Artificial Intelligence Exploration (AIE) Opportunity
DARPA-PA-18-02-03
Microscale Bio-mimetic Robust Artificial Intelligence Networks (µBRAIN)

I. Opportunity Description

The Defense Advanced Research Projects Agency (DARPA) is issuing an Artificial Intelligence Exploration (AIE) opportunity inviting submissions of innovative basic research concepts exploring new computational frameworks and strategies drawn from the impressive computational capabilities of very small flying insects for whom evolutionary pressures have forced scale/size/energy reduction without loss of performance.

This AIE opportunity is issued under the Program Announcement for AIE, DARPA-PA-18-02. All proposals in response to the technical area(s) described herein will be submitted to DARPA-PA-18-02 and, if selected, will result in an award of an Other Transaction (OT) for prototype project. The total award value for the combined Phase 1 base and Phase 2 option is limited to $1,000,000. This total award value includes government funding and performer cost share, if required.

A. Introduction

The past decade has seen explosive growth in development and training of AI systems, which are now embodied in digital computing processes spanning several key industries. However, as AI has taken on progressively more complex problems, the amount of computation required to train the largest AI systems has been increasing ten-fold annually.[1] While AI advances are beginning to have a deep impact in digital computing processes, trade-offs between computational capability, resources and size, weight, and power consumption (SWaP) will become increasingly critical in the near future. Current neuromorphic/neural architectures with massive fan-out and fan-in and extensive training rely on the digital computing architectures that attempt to mimic the way nature computes, but not the way it functions. Actual physical interactions/mechanisms that could enable improved engineered function as observed in bio-systems, such as miniature insects, remain to be fully described.

This AIE opportunity invites proposers to submit innovative basic research concepts aimed at understanding highly-integrated sensory and nervous systems in miniature insects and developing prototype computational models that could be mapped onto suitable hardware in order to emulate their impressive function. Nature has forced on these small insects drastic miniaturization and energy efficiency, some having only a few hundred neurons in a compact form-factor, while maintaining basic functionality. Furthermore, these organisms are possibly able to display increased subjectivity of experience, which extends simple look-up table responses to potentially AI-relevant problem solving. This research could lead to capability of inference, prediction, generalization and abstraction of problems in systematic or entirely news ways in order to find solutions to compelling problems.

The primary goal of this effort is to understand the computational principles, architecture, and neuronal details of small bio-systems driven by extreme SWaP needs in nature. By doing so, DARPA aims to identify new computing paradigms that will enable improved AI with considerably reduced training times and power consumption.

B. Objective/Scope

Studying miniaturized insects may reveal fundamental innovations in architecture and computation analogous to their simultaneous simplicity, efficiency, and complex functionality. Compared with larger-brained organisms, these insects may hold the keys to strategies for AI that combine energy- , time-, and space-efficient operation.

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[1] https://blog.openai.com/ai-and-compute

Several parasitic insects, such as the *Megaphragma mymaripenne*, have nervous systems consisting, when born, of what appears to be just a few thousand neurons. Their extremely small (order of microns), low-power, and fast integrated sense-control-actuate systems achieve significant guidance and locomotion functions in the service of higher-level behaviors such as feeding, reproduction, and survival. Moreover, these competing goals are achieved using far fewer neurons in adulthood as a result of a "neural downsizing." These insects develop over several days through a series of larval stages (instars) followed by a pupal step prior to emerging as adults. Training during the larval stage reflects seasonal, social, and environmental effects that lead to the final neural system while undergoing physical miniaturization during the larval stages. However, significant aspects of this process are not well understood, including: the electrical and magnetic circuitry; how that circuitry develops to manage the information processing in these miniaturized systems; and how or if extreme selection pressures to miniaturize reduces energy requirements while maintaining or increasing functionality.

Some recent hypotheses address these unknowns. For example, the "retrograde extension"[2] hypothesis postulates that sensors and neuronal processers are not separate systems, but must instead grow and be trained synergistically. It is unknown how this extension process would adapt and develop using feedback from both environmental factors and from training. It is also unknown if abstraction and problem solving continue to develop after neural downsizing, when significant functionality becomes embedded and hardwired, or if it is necessary to know *a priori* what the final input function space is going to be.

