Disruption Opportunity Special Notice
DARPA-SN-18-65
The Physics of Artificial Intelligence (PAI)

I. Opportunity Description

The Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO) is issuing a Disruption Opportunity (DO) Special Notice (SN) inviting submissions of innovative basic research concepts exploring radically new architectures and approaches in Artificial Intelligence (AI) that incorporate prior knowledge, such as known physical laws, to augment sparse data and to ensure robust operation.

This DO SN is part of DARPA's portfolio of ongoing AI research and is issued under the Program Announcement for Disruptioneering, DARPA-PA-18-01. All proposals in response to the technical area(s) described herein will be submitted to DARPA-PA-18-01 and if selected, will result in an award of an Other Transaction (OT) for prototype project not to exceed $1,000,000.

A. Introduction

For more than five decades, DARPA has been a leader in spurring groundbreaking research and development (R&D) that facilitated the advancement and application of "First Wave" (rule based) and "Second Wave" (statistical learning based) AI technologies. Today, DARPA continues to lead innovation in AI research as it continues to fund a broad portfolio of R&D programs, ranging from basic research to advanced technology development, which will help shape a future for AI technology where machines may serve as trusted and collaborative partners in solving problems of importance to national security. DARPA believes this future will be realized upon the development and application of "Third Wave" AI technologies, where systems are capable of acquiring new knowledge through generative contextual and explanatory models. The Physics of AI (PAI) basic research Disruption Opportunity supports this vision.

It is anticipated that AI will play an ever larger role in future Department of Defense (DoD) activities, ranging from scientific discovery, to human-machine collaboration, to real-time sensor processing, to the control and coordination of a variety of distributed, intelligent and autonomous composable systems. However, despite rapid and accelerating progress of AI in the commercial sector – particularly in the subfield of machine learning – AI has not yet been successfully integrated into the most transformative DoD applications, for reasons that have included:

- The demanding levels of trust, safety and performance guarantee required of AI systems in defense applications;
- The lack of success of deep learning constructs in causal, predictive modeling of complex nonlinear dynamic systems;
- The acknowledged difficulties of machine learning architectures and training protocols in dealing with incomplete, sparse and noisy data;

- The lack of robustness, which makes AI image recognition systems potentially subject to a variety of adversarial spoofing;
- The inherent challenges faced by AI approaches in dealing with "Open World problems", e.g., in unstructured environments with unknown and hidden states, as compared to relatively well-structured application domains (e.g. games) where the system state is fully observable and interaction rules are known; and
- The difficulty in obtaining useful performance guarantees and limits or even to know what questions can be asked of an AI system and whether the answers make sense.

As a consequence, the integration of AI in DoD systems has been slow relative to the private sector.

PAI aims to develop novel AI architectures, algorithms and approaches that "bake in" the physics, mathematics and prior knowledge relevant to an application domain in order to address the technical challenges in application of AI in scientific discovery, human-AI collaboration, and a variety of defense applications.

B. Objective/Scope

PAI has the following key goal:

Embed physics and prior knowledge into AI in a principled way to augment sparse data and to move from correlation to generative models that are causal and explanative ("put the physics into AI"). Demonstrate these "physics-aware" models in DoD-relevant applications.

It is anticipated that multidisciplinary teams incorporating domain expertise, physics, mathematics, AI, statistics, information theory, control theory and additional disciplines will be required to achieve the transformational goals of the program.

Research Project Objectives

Data-driven machine learning techniques have proven successful in leveraging massive training data to answer questions narrowly registered around the initial training set and questions. Deep artificial neural networks (DNNs) are extremely expressive in approximating arbitrary nonlinear functions, extracting features from data, and producing useful reduced-dimensional representations for classification purposes. Advanced computational platforms now enable the training of hundred-layer-deep networks using backpropagation methods that encompass hundreds of thousands to millions of parameters (the weights of the DNNs) as long as sufficient training data exist. However, despite some successes in transfer learning and one-shot learning, it has proven difficult for DNNs to generalize beyond their initial set of training questions. In general DNN's are not generative, although generative models such as variational autoencoders (VAEs), generative adversarial networks (GANs) and hybrid models exist and have been employed in specialized domains.

