: distributed computation and reasoning of near real-time stream data processing (e.g., full motion video) for situational awareness. A query-based approach to analyzing (i.e.: descriptive), understanding (i.e., diagnostic) and predicting (i.e., predictive) situation understanding with real-time feedback (i.e., prescriptive analytics) can be explored. Areas of interest include query robustness (i.e. quality and transactional properties), and applying machine learning (statistical) techniques with dynamic feedback loops measure to measure and adjust model fitness; applied to real-time streaming video. (Reference AFOSR’s Dynamic Data Driven Applications Systems (DDDAS) portfolio description or the community at www.1dddas.org.)
AFRL seeks innovative research in the area Big Data Analytics for Activity Based Information (ABI). More specifically, AFRL seeks automated or semi-automated procedures to characterize and locate activities and actions/transactions, identify and locate actors and entities conducting the activities and transactions, determine the existence, topology, leadership, and other characteristics of covert networks, understand the relationships between networks, and determine patterns of life from large amounts of externally observed data. Research interests also include the discovery and understanding of unknown activities and associated trends/patterns/relationships. In addition, these techniques should move beyond the limitations of traditional approaches to consider temporal dynamics and/or multi-modal networks and are most interesting when researched in the context of a variety of information sources and types and the challenges presented by “Big Data.”

Explanation of Failure States within Machine Learning Models

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The need for increased levels of autonomy has significantly risen within the Air Force. Thus, machine learning tools that enable intelligent systems have become essential. However, analysts and operators are often reluctant to adopt these tools due to a lack of understanding – treating machine learning as a black box that introduces significant mission risk. Although one may hope that improving machine learning performance would address this issue, there is in fact a trade-off: increased effectiveness often comes at the cost of increased complexity. Increased complexity then leads to a lack of transparency in understanding machine learning methods. In particular, it becomes unclear when such methods will succeed or fail, and why they will fail. This limits the adoption of intelligent systems.

This topic focuses on the explanation of failure states within machine learning models to non-machine learning experts. Here, failure states are defined to be areas of the feature space where the model systematically makes incorrect inferences, not random errors. It is believed that techniques to explain failure states can help build confidence in machine learning models, and consequently, promote the adoption of specific intelligent systems. We are interested in pursuing techniques for a variety of machine learning problems, but special emphasis is placed on domain and model agnostic approaches. Areas of interest include, but are not limited to, classification, computer vision, planning, and representation learning.
Methods for Adapting Pre-Trained Machine Learning Models

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Numerous machine learning algorithms have recently made remarkable advances in accuracies due to more standardized large datasets. Yet, designing and training an algorithm for large datasets can be time-consuming and there may be other tasks or activities for which less data exists. There is a large body of work showing the performance benefits of fusing models for the same task. Hence, the ability to adapt and fuse pre-trained models has the advantages of fewer data requirements and decreased computing resources.

The purpose of this topic will be to develop novel methods for fusing and building ensembles of pre-trained machine learning models that are task agnostic and can more closely mimic the agility that humans possess in the learning process. This topic is particularly interested in exploring and evaluating architectures and methods that involve the fusion of Convolutional Neural Networks (CNNs) or other deep learning methods. CNNs have been one class of learning algorithm that have greatly improved accuracies over numerous application domains, including computer vision, text analysis, and audio processing. Additionally, another area of interest includes methods that explain the numerical impacts of training examples on the models being learned. In other words, novel methods that conceptually describe what an algorithm is learning. Both being able to explain the impact of specific examples on the learning process and building novel algorithms and architectures for fusion of pre-trained models will support the realization of more adaptable learning methods.

Quantum Information Processing

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The topic of Quantum Information Processing is to be focused on Computational Methods and Architectures. It has been well established that a computer based on quantum interference could offer significant increases in processing efficiency and speed over classical versions, and specific algorithms have been developed to demonstrate this in tasks of high potential interest such as data base searches, pattern recognition, and unconstrained optimization.

