Internet of Battlefield Things Collaborative Research Alliance

(Phase II)

Alliance for IoBT Research on Evolving Intelligent Goal-driven Networks (IoBT REIGN)

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Executive Summary

Purpose: The IoBT CRA advances and transitions the scientific foundations of *performant and resilient* (*intelligent) computational and sensing services, tailored for the future tactical network edge*. It is motivated by the rise of machine intelligence capabilities that promise to transform defense applications, but also introduce significant performance and resilience challenges at the edge. The future tactical edge will increasingly utilize myriads of multimodal intelligent sensors and heterogeneous computing resources, deeply embedded into an adversarial environment, networked together to increase flexibility, enhance real-time decision making, increase the tempo of situational awareness, trigger effects, and improve insight into enemy actions. The execution of such sensor-to-effect loops will meet new challenges arising from spatial distribution of intelligent computation, accelerated mission-tempo, transient nature of resources, uneven environmental conditions, and the presence of adversarial activity. *The IoBT CRA develops the foundations of efficiency and resilience of sensor-to-effect loops in the new intelligent networked computational and sensing substrate* of the future tactical edge.

Accomplishments: The first five years of IoBT CRA effort shaped the scientific research frontier in three ways:

Edge Efficiency: Recognizing that *time is a weapon*, we accelerated intelligent sensor-to-effect decision loops at the tactical edge, producing up to 100x efficiency gains in edge-AI-based sensing, and nearly 10x gains in network synthesis speeds, without loss of inference quality. These advances allow pushing intelligent data analytics to the point of observation thereby significantly shortening decision cycles and latency, while offering intelligent mission-informed data filtering at the edge to reduce load on the (possibly contested) tactical network.

Edge Resilience: Recognizing that *IoBT executes in adversarial settings*, where new attacks on machine intelligence are possible (to disrupt decision loops and intelligent automation), we developed foundations of resilience for neural-network-based edge analytics. They include improved resilience to adversarial inputs, risk analysis, 10x faster sensor attack detection, and bounds on worst-case neural network outcomes in the presence of adversarial activity or surprise.

Tailored intelligence at the point of need: We tailored novel intelligent capabilities to the tactical edge to better exploit heterogeneity, multimodal and unconventional sensing, and compute uncertainty. Examples include opportunistic exploitation of commodity radios as sensors, neural networks for inference in the frequency domain, and distribution of machine learning models across heterogeneous edge systems to meet a slew of objectives and constraints.

Collectively, the work resulted in over 300 publications, with active technology and scientific knowledge transitions to Boeing, DARPA, and IARPA, inspired the design of experimentation capabilities, such as ARL's DVPG testbed, contributed to ARL experiments (ACROPOLIS) ran as a side excursion of PC21, and funded over 50 students many of whom moved on to accept positions in academia and industry.

Way Ahead: Our future investigation is driven by hypotheses that describe operational capabilities that IoBT may provide for the future fight. A recent Focused Excursion (FE), which is a deliberate investigated approach to explore a particular research area across the technical, concepts, threat and analytic communities, was conducted around these IoBT hypothesized capabilities. Through collaborative discussion in the context of operational vignettes, with participants from ARL, DoC, DoIS, several CDIDs, and DAC, the FE resulted in the refinement of these hypotheses and identification of high-impact research priorities. The resulting operational hypotheses are summarized as follows: ***Hypothesis #1*** *(greater efficiency):* IoBT will help distill prioritized information from vast amounts of data faster for improved decision making. ***Hypothesis #2*** *(reduced tactical risk):* IoBT foundations of robustness, resiliency, and adaptive services are essential to maintain confidence in data and reduce risk. ***Hypothesis #3*** *(increased SA tempo):* IoBT will help support an increased situational awareness tempo by exploiting ubiquitous, multimodal sensors, unconventional sensing, and edge computation in the operating environment. These hypotheses inspire selection of our future research directions.

Proposed Research Directions: We propose three key research directions:

Efficiently Managing the Scale of IoBT: Ubiquitous sensing will allow the future force to "look everywhere." IoBT must address data *scale* and *heterogeneity* with automated processing, communication, and prioritization to ensure it does not engulf the Soldier/Commander. This thrust will focus on prioritization of information, optimal network usage and sharing of computational resource, and uncertainty quantification as it relates to working with vast amounts of data.

