Internet of Battlefield Things

COLLABORATIVE RESEARCH ALLIANCE

IoBT REIGN

U.S.ARMY

DEVCOM ARMY RESEARCH LABORATORY

IoBT CRA Research Management Board (RMB) Review

Program Overview

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University of Illinois Urbana-Champaign

March 18, 2022

ILLINOIS · USC University of Southern California · UCLA · UMass Amherst · Carnegie Mellon University · Georgetown University · SRI International · Stanford University · The University of Texas at Austin

IOBT CRA RMB REVIEW

Objective: Provide an overview of the current research within the Internet of Battlefield Things (IoBT) Collaborative Research Alliance (CRA), discuss accomplishments and describe proposed research plan for the optional period of the CRA

Start	Topic	Presenter
1300	Welcome – Introductions	Kott
1310	Program Overview	Wigness/Abdelzaher
1350	Research Focus 1: Efficiency & Timeliness	Verma/Fragouli
1420	Research Focus 2: Resiliency	Kaplan/Tabuada
1450	**Break**	
1500	Research Focus 3: Intelligence at the Point of Need	Panneton/Shenoy
1530	Experimentation Overview	Wigness/Shenoy
1550	IoBT – Way Ahead	Swami/Abdelzaher/Wigness
1610	**Break**	
1620	RMB Caucus (Government Only)	All Government
1700	Adjourn	

BOTTOM LINE UP FRONT

The IoBT CRA is the only ARL fundamental research program addressing challenges of ubiquitous computing and sensing as an intelligent and adaptive common operating environment

- **Seeking Approval of Extension for 5-year Option Period and Guidance on Future Research Direction**
  - Are we asking the right scientific questions?
  - Are there research areas that we should expand or deemphasize?
  - Are there additional opportunities for early transition?
  - Do we have the right balance of experimentation and foundational research?

IOBT CRA OVERVIEW

Collaborative Research Alliance:

- 6.1 Basic Research Program
- University Led Consortium
- Collaboration is Executed Across the Alliance
- 5 year program with option for 5 year renewable (FY23)

	FY18	FY19	FY20	FY21	FY22	Total
6.1 Funds	$1.7	$3.7	$4.8	$4.9	$2.7	**$17.8M**

Current Government Partners

Current Consortium Partners

ILLINOIS · USC University of Southern California · UCLA · UMass Amherst · Carnegie Mellon University · Georgetown University · SRI International · Stanford University · The University of Texas at Austin

Operating Model:

- Joint leadership and execution
- BPP for continuous refresh in research directions
- Regular engagement among researchers to develop rich collaboration

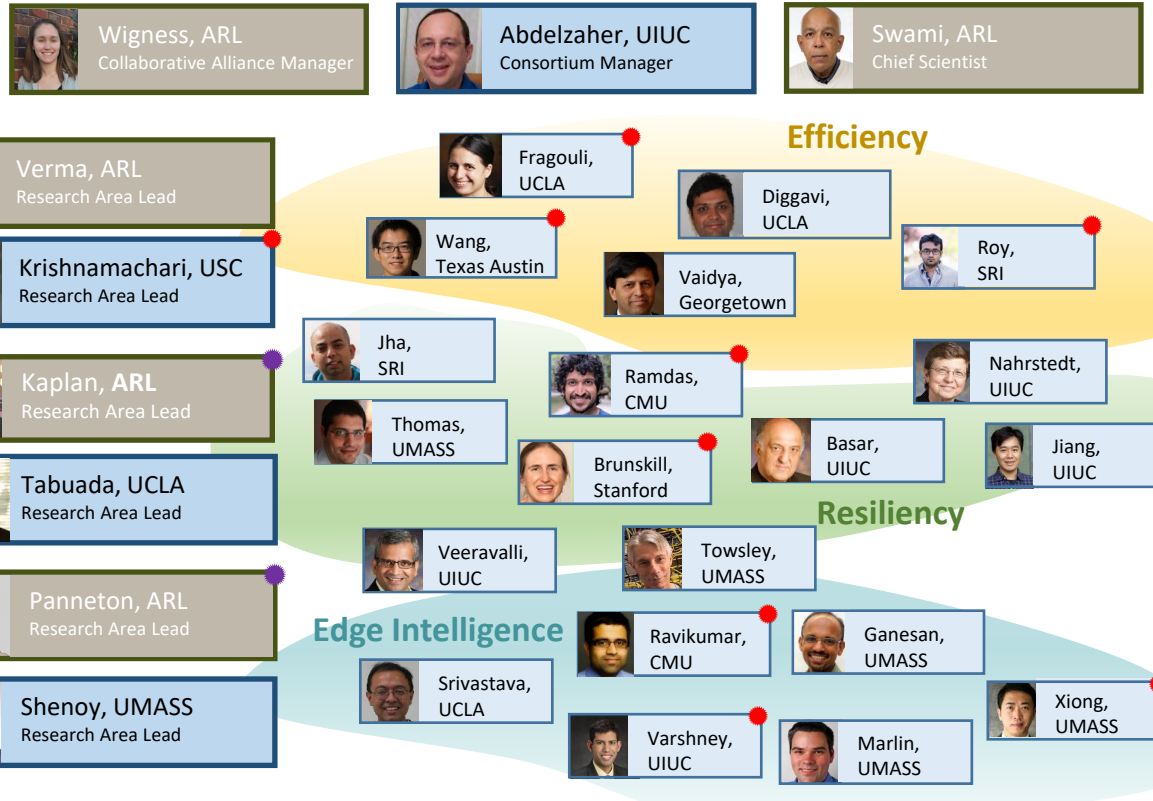
IOBT CRA TEAM

Test of Time Awards
- ACM MOBICOM
- ACM Int. Symposium on Wearable Computers
- ACM/IEEE Int. Conf. on Software Engineering

Faculty Awards
- Honorary Professorship at UIUC
- Tau Beta Pi Daniel C. Drucker Eminent Faculty
- Distinguished Professor, Umass-Amherst
- Grainger Distinguished Chair in Engineering
- Outstanding Teacher Award from the College of Information and Comp. Sciences
- Jack Kilby/Texas Instruments Endowed Faculty