However the present experimental progress, lagging far behind the theoretical, is at the level of several gates or Q bits. The entangled photon approach to quantum gates including quantum gates, cluster states, and Linear Optical Quantum Computing will be experimentally pursued with particular attention to scalability issues. Experience with generation and detection of entangled photons is essential for this interaction, with parametric amplification a plus.

Theoretical advances will also be pursued with existing and custom quantum simulation software to model computational speedup, error correction and de-coherence effects. Algorithm
Audio Processing

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AFRL/RIGC is involved in all aspect of researching and developing state of the art audio and acoustical analysis and processing capabilities, to address needs and requirements that are unique to the DoD and intelligence communities. The group is a unique combination of linguists, mathematicians, DSP engineers, software engineers, and analysts. This combination of individuals allows us to tackle a wide spectrum of topics from basic research such as channel estimation, robust word recognition, language and dialect identification, and confidence measures to the challenging transitional aspects of real-time implementation for speech; as well as detecting, tracking, beamforming and classifying specific acoustical signatures in dynamic environments via array processing. AFRL/RIGC also has significant thrusts in noise estimation and removal (both spectral and spatial), speaker identification including open-set identification, acoustical identification, keyword spotting, robust feature extraction, language translation, analysis of stressed speech, coding algorithms along with the consequences of the compressions schemes, watermarking, co-channel mitigation, and recognition of background events in audio recordings. SOA techniques such as I-vectors, deep neural networks, bottleneck features, and extreme learning are used to pursue solutions for real-time and offline problems such as SID, LID, GID, etc.

Motion Imagery (or Video) Processing and Exploitation

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Motion Imagery sources include everything from airborne collectors to YouTube. New and innovative technology is required to exploit and extract the relevant information content and manage the whole exploitation process. Visual processing is the focus, but leveraging all aspects of the data is of interest (e.g. audio and metadata) as well as using any additional correlating sources (e.g. reference imagery or coincident sensors). Both semi-automated and fully automated capabilities are of interest. Emphasis will be on overcoming or working around the current limit of computer vision to lead to a useful capability for an AF analyst. Sample topics of interest would be: biologically inspired techniques, scene classification, event detection, object detection and recognition, optimization techniques, Bayesian methods, geo-registration, indexing, etc.
Dynamic Edge Classification Algorithms and Architectures

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With recent advances in the reduced size and power requirements for on-board hardware to support machine learning, there are new opportunities for designing systems that can dynamically adjust computation between sensor platforms and more specialized data centers. A majority of distributed classification methods assume a robust communications infrastructure, with models that are engineered for a central authority to facilitate distribution. We seek new methods for training and executing machine learning models that can scale to many edge nodes and can dynamically adjust to communications constraints. These methods will use a combination of onboard processing and larger data centers to maintain a common operating picture in a specified region of interest. Areas of interest include Distributed Systems, Machine Learning, Federated Information Management.

Advanced Computing Processors Information Management

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As the number of computing processors is increased for most applications, a situation is reached where processor information management becomes the bottleneck in scaling, and adding additional processors beyond this number results in a deleterious increase in processing time. Some examples that limit scalability include bus and switch contentions, memory contentions, and cache misses, all of which increase disproportionately as the number of processors increase. The objective of this topic is to investigate existing and/or to develop novel methods of processor information management for multiprocessor and many-processor computing architectures that will allow for increased scaling.

Identification of Data Extracted from Altered Locations (IDEAL)

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The primary objective of this effort is to extract information from documents in real time, without the need to install additional software packages, utilize specialized development, or train agents to each source, even if the location of that data changes.