Developing and understanding the computing model behind a miniature insect's problem solving capabilities may provide new computational strategies. It is not only interesting to model how these minimal systems might work, but also to understand how they may work differently. Local computation is more energy-efficient in miniaturized insects; neural density and structure are different close to sensors and actuators. However, DARPA is interested in whether there are generic and generalizable adaptations rather than simply studying how yet another insect brain works. Maps of neural interconnectivity schemes without a computational model that is informed by a physical model will not meet DARPA's μBRAIN objectives. Selected performers will create computational models inspired by these insects that provides insights for new efficient approaches to contextual AI. These models should be generalizable beyond addressing Maslow level 1 and 2 physiological and safety needs and explicitly enable functional analysis.

Understanding the computational principles, architecture, and neuronal details of these miniaturized bio-systems could provide a fundamentally new way of thinking about information processing, including with regard to time and energy requirements. A number of factors related to miniaturized insects might be relevant:

i) Sensing, memory, processing, and actuations are integrated into a system that can be smaller than a few human neurons.
ii) During growth, a reduction in neuron count takes place and some neurons become anuclear, and have no obvious input or output. In *M. mymaripenne*, the pupa has ~7,400 nuclei, reducing by a factor of 10 after emergence into adulthood, while still retaining vital behaviors (flight, feeding, and search for host to lay eggs).
iii) Neurons vary less in size (reducing to ~40nm) and the volume of the cytoplasm decreases with the neuron occupying up to 90% of the cell volume.

[2] https://doi.org/10.1016/j.cell.2009.01.057

iv) Signaling migrates from spiking neuronal behavior to graded potentials due to much shorter distances between neurons. Closer proximity may result in other forms for signaling (e.g. electric near-field coupling, magnetic coupling with the presence of magnetite, etc.)
v) Evidence suggest even small insects have subjective experiences, the first step towards a concept of "consciousness" may imply some ability to infer/generalize/abstract.
vi) Mushroom bodies in the insect brain are associated with learning and memory and are larger in social insects.

It is postulated that in achieving this level of performance with such low SWaP, biological systems require a different set of guiding principles operating at multiple levels (physics, chemistry, components, architecture, and computational model). Approaches to identify these principles and extend them, if possible, to arbitrary situations that can inform our current problem-solving capabilities using AI would be of specific interest. Proposers should address if their models, when taken to increasingly higher levels of complexity and abstraction, can provide new explainable mechanisms underlying thought and intelligent behavior.

II. Structure

Proposals submitted to DARPA-PA-18-02 in response to this AIE opportunity must be UNCLASSIFIED and have an 8-page limit. Proposals must address two independent and sequential project phases (a Phase 1 Feasibility Study (base) and a Phase 2 Proof of Concept (option)). The periods of performance for these phases are 6 months for the Phase 1 base effort and 12 months for the Phase 2 option effort. Combined Phase 1 base and Phase 2 option efforts for this AIE opportunity should not exceed 18 months. The Phase 1 (base) award value should not exceed $200,000. The Phase 2 (option) award value should not exceed $800,000. The total award value for the combined Phase 1 and Phase 2 is limited to $1,000,000. This total award value includes government funding and performer cost share, if required.

III. Schedule/Milestones

Proposers must address the following research project objectives, metrics, and deliverables, along with fixed payable milestones in their proposals. The task structure must be consistent across the proposed schedule, Task Description Document (TDD), and the Vol. 2 - Price Volume. Proposers must complete the "Schedule of Milestones and Payments" Excel Attachment provided with this AIE opportunity as part of submitting a complete proposal and fulfilling the requirements under Vol. 2 Price Volume. Performers can supplement the required milestones with additional milestones if needed, and should propose estimated funding for each. If selected for award negotiation, the fixed payable milestones provided will be directly incorporated into Attachment 2 of the OT agreement ("Schedule of Milestones and Payments"). Proposers are encouraged to use the TDD template provided with this AIE opportunity, which will be Attachment 1 of the OT agreement.

For planning and budgetary purposes, proposers should assume a program start date of April 3, 2019. Schedules will be synchronized across performers, as required, and monitored/revised as necessary throughout the program.

It is expected that proposed efforts in the µBRAIN program would develop a prototype model via several approaches that may include but are not limited to:

- Creating a physical model of neuronal systems and information processing of miniaturized insects and how their energy needs would scale with complexity.
- Analyzing structural changes of neuronal systems of miniaturized insects through their development to understand training and the process of eliminating neuronal resources as they develop into adulthood.