Research Awards
- Many Awards from Google, Amazon, Sandia National Labs, Adobe, Facebook, J.P. Morgan
- Healthy Longevity Award, Interstellar Initiative
- Healthy Longevity Catalyst Award, U.S. National Academy of Medicine
- IEEE Internet Award
- USC Stevens Center Commercialization Award
- Honorary Doctorate, KTH Royal Inst. of Tech.
- National Academy of Science

Alumni Awards
- Wilbur Cross Medal, Yale University



IOBT STRATEGIC GUIDANCE

IoBT REIGN

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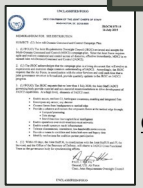
Joint All-Domain C2 Campaign Plan



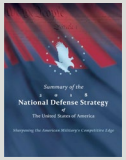
converge service and partner capabilities across all-domains

interoperability, C2 flexibility, and hyper-connectivity needed between all sensors to all shooters

robust, protected, and resilient network

flexible integration of emerging technologies (AI, Machine Learning, Self-healing networks)

National Defense Strategy

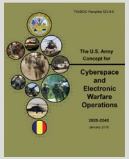


information superiority

resilient, survivable, federated networks and information ecosystems

autonomy, artificial intelligence, and machine learning

Army Cyberspace and EW Operations



machines make decisions for themselves on the battlefield

fail-safe technologies

collect, process and disseminate information

IoT data collection and management

DoD IoT Policy Recommendations

improve situational awareness

security with inexpensive and precise monitoring devices

Army Science Board IoT Study

meaningful situational awareness on the status of Soldiers and equipment, on the battlefield and in the logistics pipeline

enhance autonomous vehicles, to exploit IoT

proficiency in exploiting adversaries' smart cities and defending from attacks

requirements for the acquisition community to integrate IoT

understand risks associated with IoT

Multi-Domain Operations

accelerated and likely highly automated decision making from devices

enable collection, analysis, and display of multi-domain data

mechanical sensors enable intelligence collection

Influencing Future Concepts

Army Concept Framework 2040

- The IoBT CRA contributed as research SMEs for a Focused Excursion (FE) that investigated IoBT implications on select learning demands of this new framework
- Used FE discussions and feedback to validate and refine the future research direction of the IoBT CRA

Army Mission Command

Army information network links leaders, Soldiers…and sensors to help create a synergistic, globally-connected total Army force

sensors coupled with deep-learning technologies

interoperability, collaboration, and uninterrupted mission command

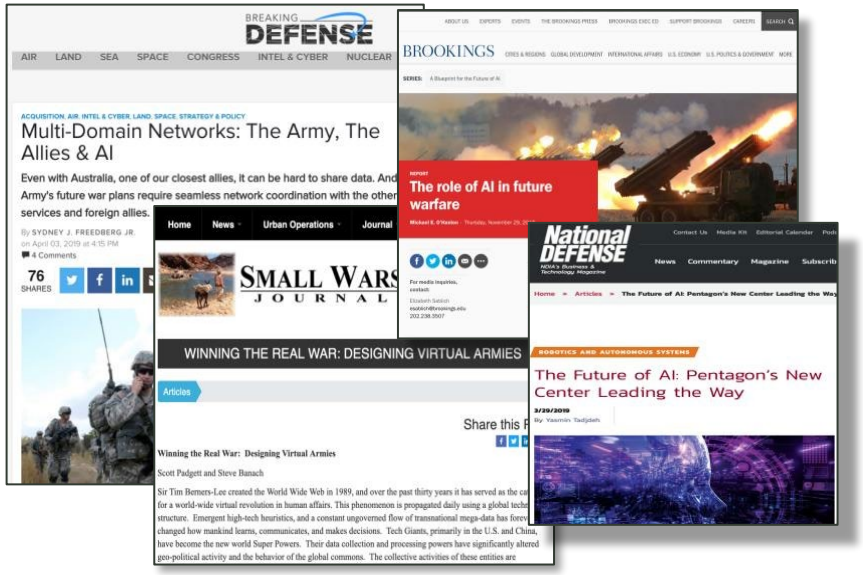
require sensors linked by a tailorable suite of mission command applications, information services, and communications

THE "WHY"? MACHINE INTELLIGENCE IS REDEFINING FUTURE WARFARE

IoBT REIGN DEVCOM ARMY RESEARCH LABORATORY

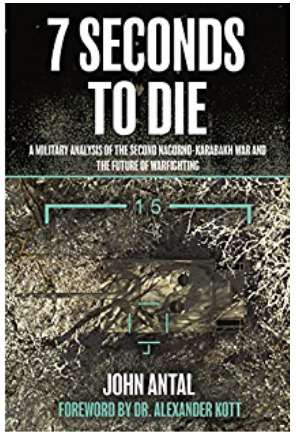
Value proposition:

Develop the scientific foundations for Efficiency and Resilience (of Edge-AI Services) for the Tactical Edge



The Future is Here:

- ***Nagorno-karabakh War, Fall 2020:*** Featured early use of drones to stimulate, find, and strike anti-aircraft (Armenian) defenses.
- ***Israeli anti-Hamas Operation, Spring 2021:*** Featured early use of AI to identify and prioritize key targets in real-time (e.g., missile launchers aimed at Tel Aviv and Jerusalem).



Computational Challenges:

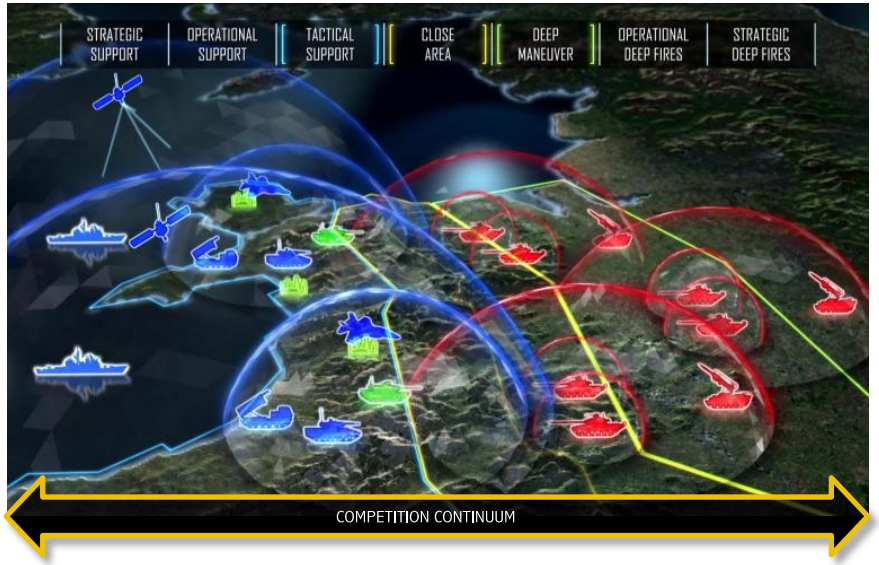
- Push intelligence to the edge
- Support faster sensing-to-effects loops