Seeking data from multiple documents is a manual, time consuming, undocumented process, which needs to be repeated every time an update, or change, to that data is requested. Automating this process is a challenge because the documents routinely change. Sometimes, the mere act of
refreshing a web page changes the document as the ads cycle. Such changes are damaging to most of today's web scraping techniques. The lack of data, or inaccurate data, from failed updates during the extraction process also creates many problems when attempting to update the data, as unexpected results are returned. Extracting data from documents, typically requires training or expert analysis for each source before the data can be used. This means that documents must first be identified before a script or agent can be written to extract data from it by a developer. A user cannot discover a document, and immediately begin extracting data from it. This diverts time away from an analyst, as the analyst begins spending more time managing data, opposed to performing the intended analysis. Services that provide access to data such as RSS feeds, Web Services, and APIs, are useful, but are not necessarily what is needed by the requestor. For example, the Top Story from a news publisher may be available as an RSS feed, whereas the birth rate of the country may not be.

This assignment will focus heavily on enhancing the web browser extension prototype. The extension will be used for routine extraction of data elements from open source web pages/documents, and be developed for the Firefox web browser. In addition to Web Browser extension development, this assignment will include adding additional functionality such as visualization enhancements, search and transposition, crawl, and a process for identifying similar data. Consideration will also include expanding to additional web browsers such as Internet Explorer.

**Random Projection Networks**

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One of the characteristic features of artificial neural networks (ANN) is that all the synaptic connections (weights) between neurons are adjusted during training of the neural network, typically by back propagation. While straightforward in software, hardware realizations of ANNs have proven challenging in part because of the requirement for individually tunable weights. However, for certain classes of problems, this approach is overkill. Rather fixed, random weights in an ANN can be used to project data into sufficiently high-dimensional space such that training only a subset of weights, typically the output layer, are necessary to attain state of the art accuracies. For example, reservoir computing, a type of recurrent neural network where only the output layer weights are trained, has been used for speech recognition and RF non-linear channel modelling. From a hardware perspective such networks are easier to engineer, train, and field because of a) the relaxed hardware tolerances and b) the reduced training requirements. Random projection networks (RPN) include echo state networks (ESN), liquid state networks (LSM), extreme learning machines (ELM), random filters for convolutional neural networks (CNN), vector symbolic architectures/hyper-dimensional computing, and stochastic computing. This research effort encompasses mathematical formalisms, hardware characterization, network modelling, and hardware RPN development, with special emphasis on the lattermost.
AFRL is interested in exploring recent machine learning advances via neural networks such as Recurrent Neural Networks (RNN) combined with Conditional Random Fields (CRF), Long Short-Term Memory (LSTM) networks, Convolutional Neural Network (CNN), and potentially others for improving extraction capabilities from text. The challenge would be to setup the network in-house, replicate performance on a known dataset, and then test on internal AFRL data. Examples of information that can be extracted from text include: (1) people and groups, (2) events (who, what), (3) geo-spatio-temporal information (where, when), (4) causal explanations (why, how), (5) facilities and equipment, (6) modality and beliefs, (7) anomaly, novelty, emerging trends, (8) interrelationships, entailments, coreference of entities and events, (9) disfluencies/disjointedness, (10) dynamic, perishable, changing situations. It is preferable that the learning environment is setup via known packages such as TensorFlow or Torch.

The discovery and extraction of dynamical systems models from data is fundamental to all science and engineering disciplines, and the recent explosion in both quantity and quality of available data demands new mathematical methods. While standard statistical and machine leaning approaches are capable of addressing static model discovery, they do not capture interdependent dynamic interactions which evolve over time or the underlying principles which govern the evolution. The goal of this effort is to research methods to discover complex time evolving systems from data. Key aspects include discovering the governing systems of equations underlying a dynamical system from large data sets and discovering dynamic causal relationships within data. In addition to model discovery, the need to understand relevant model dimensionality and dimension reduction methods are crucial. Approaches of interest include but are not limited to: model discovery based on Taken’s theorem, learning library approaches, multiresolution dynamic mode decomposition, and Koopman manifold reductions.
Uncertainty Propagation for Space Situational Awareness