- Proposing alternate hardware platforms that mimic neuronal systems of such insects as a method to develop hardware implementations of computational models.

The program will be comprised of 2 phases: Phase 1 (6 months) will be mapping input/output channels of a model insect's central intelligence system and understanding fundamental physical interactions involved in signaling; Phase 2 (12 months) will be focused on developing prototype computational models based on the analysis in Phase 1 and proposing new hardware platforms and training/developmental strategies that can be applied to general problem spaces. This knowledge could result in energy efficient and more capable AI hardware.

Proposing teams are expected to have significant expertise in i) the physiology of insects and their neural-sensory systems; and ii) computer science, signal processing, and computing architectures. Teams need to be able to identify the chemical and electromagnetic interactions involved in signaling in miniaturized distributed neural systems.

Phase I fixed milestones for this program must include, at a minimum, the following (but proposers should provide additional detail, specific to their proposed project, as necessary):

Month 1: Based on an in-depth literature survey, provide a comprehensive description of the neural system of a class of miniaturized insect to be studied. Include an overview of known information regarding the optimization of the neural system through all larval and pupa stages. Specify what further information/analysis would be required to fully capture all signaling mechanisms through development to maturity in the neural system and what further information/analysis would be required to identify an appropriate hardware platform to implement such neural architectures.

Month 3: Provide a report detailing new findings of the physiology of the larval/pupal/insect neural system, including neuron structure (e.g. nucleate/anucleate), physical structure of the neural system (e.g. identification of mushroom bodies), and how they change in the maturation stages.

Month 4: Provide an analysis of the signaling mechanisms involved (e.g. chemical, mechanical, electromagnetic) in the development of the chosen neural system as well as the energy requirements for all pathways as the system matures. Identify and prioritize potential hardware platforms that this signaling framework could map onto.

Month 6: Abstract the input and output channels and map findings onto a new computational model for problem solving in generic function/problem spaces. Provide a report detailing input/output channels and new computation model. Submit Phase I Final Report for μBRAIN prototype project if Phase 2 effort is not awarded.

Phase II fixed milestones for this program must include, at a minimum, the following (but proposers should provide additional detail, specific to their proposed project, as necessary)::

Month 9: Provide a report with an initial hardware design for a single neuron unit cell and neural system that the model could map onto. Indicate how energy requirements scale with the number of neurons, given the physical mechanisms responsible, e.g. energy minimization or active inference for learning/training for information processing.

Month 12: Provide a prototype computational model comprising 1000 insect neurons. Quantify how energy requirements scale with the number of neurons, and explain what physical processes drive performance in information processing and prediction capabilities.

Month 15: Provide a report identifying and detailing the full analog/digital hardware platform on which the prototype computational model could be implemented and verified.

Month 18: Determine how new principles scale in the energy and time domain as a function of:

i. Complexity of input/output signals

ii. Number of input and output channels
iii. Adaptability to changing problems/contexts
iv. Training to update for dynamic function spaces

Submit Final Report for μBRAIN prototype project.

All proposals must include the following meetings and travel in the proposed schedule and costs:

- To foster collaboration between teams and disseminate program developments, a two-day Principal Investigator (PI) meeting will be held approximately every six months, with locations split between the East and West Coasts of the United States. For budgeting purposes, plan for four two-day meetings over the course of 18 months: two meetings in Phase 1 (kick-off and at four months), and two meetings in Phase 2, with one meeting in the Washington, D.C. area and one on the West Coast in each Phase.
- Regular teleconference meetings will be scheduled with the government team for progress reporting as well as problem identification and mitigation. Proposers should also anticipate at least one site visit per phase by the DARPA program manager during which they will have the opportunity to demonstrate progress towards agreed-upon milestones.

IV. Deliverables

Performers will be expected to provide at a minimum the following deliverables:

- Negotiated deliverables specific to the objectives of the individual efforts and milestone requirements. These may include registered reports, experimental protocols, publications, intermediate, and final versions of software libraries, code, and APIs, including documentation and user manuals, and/or a comprehensive assemblage of design documents, models, modeling data and results, and model validation data.