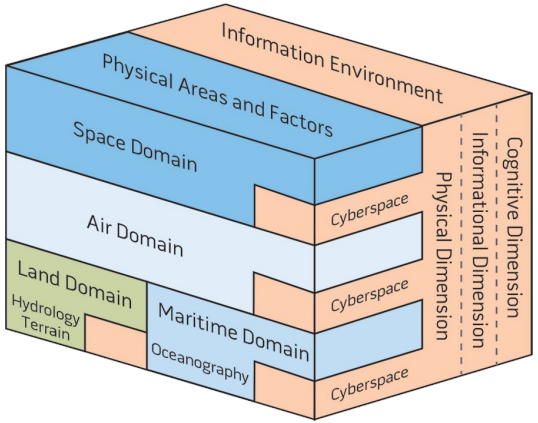
~~Future~~ **Intelligent battlefield systems require autonomic behaviors with efficient closed-loop (safety) controls to ensure reliable and resilient operation at machine-speed in contested environments**

THE "WHY"? MULTI DOMAIN OPERATIONS INCREASE COORDINATION NEEDS

Value proposition:

Support coordination at scale in Contested High-tempo, Heterogeneous, and Distributed Environments





Future command & control information-networks require tighter (cyber-physical) integration across heterogeneous assets in multiple domains

THE IOBT INNOVATION SPACE

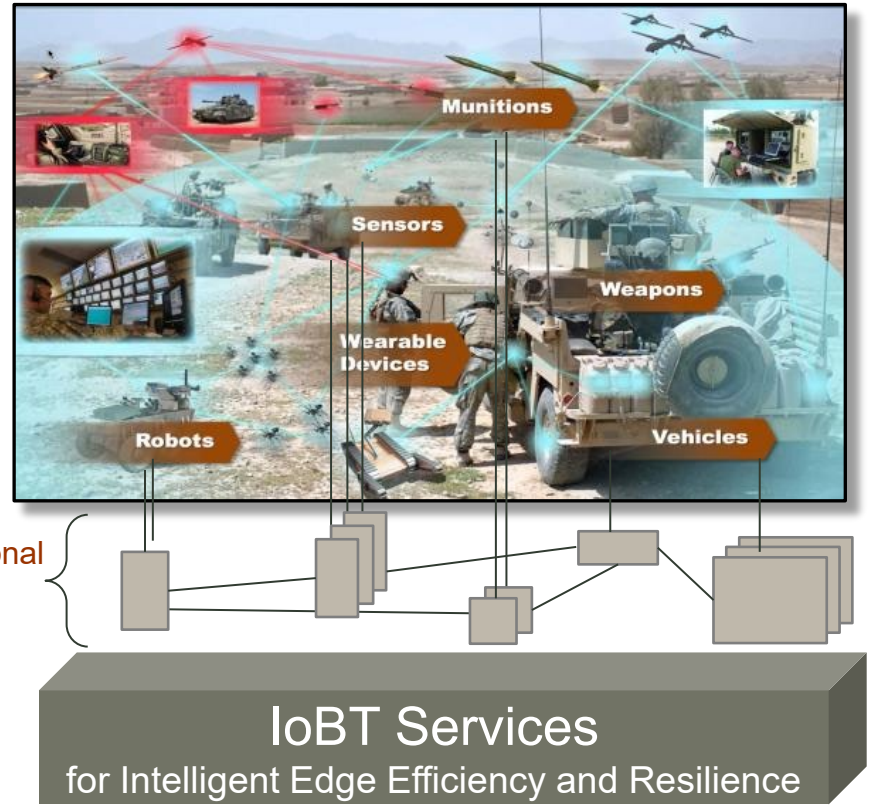
IoBT:

Endows a set of interdependent and interconnected entities at the tactical edge (the "*battlefield things*")

- Smart devices (e.g., sensors, actuators, weapons, vehicles, robots)
- Computing infrastructure (e.g., networks, storage, processing)
- Intelligent analytics (on-node, in-network, de-centralized or centralized)

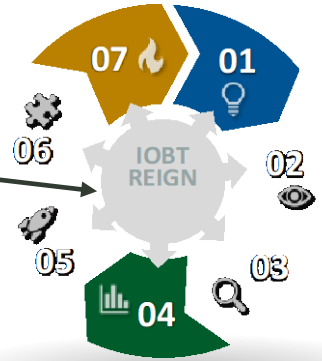
with the capabilities to:

- ***Operate in real time* at the *point of need*** to form a collectively-intelligent complex system-of-systems intended to meet multiple missions, tasks, or goals in contested environments
- Exhibit self-* characteristics (Self-* = *SELF* organizing, configuring, adapting, maintaining, protecting) ***resilient to a wide array of attacks against the computational elements in the system***
- ***(In order to) accelerate the sensor-to-effects loop*** and impact the physical world



DECISION ADVANTAGE WITHIN THE MDO EFFECT LOOP

Intelligent real-time technologies must operate **at the point of need** as a highly **resilient** system-of-systems, dynamically composed to **accelerate the MDO Effect Loop**



Two sides to this concept

- *Red side:* Adversarial engagement in the MDO phases (i.e., **threat** recognition)
- *Blue side:* Cross domain utilization of Joint or Coalition assets (i.e., **asset** recognition)