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One of the significant technical challenges in space situational awareness is the accurate and consistent propagation of uncertainty for a large number of space objects governed by highly nonlinear dynamics with stochastic excitation and uncertain initial conditions. Traditional uncertainty propagation methods which rely on linearizing the dynamics about a nominal trajectory often break down under a high degree of uncertainty or on long time scales. In addition the data uncertainty is usually poorly characterized or the data may be sparse or incomplete. Many recent developments which attempt to address these issues such as the unscented Kalman filters, Gaussian sum filters, and polynomial chaos filters tend to be ad hoc approaches with limited foundational rigor. The objective of this topic is to research accurate, computationally efficient, and rigorously validated methods for uncertainty propagation for the dynamical systems which address the nonlinear nature of the underlying dynamics, and the high degree of uncertainty and lack of completeness in the data. Of interest are approaches which leverage methods of modern dynamical systems theory, theory of stochastic differential equations, unique methods for numerically approximating solutions to the Fokker-Planck equation.

Many-Node Computing for Cognitive Operations

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The sea of change in computing hardware architectures, away from faster cycle rates and towards processor parallelism, has expanded opportunities for development of large scale physical architectures that are optimized for specific operations. Porting of current cognitive computing paradigms onto systems composed of parallel mainstream processors will continue in the commercial world. What higher cognitive functionality could we achieve if we take better advantage of physical capabilities enabled by new multi-processor geometries?

Perception, object recognition and assignment to semantic categories are examples of lower level cognitive functions. Assignment of valence, creation of goals and planning are mid level functions. Self awareness and reflection are higher level processes that are so far beyond current cognitive systems that relatively little has been done to model the processes. Often, models assume higher cognitive processes will emerge, once the computing system reaches some level of speed/complexity. The problem is that the computational power required exceeded the reachable limit of single processor architectures and probably exceeds the limits of conventional parallel architectures. This topic seeks to enable mid and higher level cognitive function by creation of new physical architectures that address the computation demand in novel ways.

We are interested in developing models for the computational scale of the mid and higher functions and processor / memory node architectures that facilitate cognitive operations by configuring the
physical architecture to closely resemble the functional cognitive architecture, e.g., where each node in a network represents and functions as a processor for a single semantic primitive. What new hierarchical architectures could we design for million node systems, where the individual nodes may be small ASPs, with very fast communication between nodes? A project of interest would combine both sides, new algorithms for higher level cognitive functions and new architectures to enable the computation in a realistic time frame. AFRL/RIT has projects on line to enable million node systems.

**Robust Adversarial Resilience**

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In recent literature, deep learning classification models have shown vulnerability to a variety of attacks. Recent studies describe techniques employed to defend against such attacks, e.g. adversarial training, mitigating unwanted bias, and increasing local stability via robust optimization. Further studies, however, demonstrate that these defenses can be circumvented through adapted attack interfaces. Given the relative ease by which most defenses are circumvented with new attacks, we will explore adversarial resilience from two angles. The first will be to improve the resistance of models against attacks in a robust fashion such that one-off attacks won’t circumvent defensive measures. The second will be to attempt to classify subversion attacks by training a separate model to identify them. In order to accomplish both tasks, we will seek to understand the fundamental theory of deep learning architectures and attacks. We hypothesize that a mathematical analysis of attacks will show similarity between attacks that can be exploited by a classifier. We also hypothesize that a mathematical analysis of deep learned models will identify algorithmic weaknesses that are easily exploited by attacks. Understanding how attacks are generated, and how to identify the resultant adversarial examples, is necessary for generalizing countermeasures. Attacks may prey on measures used by the classifier, allowing for targeted deception or misclassification. These attacks often are designed for transferability; even classifiers employing typical countermeasures remain vulnerable. Other attacks prey on the linearity of the underlying model – these adversarial attacks require minimal modification to the data. Considering a nonlinear basis, such as radial basis functions, may improve resilience against such attacks. Exploring this design space will provide insight into methods we can employ to reduce adversarial impact.