PAI hypothesizes that many challenges associated with current state-of-the art machine learning and DNN-based AI can be overcome, especially in physically-grounded application domains, by baking in physics from the outset. Here, "putting the physics into AI" broadly means effectively

exploiting a diverse set of prior knowledge, including scientific and mathematical knowledge relevant to the problem at hand. Proposals should address the following research project objectives:

1. Develop an AI prototype that makes optimal use of both observational and experimental data, simulated data, and prior knowledge. Architectures and algorithms incorporating reusable building blocks that need not be retrained for every narrow domain or for every new set of questions are preferred. AI architectures and algorithms should embed or bake in prior knowledge, including scientific knowledge, mathematical/topological knowledge, statistical models, logical inference, linguistic or physical grammars, symmetries, conservation laws, and other physical constraints in order to overcome the limitations of sparse, noisy or incomplete data and in order to learn resilient and parsimonious representations that are physically meaningful. The aim is to learn the structure of underlying generating functions, grammars, or relationships, not simply classify the structures found in observed data.
2. Demonstrate an AI prototype system using simulated and/or real data in a representative DoD-relevant systems application. Examples of relevant application domains include predictive nonlinear systems control; satellite or radar image processing; high dimensional systems modeling; and the use of AI in human-machine collaborative scientific discovery and exploitation.
3. Address the fundamental performance limits of your prototype system. Specifically, describe your approach in terms of its accuracy, generalizability (ability to effectively predict behaviors outside of the training set or to perform in other domains), robustness (to noise, sparse data and adversarial spoofing), and data and computational requirements. Quantitatively compare your physics-aware approach with current practice.

PAI is seeking innovative approaches that address the above and can substantially improve upon current machine learning approaches in bringing “deep insight” into physics-centric application domains. AI architectures, algorithms and approaches that make use of DNNs as one of several component are welcome, but conventional learning algorithms using DNNs (including convolutional and recurrent neural networks) by themselves are not considered likely to meet the broad goals of the program. Hybrid architectures are encouraged that embed hierarchical physical models into generative cores; that incorporate manifold learning techniques; that incorporate operator theoretic spectral methods, and/or that bake in topological knowledge, group symmetries, projection knowledge, or gauge invariances into the network architecture. Generative approaches that can reproduce the multiscale structures of observed data; distinguish between semantic and stylistic differences; are resilient to noise, data dropouts, data biases, and adversarial spoofing; and can learn with minimal labeled data are also encouraged.

C. Structure

PAI is an aggressive 18 month program. During the initial nine month Phase I, performers will develop new prototype AI architectures, algorithms and approaches that have the potential to meet the broad goals of the program. These systems will be tested in well understood “toy” or “model” systems using either simulated or real data. Initial methods will be developed to assess

"accuracy," "robustness" and "generalizability," and novel approaches will be validated against current baseline machine learning methods.

In the following nine month Phase II, performers will extend and refine their prototype approach, quantify performance in DoD-relevant, real-world application domains, and compare with existing state-of-the-art machine learning methods.

Proposals submitted to DARPA-PA-18-01 in response to the technical areas of this DO SN must be UNCLASSIFIED and must address two independent and sequential project phases, Phase I and Phase II. The combined Phase I Base and Phase II Option efforts for this DO shall not exceed 18 months. Base Phase award value shall not exceed $500,000. The Phase II Option award value shall also not exceed $500,000, and the total combined award is limited to $1,000,000.