Critical high-level research challenges for AI-enabling MDO Effect Loop

- Improve efficiency, reduce latency
- Mitigate risk, reduce false positives

Automation will reduce full cycle time from hours/minutes to seconds/sub-minutes

1. Assess & Detect
Conduct reconnaissance and detect entities

2. Identify
Identify threat/asset and relate threat/asset capabilities

3. Locate & Track
Determine location and maintain situation awareness

Threat Recognition
Asset Recognition

4. Aggregate & Synthesize
Collect and communicate sensor data

5. Distribute
Distribute information and actuation recommendations (Capability COAs) in COP updates

6. Decide
Commander's decision enabled and enacted by automated orders

Intelligent Decision Support

7. Effect / Actuate
Affect the physical world and assess decision outcomes

Engage

S. Russell, T. Abdelzaher, N. Suri, (2019) "Multi-Domain Effects and the Internet of Battlefield Things," in *IEEE Military Communications Conference* (MILCOM 2019)

WHAT DISTINGUISHES THE BATTLEFIELD

What is challenging about supporting battlefield functions (putting the "B" in "IoBT")?

The Environment

1. Rapid dynamics
2. Presence of adversaries
3. Contested, constrained, predominately wireless environment

The System

4. Significant heterogeneity
5. Ubiquitous scale in multiple dimensions
6. Resource distribution

Advantage = the ability to outpace/disrupt/degrade peer-adversary's decision cycles

- Competing decision cycles: *Who can best connect their sensors and shooters?*
- Converging distributed sensors/data/effects from ALL domains, at capacity to achieve commander's intent; agnostic to domain, platform, and Service

THREE KEY DIRECTIONS

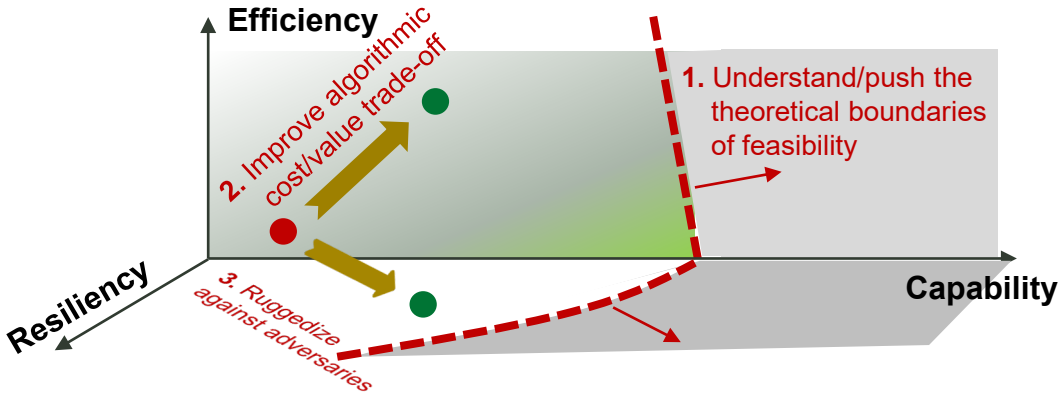
Concepts driving IoBT evolution:

Value proposition: Efficient and Resilient Tactical Edge Analytics for the Sensing-to-Decision (MDO Effect) Loop

1. Efficient → Time is a weapon
Design for timeliness and efficiency of intelligent processing and network communication on edge devices

2. Resilient → IoBT is a fighting network
Offer strong assurances of correctness in the face of adversarial disruption

3. Edge AI → Tailored intelligence at the point of need
Tailor multimodal services for the distributed tactical edge



EXAMPLE INNOVATIONS

Focus #1: Edge Efficiency (Time is a weapon)

Rapid Sensing

- Submodular optimization for network synthesis: **Fast approximations to NP-hard network synthesis** problems
- Statistical theory of **quickest change detection**

Rapid Communication

- Communication efficient compressed distributed learning: **Over 1000x improvement** in distributed learning cost
- Compressive offloading: **Beating state-of-the-art compression by 2x-4x** (e.g., JPG)

Rapid Inference

- Criticality-based attention prioritization for **fast inference**
- Adaptive execution of DNN inference: **Controllable speed/quality trade-offs**
- Theory of model compression: **Fundamental storage bounds**

Focus #2: Resiliency (of Decision Loop Analytics)

Intrinsically Resilient Edge Systems

- New neural **network architectures for improved edge resiliency** and interpretability
- **Robust inference** despite distribution shifts
- **Secure deep learning** inference for IoT devices

Safe Resource Allocation

- Risk-aware resilient task placement: **Tolerance to resource outages** via risk-aware placement
- Safe reinforcement learning

Adaptation to Contextual Shifts

- Robustness to adversarial inputs: **Deep learning robustness** to out-of-distribution data
- Detection and **mitigation of attacks on sensors**
- Detection and mitigation of data attacks on distributed learning

Focus #3: Tailored Intelligence (at the Point of Need)

Opportunistic & Unconventional Sensing

- **Opportunistic and unconventional sensing** exploiting common radios (WiFi, LoRa, LTE) for sensing purposes

Adaptive, Distributed Prediction

- Adaptive distributed inference: **Splitting tactical edge analytics across heterogeneous devices**

Theory of Uncertainty Quantification

- Theory of **uncertainty quantification at the point of observation**
- Novel learning paradigms: **Learning in the frequency domain** to reduce inference cost

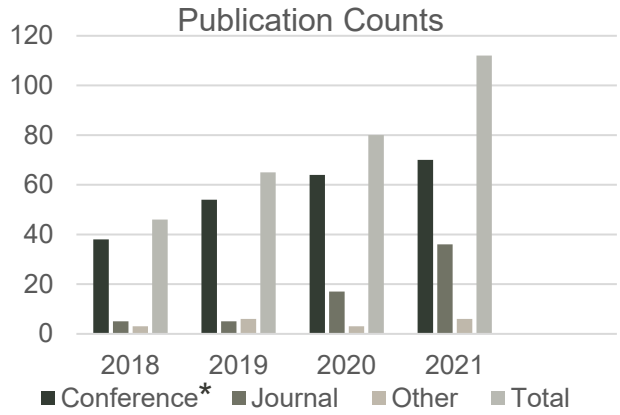
TECHNICAL ACCOMPLISHMENTS

IoBT REIGN

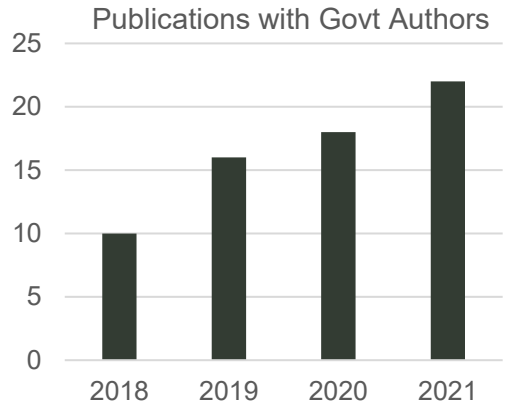
DEVCOM ARMY RESEARCH LABORATORY

Recent Distinguished/Best Paper Awards:

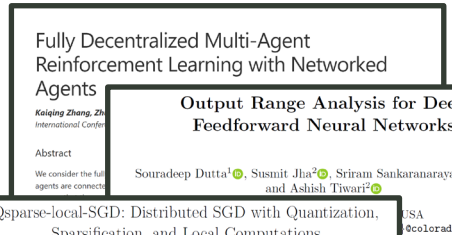
- ***Krishnamachari:*** Best Paper Award, "DEFER: Distributed Edge Inference for Deep Neural Networks," Workshop on Machine Intelligence in Networked Data and Systems (MINDS), held in association with COMSNETS 2022.
- ***Krishnamachari:*** Best Paper Award, "Revealing a Hidden, Stable Spectral Structure of Urban Vehicular Traffic," IEEE Vehicular Networking Conference (VNC), 2021
- ***Xiong:*** Distinguished Paper Award, "Exploring LoRa for Long-range Through-wall Sensing," IMWUT '20 (UbiComp '21)
- ***Abdelzaher:*** Best paper award, "On Removing Algorithmic Priority Inversion from Mission-critical Machine Inference Pipelines," IEEE RTSS, 2020
- ***Nahrstedt:*** Best Paper Award, "SEAWARE: Semantic-Aware View Prediction System for 360-degree Video Streaming," IEEE International Symposium on Multimedia, 2020
- ***Abdelzaher:*** Best paper award, "Deep Compressive Offloading: Speeding Up Neural Network Inference by Trading Edge Computation for Network Latency," ACM Sensys, 2020
- ***Srivastava:*** Award for 2nd Runner Up, Activity Recognition Challenge, International Conference on Activity and Behavior Computing, 2020
- ***Shenoy:*** Best Paper Award, IEEE International Green and Sustainable Computing Conference (IGSC), 2020
- ***Abdelzaher:*** Distinguished Paper Award, "SenseGAN: Enabling Deep Learning for Internet of Things with a Semi-Supervised Framework," IMWUT Vol. 2
- ***Tabuada:*** Best New Application Paper Award, "Correctness Guarantees for the Composition of Lane Keeping and Adaptive Cruise Control," IEEE Transactions on Automation Science and Engineering 2019
- ***Abdelzaher:*** Top 3 paper award, "Unsupervised Fact-finding with Multi-modal Data in Social Sensing," Fusion 2019.
- ***Shenoy:*** Best Paper Award, "Combining Renewable Solar and Open Air Cooling for Greening Internet-Scale Distributed Networks," 10th ACM International Conference on Future Energy Systems (ACM e-Energy), 2019



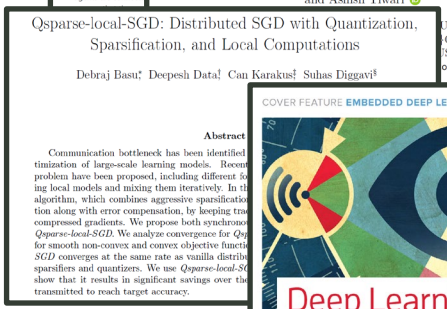
***Note:** Computer Science conferences are as competitive as journals (usually 15-25% acceptance rate)



WELL-CITED AND OTHER IMPACTFUL PUBLICATIONS

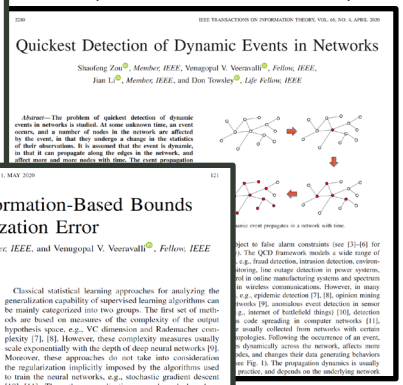


PMLR Proceedings of Machine Learning Research
(**320+ citations** since 2018)



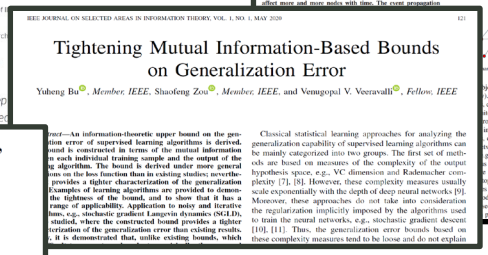
NASA Formal Methods Symposium
(**190+ citations** since 2018)

IEEE Computer Cover Feature
(**100+ citations** since 2018)

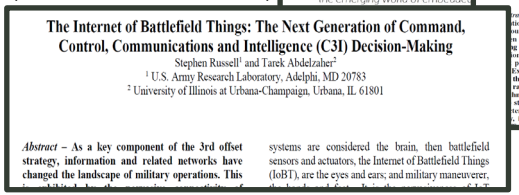


IEEE Trans. Information Theory
(**25+ citations** since 2020)

arXiv, IEEE JSAC
(**140+ citations** since 2019)



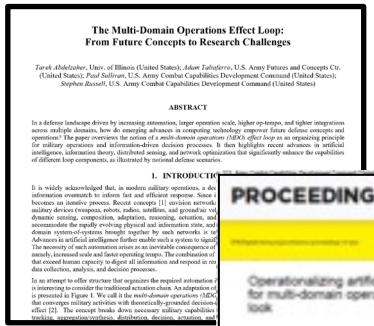
MILCOM
(**45+ citations** since 2018)