**Feature-Based Prediction of Threats**

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Methods have been developed to detect anomalous behaviors of adversaries as represented within sensor data, but autonomous predictions of actual threats to US assets require further investigation.
and development. The proposed research will investigate foundational mathematical representations and develop the algorithms that can predict the type of threat a red (adversary) asset poses to a blue (friendly) asset. The inputs to the system may be assumed to include: 1) an indication/warning mechanism that indicates the existence of anomalous behavior, and 2) a classification of the type of red/blue asset. Approaches to consider include, but are not limited to, predictions based on offensive/defensive guidance templates and techniques associated with machine learning, game theoretic approaches, etc. The proposed approach should be applicable to a variety of threat scenarios.

The example that follows illustrates an application to U.S. satellite protection. The offensive template determines the type of threat. Mechanisms such as templates are used to predict whether or not this asset is a threat by comparing configuration changes with known threatening scenarios through probabilistic analyses, such as Bayesian inferences or game theoretic analyses. Robustness tests may be employed as well. (For example, a threat can be simulated that is not specific to one template.) Once the threat is determined, the classification algorithm provides notification of the type of asset. The classification approach is employed to (for example) determine whether the asset is intact or a fragment, its control states, the type of control state, and whether it is a rocket body, payload, or debris. (An example of an offensive assessment is a mass-inertia configuration change in an active red asset that is specific for robotic arm-type movements.) In the above example, a question to be answered is: can a combination of the templates handle this case? The defensive portion must also provide recommended countermeasures, i.e. as in the case of a blue satellite, thruster burns to move away from possible threats. Although our specific application interests for this research topic are represented by the above example, many application areas are likely to benefit from this research, including cyber defense, counter Unattended Aerial Systems (UASs), etc.

Communications Processing Techniques

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We are focusing our research on exploring new and novel techniques to process existing and future wireless communications. We are developing advanced technologies to intercept, collect, locate and process communication signals in all parts of the spectrum. Our technical challenges include: interference cancellation in dense co-channel environments, multi-user detection (MUD) algorithms, hardware architecture and software methodologies, techniques to geo-locate and track emitters and methodologies to improve the efficiency of signal processing software. Research into developing unique and advanced methods to process communication signals in a high density, rapidly changing environment is of great importance. The research is expected to be a combination of analytical and experimental analyses. Experimental aspects will be performed via simulations using an appropriate signal processing software tool, such as MATLAB.
Optical Interconnects
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Our main area of interest is the design, modeling, and building of interconnect devices for advance high performance computing architectures with an emphasis on interconnects for quantum computing. Current research focuses on interconnects for quantum computing including switching of entangled photons for time-bin entanglement.

Quantum computing is currently searching for a way to make meaningful progress without requiring a single computer with a very large number of qubits. The idea of quantum cluster computing, which consists of interconnected modules each consisting of a more manageable smaller number of qubits is attractive for this reason. The qubits and quantum memory may be fashioned using dissimilar technologies and interconnecting such clusters will require pioneering work in the area of quantum interconnects. The communication abilities of optics as well as the ability of optics to determine the current state of many material systems makes optics a prime candidate for these quantum interconnects.

Optimization for Data Analysis
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In aerospace systems, there is a growing gap between the amount of data generated and the amount of data that can be stored, communicated, and processed. Moreover, this gap keeps widening. One promising approach to solving this problem is to utilize optimization to reliably extract patterns for large scale data. This topic addresses the theory and application of optimization for pattern analysis. This includes the development of:

