I. Opportunity Description

The Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO) invites submission of innovative basic or applied research concepts as described in Section IX of the DSO Office-wide Broad Agency Announcement (BAA), HR001117S0040, as amended.¹

A. Introduction and Background

The design of complex mechanical systems such as aircraft, ground vehicles, or submarines is a multi-stage process where the majority of the asset’s risk and life cycle cost is locked in at the initial conceptual stage of the three-stage design process. Conceptual design involves the designer combining behaviors to encode the physical phenomena (e.g., lift, propulsion, energy transfer) that describes a configuration (the topological layout) in order to achieve the desired mission objective or function. Next, during preliminary design, the combination of these behaviors is mapped into one or more physical embodiments (e.g., assembly of component geometries) where the precise shape, size and relative position of components are determined to achieve the desired function. Finally, the process of detailed design is primarily concerned with decomposing a preliminary design into manufacturable pieces to build the final product. There are a number of computational design tools (e.g., CAD) available to assist the designer with this “detailed design” process. Conversely, conceptual design is largely a human artisan activity with few general purpose computational methods available for assisting in design exploration. This limits the designer’s ability to generate radical new ideas that realize the potential of attainable design possibilities and restricts the agility to adapt a design to evolving requirements.

B. Objective/Scope

The goal of the Fundamental Design (FUN DESIGN) program is to investigate new fundamental computational and mathematical building blocks to represent conceptual designs of mechanical systems and enable the generation of novel configurations through the exploration of various combinations of these design building blocks. The ability to mathematically represent the preliminary components of a design as a formula enables the designer to discover new and improved species of designs by changing the build formulas, for example, through perturbation, combining best of breed formulas, and by elimination. One of the fundamental insights of the FUN DESIGN program is that locking down specific geometry early in the design process is unnecessarily restrictive and hinders adaptability as design requirements evolve. Another insight is that the shift from hand coding to deep learning techniques in other domains such as image recognition and language understanding may have analogs for design. FUN DESIGN will explore the possibility of using compositional mathematics (e.g., category theory, operads, sheaf theory), functional programming, symbolic computations, automated code generation,

¹ The BAA may be found at https://www.fbo.gov/spg/ODA/DARPA/CMO/HR001117S0040/listing.html.
evolutionary techniques, constraint management, machine learning and other techniques deemed applicable to establish the building blocks for conceptual design. The design building blocks must capture enough of the components’ underlying physics to describe a family of candidate solutions potentially expressed in terms of functions, constraints, boundary conditions, envelopes, and connectivity. Candidate solutions must result in conceptual designs having sufficient detail for the preliminary design step to synthesize an optimal assembly of components and their geometric shapes by optimizing the shape, size and relative position of the components. The result of this process will allow a user to choose best in class configurations or to repeat the exploration process by combining the best properties of candidate solutions. Techniques that generate inputs to topology optimization processes or parameterized descriptions of components to be optimized in a multi-disciplinary optimization process are within scope for this program; however, they are not the only approaches that may be proposed. Proposers should assume availability of massive compute power to enable rapid evaluation of the physics to evaluate merits of the design.

Successful outcomes of this work must show a path forward to enable rapid discovery of novel configurations with sufficient generality to be applicable to a large range of mechanical design domains. The benefits of FUN DESIGN include the ability to evolve and adapt designs rapidly in response to changing requirements and provide a thorough understanding of trade-offs early in the design process.

C. Program Structure

The FUN DESIGN program is an 18-month, basic research effort consisting of a 3-month Feasibility Study (Phase 1) and a 15-month Proof of Concept (Phase 2) as detailed below. Note: if appropriate to the proposed work, the proposed period of performance for Phase 2 may be less than 15 months.

Due to the nature of the program objectives as described herein, intellectual property (IP) rights asserted by proposers are strongly encouraged to be aligned with open source regimes (See Section VI.B.4 of BAA HR001117S0040 for additional information on IP.).

Phase 1: Proposers are expected to develop and document a detailed approach to discover or create design building blocks that can be composed to describe a conceptual mechanical design and to enable generation and exploration of novel designs. Proposers must identify how they will establish these building blocks in a Phase 2 software prototype. Additionally, they must explain how the building blocks will be associated to functional requirements or mission objectives as well as how the building blocks will be represented and combined or composed to represent a set of candidate solutions. Proposers must also explain how a candidate solution could generate an optimization problem formulation resulting in a physical embodiment with associated performance metrics. Proposers must identify a manageable mechanical design challenge that their design building block solution would be able to solve. Proposers must also specify the resources required, including computational needs to develop and test the software prototype developed in Phase 2 (e.g., hardware, storage, software libraries). In addition, proposals may include ideas to discover the building blocks by mining a design repository. If a design repository is needed, the proposer must identify which repository it intends to leverage or how it
intends to build the design repository. The result of this 3-month effort will be a report on the approach, including a Phase 2 feasibility demonstration problem, with sufficient detail to prove viability.