D. 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. If selected for award negotiation, the fixed payable milestones provided in Section 9.c of the Vol. 2 Price Volume will be directly incorporated into Attachment 2 of the OT agreement ("Schedule of Milestones and Payments"). Proposers must complete a Schedule of Milestones and Payments table as part of submitting a complete proposal and fulfilling the requirements under Vol. 2 Price Volume. Phase I fixed payable milestones for this program should include:

- Month 1: Report on initial architectures, algorithms, and learning approaches
- Month 3: Report on acquisition of initial training and test data sets (experimental, simulated or modeled), proposed evaluation metrics and initial analyses results
- Month 5: Interim report describing performance of prototype system
- Month 7: Demonstration of impact of inclusion of prior knowledge on enhanced performance
- Month 9: Final Phase I Report summarizing approach; prototype architectures andalgorithms; data sets; results; comparison with alternative state-of-the-art methodology; quantification of accuracy; quantification of robustness to errors, noise, dropouts, distortions; and quantification of generalizability (ability to model and predict behaviors not explicitly trained on)

Phase II fixed milestones for this program should include:

- Month 10: Report on lessons learned, updated architectures, algorithms and learning approaches
- Month 12: Report on acquisition of Phase II real-world data sets, proposed evaluation metrics and initial analyses results
- Month 14: Interim report describing performance of real-world system

- Month 16: Interim report quantifying system performance, comparing with alternative state-of-the art approaches using machine learning, control theory or other conventional methods, and documenting lessons learned
- Month 18: Final Phase II report documenting final prototype architectures and algorithms; methods; results; comparisons with alternative methods; and quantification of accuracy, robustness and generalizability

For planning and budgetary purposes, proposers should assume a program start date of September 24, 2018.

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

- For budgeting purposes, plan for two two-day meetings or hackathons during Phase 1, one on the east coast and one on the west coast. Similarly, plan for two two-day meetings during Phase 2, one on the east coast and one on the west coast.
- Regular teleconference meetings will be scheduled among program participants and the Government team for progress reporting, problem identification and mitigation. Plan for one teleconference meeting every two months.

E. Deliverables

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

- Negotiated deliverables specific to the proposed effort and TDD. These may include reports; experimental and simulated data sets; architectures; protocols; software codes; publications; model data; metrics; validation data; and other associated documentation and results.

II. Award Information

Proposals identified for negotiation will result in an award of an OT for prototype project. See Section 3 of DARPA-PA-18-01 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-18-01 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 Disruptioneering which is to enable DARPA to initiate a new investment in less than 90 days from idea inception. The model OT is representative of the terms and conditions that DARPA intends to award for all DOs. 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.

III. Eligibility

See Section 4 of DARPA-PA-18-01 for information on who may be eligible to respond to this notice.

PAI is a fundamental research effort and does not impose citizenship requirements for program participation.

IV. Opportunity Responses

Responses to this DO SN must be submitted as full proposals to DARPA-PA-18-01 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-18-01. All proposals must use the templates provided as Attachments to the PA and follow the instructions therein.

Information not explicitly requested in DARPA-PA-18-01, its Attachments, or this notice may not be evaluated.

B. Proposal Submission Instructions

See Section 5 of DARPA-PA-18-01 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 August 6, 2018. Full proposal packages as described in Section 5 of DARPA-PA-18-01 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 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.

V. Proposal Evaluation and Selection

Proposals will be evaluated and selected in accordance with Section 6 of DARPA-PA-18-01. Proposers will be notified of the results of this process as described in Section 7.1 of DARPA-PA-18-01.

VI. Administrative and National Policy Requirements

Section 7.2 of DARPA-PA-18-01 provides information on Administrative and National Policy Requirements that may be applicable for proposal submission as well as performance under an award.

VII. Point of Contact Information

Jim Gimlett, Program Manager, DARPA/DSO, PAI@darpa.mil

VIII. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this notice must be emailed to PAI@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 Special Notice 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 Disruptioneering General FAQ list on the DARPA/DSO Opportunities page under the Disruptioneering Program Announcement (DARPA-PA-18-01).