IEEE JSIT
(**80+ citations** since 2020)

Associate Editorships

FCC Co-Authored Papers



SPIE, 2020
(2nd **most downloaded/viewed brief**, according to press release)

INTEGRATED EXPERIMENTATION

IoBT REIGN DEVCOM ARMY RESEARCH LABORATORY

Objectives

- Establish collaborative experiments validating synergies and exposing opportunities for IoBT research
- Evaluate IoBT technology in an operational context with full decision cycles
- Drive academic-government collaboration and technology transition

Multimodal Reconnaissance in Resource-Constrained Environments

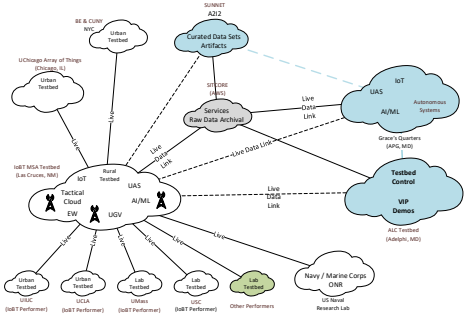
Target identification

Distributed processing

Detection verification

Compressed communications

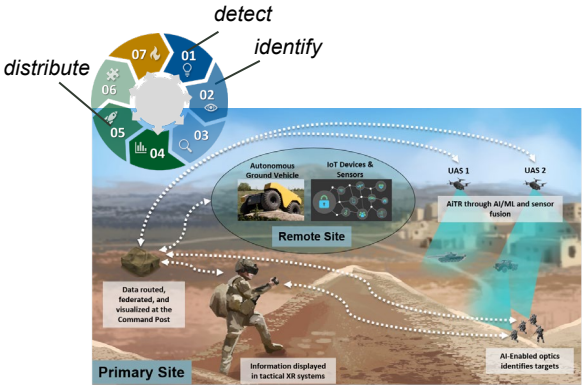
Distributed Virtual Proving Ground



Environment for live, physically distributed experimentation

Rapid assessment and learning of emerging capabilities

Full MDO Decision Cycle Applications



Integration with ongoing experiments for decision cycle evaluation

KNOWLEDGE PRODUCTS AND APPLICATIONS

IoBT REIGN DEVCOM ARMY RESEARCH LABORATORY

Technical Research Focus

Focus #1: Edge Efficiency (Time is a Weapon)

Focus #2: Resiliency (of Decision Loop Analytics)

Focus #3: Tailored Intelligence (at the Point of Need)

Accomplishments

- Rapid Task-driven IoBT Asset Synthesis
- Compressed Learning and Inference at the Distributed IoBT Edge
- Resilience to Surprise
- Robust Estimation/Learning in Non-stationary and Adversarial Settings
- Uncertainty Estimation
- Unconventional, RF, and Multimodal Sensing

Applications and Tools

- IoBT Digital Twin (with Boeing)
- DARTS
- ACROPOLIS
- MedEvac Systems
- Trinity
- URSA Bench
- Urban Operations, Triage

Concept Evaluation

Distributed Virtual Proving Ground (DVPG) Testbed

KNOWLEDGE TRANSITION & INTEGRATION SUMMARY

IoBT REIGN

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NATO OTAN

JAIC

UQ software for edge computation

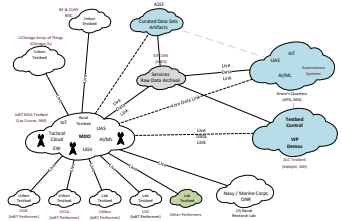
URSA Bench
Uncertainty • Robustness • Speed • Accuracy
https://github.com/reml-lab/URSABench

IoBT FE to support Army Concept Framework

AFC Deep Dive on IoBT

AI STRATEGIC CHALLENGE

Multimodal AI technology integration for TATE pillar experimentation



***DVPG**: distributed experimentation at IoBT relevant scale*

IoBT Special Session & Panel
MILCOM, December 2021

Special Session Topics
- **ML & Optimization**
- **Computation at the Edge**
- **Security**

MILCOM IEEE ComSoc IEEE Communications Society

Panel: *The IoBT: From Research Priorities to Decision Overmatch*

DoD

Scientific Community

ARL

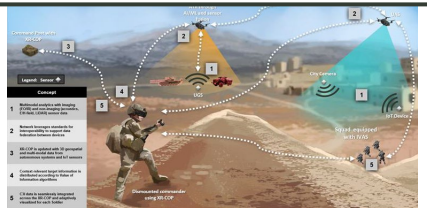
Industry

Connections to Competencies

Military Information Sciences
Use of information to maximize effectiveness of information systems and decision-making

Network, Cyber & Computational Sciences
Unifying approaches for highly adaptive network-cyber-computing to achieve decision dominance

Pathway to PC and EDGE Events



DARTS and ARL Experiment Excursion: ACROPOLIS

George Mason University · The University of Texas at Austin · MIT Massachusetts Institute of Technology · Technische Universität Berlin · Princeton University · Drexel University · Chalmers University of Technology · The University of Edinburgh · University at Buffalo

@WalmartLabs · amazon · Samsung Research · Pinterest · MITRE · STARTUP · Google · facebook · intuit

The IoBT CRA has trained over 50 students who have gone on to academia and industry

BOEING

IoBT digital-twin implementation to simulate multi-domain operations involving Navy drone/UAS carriers.