V. Award Information

Selected proposals that are successfully negotiated will result in award of an OT for prototype project. See Section 3 of DARPA-PA-18-02 for information on awards that may result from proposals submitted in response to this notice.

Proposers must review the model OT for Prototype agreement provided as an attachment to DARPA-PA-18-02 prior to submitting a proposal. DARPA has provided the model OT in order to expedite the negotiation and award process and ensure DARPA achieves the goal of AIE which is to enable DARPA to initiate a new investment in less than 90 days from the date that this AIE opportunity is posted to www.FBO.gov. The model OT is representative of the terms and conditions that DARPA intends to award for all AIE Awards. The task description document, schedule of milestones and payments, and data rights assertions requested under Volumes 1, 2, and 3 will be included as attachments to the OT agreement upon negotiation and award.

Proposers may suggest edits to the model OT for consideration by DARPA and provide a copy of the model OT with track changes as part of their proposal package. Suggested edits may not be accepted by DARPA. The government reserves the right to remove a proposal from award consideration should the parties fail to reach agreement on OT award terms and conditions. If edits to the model OT are not provided as part of the proposal package, DARPA assumes that the proposer has reviewed and accepted the award terms and conditions to which they may have to adhere and the sample OT agreement provided as an attachment, indicating agreement (in principle) with the listed terms and conditions applicable to the specific award instrument.

In order to ensure that DARPA achieves the AIE goal of award within 90 days from the posting

date (January 4, 2019) of this announcement, DARPA reserves the right to cease negotiations when an award is not executed by both parties (DARPA and the selected organization) on or before April 3, 2019.

VI. Eligibility

See Section 4 of DARPA-PA-18-02 for information on who may be eligible to respond to this notice.

VII. AIE Opportunity Responses

Responses to this AIE opportunity must be submitted as full proposals to DARPA-PA-18-02 as described therein. All proposals must be unclassified.

A. Proposal Content and Format

All proposals submitted in response to this notice must comply with the content and format instructions in Section 5 of DARPA-PA-18-02. All proposals must use the templates provided as Attachments to the PA and the "Schedule of Milestones and Payments" Excel Attachment provided with this AIE Opportunity and follow the instructions therein.

Information not explicitly requested in DARPA-PA-18-02, its Attachments, or this notice may not be evaluated.

B. Proposal Submission Instructions

See Section 5 of DARPA-PA-18-02 for proposal submission instructions.

C. Proposal Due Date and Time

Proposals in response to this notice are due no later than **4:00 PM on Monday, February 4, 2019**. Full proposal packages as described in Section 5 of DARPA-PA-18-02 must be submitted per the instructions outlined therein *and received by DARPA* no later than the above time and date. Proposals received after this time and date may not be reviewed.

Proposers are warned that the proposal deadline outlined herein is in Eastern Standard Time and will be strictly enforced. When planning a response to this notice, proposers should take into account that some parts of the submission process may take from one business day to one month to complete.

VIII. Proposal Evaluation and Selection

Proposals will be evaluated and selected in accordance with Section 6 of DARPA-PA-18-02. Proposers will be notified of the results of this process as described in Sec. 7.1 of DARPA-PA-18-02.

IX. Administrative and National Policy Requirements

Section 7.2 of DARPA-PA-18-02 provides information on Administrative and National Policy Requirements that may be applicable for proposal submission as well as performance under an award.

X. Point of Contact Information

Michael Fiddy, program manager, DARPA/DSO, MicroBrain@darpa.mil

XI. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this notice must be emailed to MicroBrain@darpa.mil. Emails sent directly to the program manager or any other address may result in delayed or no response.

All questions must be in English and must include name, email address, and the telephone number of a point of contact. DARPA will attempt to answer questions publically in a timely manner; however, questions submitted within 7 days of the proposal due date listed herein may not be answered.

DARPA will post an FAQ list under the AIE opportunity on the DARPA/DSO Opportunities page at: http://www.darpa.mil/work-with-us/opportunities?tFilter=&oFilter=2&sort=date. The list will be updated on an ongoing basis until one week prior to the proposal due date. In addition to the FAQ specific to this notice, proposers should also review the program announcement for AIE General FAQ list on the DARPA/DSO Opportunities page under the program announcement for AIE (DARPA-PA-18-02).