- An optimization-based theoretical framework for pattern analysis. Some promising directions are based in part on the study of multilevel and nonconvex optimization.
- Paradigms based on the idea that accuracy can be enhanced for many important problems (including important nonconvex problems) by utilizing their common geometric structures, while exploiting approximation theory to yield speed improvements.
- Optimization applications to permit novel computational paradigms, such as computation of numerical rank, which is critically important for machine learning and signal processing.
Neuromorphic Computing
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The high-profile applications of machine learning (ML)/AI, while impressive, are a) not suitable for Size, Weight, and Power (SWaP) limited systems and b) not operable without access to “the cloud.” Neuromorphic computing is one of the most promising approaches for low-power, non-cloud-tethered ML, potentially operable down at the sensor level, also called “edge computing,” because it implements aspects of biological brains, e.g. trainable networks of neurons and synapses, in non-traditional, highly-parallelizable, reconfigurable hardware. As opposed to typical ML approaches today, our research aims for “the physics of the device” to perform the computations and for the reconfigurable hardware itself to be the ML algorithm. This research effort encompasses mathematical models, hardware characterization, hardware emulation, hybrid VLSI CMOS architecture designs, and algorithm development for neuromorphic computing processors. We are particularly interested in approaches that exploit the characteristic behavior of the physical hardware itself to perform computation, e.g. optics, memristors/ReRAM, metamaterials, nanowires. Again, special emphasis will be placed on imaginative technologies and solutions to satisfy future Air Force needs for non-cloud-tethered ML on SWaP limited assets.

Nanocomputing
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Advances in nanoscience and technology show great promise in the bottom-up development of smaller, faster, and reduced power computing systems. Nanotechnology research in this group is focused on leveraging novel emerging nanoelectronic devices and circuits for neuromorphic spike processing on temporal data. Of particular interest is biologically inspired approaches to neuromorphic computing which utilize existing nanotechnologies including nanowires, memristors, coated nanoshells, and carbon nanotubes. We have a particular interest in the modeling and simulation of architectures that exploit the unique properties of these new and novel nanotechnologies. This includes development of analog/nonlinear sub-circuit models that accurately represent sub-circuit performance with subsequent CMOS integration. Also of interest are the use of nanoelectronics as a neural biological interface for enhanced warfighter functionality.
Making best use of multi-point observations and sensor information for event detection and predictive assessment in complex, near real time systems is a challenge which presents itself in many military domains. The first step in tackling these challenges is to analyze and understand the data. Depending on the algorithm used to detect an anomalous event, the nature and extent of variable correlations must be understood. This research will consider methods to quantify the strength of the correlations of input variables to output variables and develop techniques to account for lag times in the data itself. This is no easy task since sensor readings and operator logs are sometimes inconsistent and/or unreliable, some catastrophic failures can be almost impossible to predict, and time lags and leads in real world systems may vary from one day to the next. After detecting where the strongest correlations exist, one must choose a model which can best assess the current conditions and then predict the possible outcomes that could occur for a number of possible scenarios. Scientific issues of interest include, but are not limited to (1) advanced statistical methods to determine dependencies between sensor inputs and the combined effect of multiple-sensors (2) adaptive correlation analysis techniques which will evolve to discover new dependencies in time as conditions change (3) adaptive pattern matching methods to take correlated sensor inputs and characterize normalcy and anomalous conditions.

Multi-sensor and Multi-modal Detection, Estimation and Characterization

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Air Force mission space is varied and complex, involving many sensing modalities to understand and derive actionable intelligence from. Interfering sources, low probability of intercept signals and dynamic scenes all collude to deceive the Air Force’s ability to derive accurate situational awareness in a timely fashion. Furthermore, legacy sensing systems typically provide stovepiped human interpretable intelligence that may have missing information, due to processing, that would likely be more valuable if thought of collectively with other sensing data, further up the sensor processing stream; upstream sensor data fusion.

The fundamental research of interest under this topic includes areas such as multi-modal target association/fusion, multi-sensor/modal detection, tracking, characterization, and multi-sensor selection, parameter optimization and location for improved sensor fusion performance; exploiting fusion results to actively tune sensors to improve the solution. We are interested in advancements in solutions to these areas that can come from a variety methods; Bayesian based, geometric algebra, machine learning and information theory. Trade-offs include computational complexity,
communication requirements, the balancing of smart computational nodes vs centralized processing vs distributed processing. The overall research goal is to leverage all available signals and data from the sensed environments and domains, to generate a cohesive situational awareness of the complete mission space.