PROGRAM PLANNING & REVIEW

1: TMG Strategic Planning Meeting

Strategic planning meeting to adjust for Army & Alliance dynamics and plan for BPP landscape; target transition opportunities, and strategic communications

2: Annual Tech Review

Review CRA status & progress in context of approved BPP; assess performance metrics

3: Competitive BPP

Competitive BPP proposal solicitation, open to broad consortium member orgs and reviewed by internal and external stakeholders

4: BPP Approval

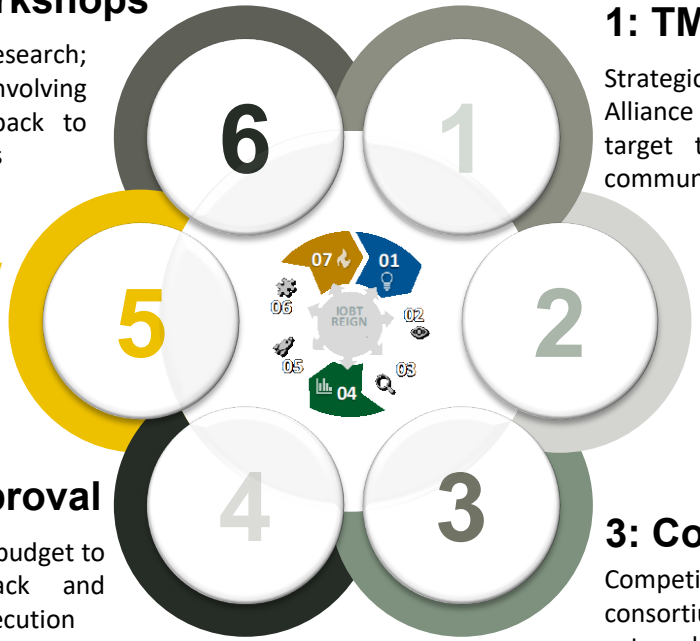
Revise BPP and adjust budget to account for feedback and approve tasking for execution

5: RMB / CRA Review

CRA review engages ARL and selective strategic stakeholders for feedback in non-RMB years

6: Bootcamps & Workshops

Collective meetings to present research; strategic topic focus and involving stakeholders; incorporate feedback to adjust research and define demos



SUMMARY OF ACTIONS SINCE LAST RMB

What we heard…

Programmatic Guidance

1. Some similarity to the Distributed and Collaborative Intelligent Systems and Technology (DCIST) CRA
2. What is the plan for *early* transition?
3. “Didn't claim enough credit for collaborative work.”
4. How many students has IoBT graduated and how many government-collaborative publications were made?

What we have done…

Programmatic Adjustments

1. Refactored research to concentrate on “enabling the common operating environment," putting greater emphasis static assets and the full MDO decision cycle
2. Identified early transition opportunities via experimentation (e.g., Project Convergence, AISC); Added 3 new agency collaborations (AI2C, JAIC, USMA)
3. Reporting collaboration efforts regularly in briefs
4. Continued to collect metrics quarterly and incorporated into review briefs

SUMMARY OF ACTIONS SINCE LAST RMB

What we heard…

Technical Guidance

1. Continue/increase emphasis on the challenges of scale, heterogeneity, dynamics, and adversarial threats
2. Should address issues of a fighting network, not just one that optimally places sensors or addresses distributed inference/learning
3. Focus on non-combatant (gray) resources/assets should include further emphasis on securing the channels
4. Would be great to demonstrate technology in a larger empirical demonstration context, such as Project Convergence (PC)

What we have done…

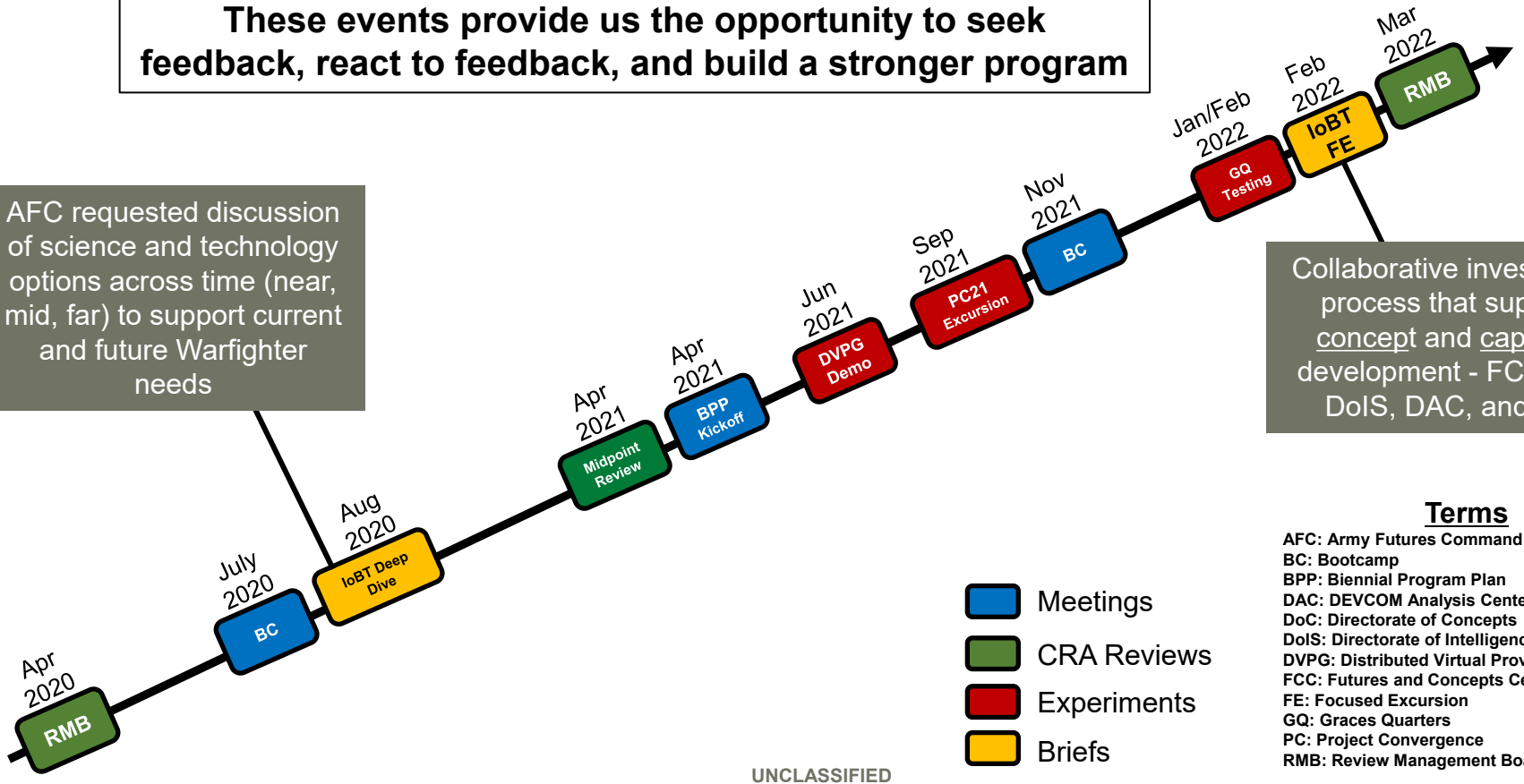
Technical Adjustments

1. Reorganized research areas into major knowledge product themes: Efficiency, Resiliency, and Edge Intelligence
2. Added emphasis on the Resiliency theme, which specific focus on detection of adversarial manipulation and safey decision making
3. Reduced the emphasis on gray assets, thus minimizing concentration on securing channels (securing channels is research area in Cyber CRA)
4. Identified ways to inject technology into larger experimentation and demonstration efforts e.g., PC and TTCP exercises, and redesigned CRA integrated experimentation to align with full decision cycle execution