> ***Gaps:*** Lack of longevity of edge AI capabilities on resource-limited devices (some analytics may fit on the edge but cannot last the entire mission) in the presence of vast amounts of data. Limited emphasis on uncertainty quantification in the presence of mostly non-sympathetic (e.g., commercial) resources, and characteristics (e.g., asynchronous data rates) observed due to large scale and heterogeneity.
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> ***Proposed Solutions:*** We aim to achieve efficiency across scale and heterogeneity via (i) an additional 10x-100x reduction in edge resource consumption, allowing for greater data throughput, (ii) performing mission-based filtering to generate data prioritization for task assignment, and (iii) breaking functional barriers by integrating sensing and communication for hyper-efficiency in both network synthesis and network operation. The above will be complemented by analysis to understand theoretical limits, bounds, and near optimal algorithms guided by fundamental limits, in the solution space of the above capabilities.

Reconfigurable and Adaptable Systems to Induce Flexibility: The future battlefield will be highly dynamic due to changing environment conditions, adversarial disruption/deception, and changing mission goals. IoBT must provide self-* (*=aware, organizing, adapting, maintaining, protecting) characteristics to maintain resiliency. This thrust will focus on foundations of resilient optimization and on quantifying/mitigating tactical risk, both in the presence of highly dynamic and adaptive adversaries that cause continual changes and disruptions, thereby preventing the IoBT from ever reaching a steady state. This includes dynamic network synthesis, processing and communication strategies based on evolving objectives, and fast optimization across latency, energy and accuracy.

Gaps: Lack of theory for resiliency, safety, risk-analysis and optimization in persistently transient systems (that are in a state of perpetual change, or non-stationarity, at fast rates due to adversarial action/adaptation). Limited theory for risk/tail analysis in ML, such as bounds on the tail of the outcomes distribution to understand worst-case risks, and dynamically tunable system parameters for changing priorities.

Proposed Solutions: New theoretical foundations will be developed for optimization, resilience, and risk analysis in persistently transient distributed systems. Foundations will be developed for effective and safe actuation despite non-stationarity (in an adversarial setting), as well as foundations for risk analysis and resilient optimization in ultra fast-changing environments. Relevant theoretical feasibility bounds will be derived.

Tactical Edge Coordination: Edge processing is critical to provide information at the point of need, but needs to evolve to incorporate coordination among entities to generate insights within a larger, global battlespace context. This thrust will focus on flexible exploitation of heterogeneous and multi-vantage sensing for joint inference, distributed edge inference and composability at multiple timescale, and multi-modal verification.

Gaps: Current (neural-network-based) analytics do not offer plug-and-play functionality with respect to highly heterogeneous underlying hardware and sensing modalities, and do not compose well across different time-scales, thereby reducing flexibility in available course-of-action alternatives at the tactical edge.

Proposed Solutions: Solutions will be investigated for compositionality at the tactical edge that break existing stovepipes: devices are "more intelligent together". These include unified latent representations across multiple sensing modalities for flexible and interchangeable opportunistic exploitation of available heterogeneous sensors; extensions of neuro-symbolic computations to support compositional reasoning at multiple time-scales; and scalable algorithms for load distribution in heterogeneous edge systems.

Validation

Loosely following a DARPA Challenge model, future efforts of the IoBT CRA will be structured into a matrix of Experimental Validation Challenges, supported by cross-cutting research themes aligned with the innovation axes above. The selection and refinement of challenges is driven by stakeholder needs and concepts of future warfare. The validation plans will also both advance and leverage ARL's Distributed Virtual Proving Ground (DVPG), enabled in part by activities from the first five years of the IoBT CRA. Validation efforts will feature collaboration with stakeholders to identify scenarios and metrics, such as (i) classification at the point of observation (to increase the tempo of situational awareness), (ii) improving the target-decoy discrimination gap (in collaboration with DARTS), (iii) increasing the efficacy of logistics and MedEvac (in collaboration with West Point), and (iv) tailoring intelligence for the tactical edge (in collaboration with the TATE pillar of the Artificial Intelligence Strategic Challenge of the TTCP program). We shall leverage the CRA's BPP process to continually refine and augment such validation challenges as the project evolves and opportunities arise. If successful, optional years of the IoBT CRA will address *scale*, *adaptation, heterogeneity*, and *coordination* challenges in resilient and performant networked edge systems, supporting command and control (C2).