MAJOR EVENTS SINCE LAST RMB

These events provide us the opportunity to seek feedback, react to feedback, and build a stronger program

AFC requested discussion of science and technology options across time (near, mid, far) to support current and future Warfighter needs



Collaborative investigative process that supports concept and capability development - FCC DoC, DoIS, DAC, and ARL

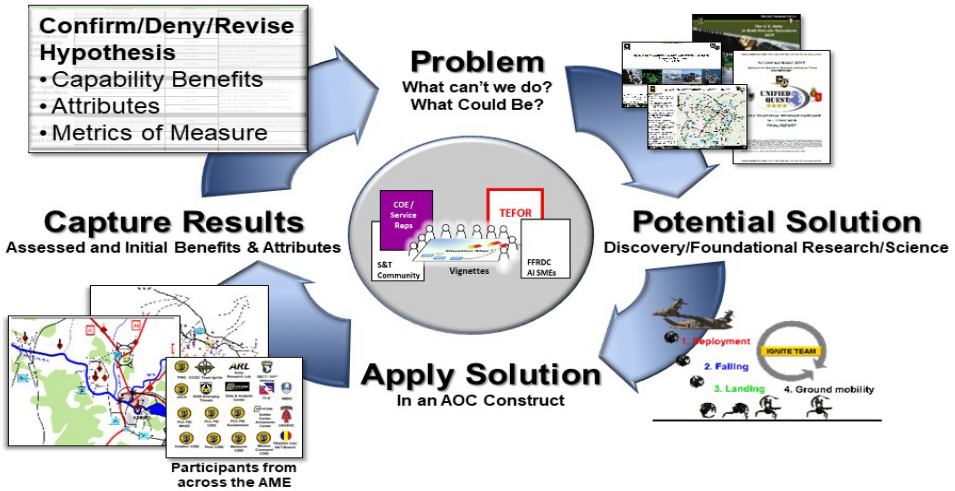
Terms

AFC: Army Futures Command
BC: Bootcamp
BPP: Biennial Program Plan
DAC: DEVCOM Analysis Center
DoC: Directorate of Concepts
DoIS: Directorate of Intelligence and Security
DVPG: Distributed Virtual Proving Ground
FCC: Futures and Concepts Center
FE: Focused Excursion
GQ: Graces Quarters
PC: Project Convergence
RMB: Review Management Board

IOBT FOCUSED EXCURSION

- **Focused Excursion:** a deliberate investigative process that supports concept and capability development through a collaborative examination of a particular research area across the technical, concepts, threat, and analytic communities
- **IoBT Focused Excursion:**
  - Collaboratively hosted by DEVCOM & FCC
  - IoBT CRA leadership team (ARL and academia) represented the technical SMEs
  - Initial Hypotheses centered around our research thrust areas: Efficiency, Resiliency, Edge Intelligence

FCC's Future Study Program (FSP) and **DEVCOM-FCC's Focused Excursions (FE) are the key experiments used to assess and refine how the Army of 2040 could operate, be equipped, and be organized**; and the associated concepts' priority S&T needs



FOCUSED EXCURSION TAKEAWAYS

Operational Hypotheses

IoBT will help commanders distill prioritized information from vast amounts of data faster for decision making by providing efficient, real-time processing

IoBT capabilities that provide robustness, resiliency, and adaptive services in the face of adversarial disruption and deception in conjunction with camouflaged sensing and communication, are essential to maintain commander confidence in data and reduce risk

IoBT will increase situation awareness tempo by exploiting ubiquitous, multimodal sensors, unconventional sensing, and edge computation in the operating environment

IoBT, with rigorous testing and training, will enable trust despite a contested and dynamic environment by providing performance guarantees, uncertainty quantification and the ability to explain

Key Takeaways

Potential High Impact Research Priorities:

- **Efficiency at scale** in the presence of vast amounts of data
  - Semantic compression; processing at the edge
  - Prioritization and filtering of data push
  - Optimal network usage and network inference
- **Reconfigurable and adaptable algorithms** to induce **flexibility** (flexibility empowers creative alternatives)
  - Dynamic tuning to changing priorities/objectives
  - Resilience, safety, and risk mitigation (a distribution-tail challenge)
  - Fast optimization
- Information verification by exploitation of **multi-modal and multi-vantage sensing** for joint inference
  - Hybrid analytics – ML and rule-based; multiple time-scales
- **Uncertainty quantification** of network or analytics composition (in the presence of open/commercial sources)

FOCUSED EXCURSION TAKEAWAYS

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IoBT will be critical for future success on the battlefield

Key Takeaways

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IOBT CRA RMB REVIEW

Questions?

To view read-ahead material visit:

https://iobt.illinois.edu/RMB22-Readahead

Start	Topic	Presenter
1300	Welcome – Introductions	Kott
1310	Program Overview	Wigness/Abdelzaher
1350	Research Focus 1: Efficiency & Timeliness	Verma/Fragouli
1420	Research Focus 2: Resiliency	Kaplan/Tabuada
1450	**Break**	
1500	Research Focus 3: Intelligence at the Point of Need	Panneton/Shenoy
1530	Experimentation Overview	Wigness/Shenoy
1550	IoBT – Way Ahead	Swami/Abdelzaher/Wigness
1610	**Break**	
1620	RMB Caucus (Government Only)	All Government
1700	Adjourn	