Specifically excluded from consideration are approaches that lack generality (e.g., specialized solutions to design a specific commodity such as aircraft) or lack practicality (e.g., approaches that do not lead to an embodiment such as generation of shape); predefined building blocks with limited or parametric shapes and behaviors (e.g., shafts, axles, bolts, "Lego™" blocks and "Minecraft™" inspired ideas); and any approach whose applicability is limited to a single physical phenomenon (e.g., structural design). Furthermore, this program is not focused on material design or tied to any specific manufacturing methodology.

**Phase 2:** Performers will design and prototype software based on their approach developed in Phase 1 to prove the efficacy of their ideas. An independent Government agent will validate software performance on several Government-supplied challenge problems in addition to the Phase 1 proposed problem. Proposers must address how they will move from a paper study to final software demonstration in 15 months (or less) with sufficient generality, despite limited scope due to the aggressive period of performance, to prove a viable path to build future conceptual design systems. Delivered software must demonstrate establishment of conceptual design building blocks, composability of the building blocks to represent candidate solutions to conceptual design problems, and provide a convincing feasibility argument to synthesize physical embodiments from the candidate solutions. DARPA will supply access to computational hardware (HPC as well as GPUs), storage, software development and test environments, and the ability to install required software libraries. Use of the DARPA-supplied resources is not required; however, if proposers choose not to use them, proposals must provide justification for any proposed computing costs. The outcome of this phase should provide enough evidence to select a viable path forward to build the next generation design systems to explore innovative conceptual design solutions and rapidly adapt to evolving mission requirements.

**D. Schedule/Milestones**

Proposers must provide a technical and programmatic strategy that conforms to the entire program schedule and presents an aggressive plan to fully address all program goals, metrics, milestones, and deliverables. The task structure must be consistent across the proposed schedule, Statement of Work, and cost volume. For planning and budgetary purposes, proposers should assume a program start date of October 15, 2017. Schedules will be synchronized across performers, as required, and monitored/revised as necessary throughout the program. All proposals must include the following meetings and travel in the proposed schedule and costs:

- For budgeting purposes, plan for three two-day meetings over the course of 18 months: two meetings in the Washington, D.C. area and one meeting in the San Francisco, CA area.
- 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 in Phase 2 by the DARPA Program Manager during
which they will have the opportunity to demonstrate progress towards agreed-upon milestones.

E. Deliverables

Performers will be expected to provide at a minimum the following deliverables:
- A Phase 1 feasibility study is expected 3 months after the award to serve as a gate for Phase 2
- Phase 2 will require comprehensive quarterly technical reports due within ten days of the end of the given quarter, describing progress made on the specific milestones as laid out in the SOW
- Phase 2 software prototype
- A Phase 2 completion report submitted within 30 days of the end of the phase, summarizing the research done
- Reporting as outlined in Section VI of BAA HR001117S0040.

II. Award Information

See Section II and Section IX of BAA HR001117S0040 for information on awards that may result from proposals submitted in response to this notice.

III. Eligibility

See Section III of BAA HR001117S0040 for information on who may be eligible to respond to this notice.

IV. Opportunity Responses

Responses to this Disruption Opportunity Special Notice must be submitted as full proposals to BAA HR001117S0040 as described therein; executive summaries and abstracts will not be accepted. All proposals must be unclassified.

A. Proposal Content and Format

The following sections of BAA HR001117S0040 provide content and format instructions for all proposals submitted in response to this notice:
- IV.B Content and Form of Application Submission
- IV.B.3 Full Proposal Information o Attachments 5, 6, and 7 provide specific guidance for Disruption Opportunity proposal submissions
- IV.B.4 Proprietary Information

B. Proposal Submission Instructions

See Section IV.E.1 of BAA HR001117S0040 for instructions on transmitting proposals submitted in response to this notice.
C. Proposal Due Date and Time

Proposals in response to this notice are due no later than 4:00 PM on September 11, 2017. Full proposal packages as described in Section IV.B.3 of BAA HR001117S0040 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.

See Section IV.C.3 of BAA HR001117S0040 for additional information.

V. Proposal Evaluation and Selection

Proposals submitted in response to this notice will be evaluated and selected in accordance with Section V of BAA HR001117S0040. Proposers will be notified of the results of this process as described in Section VI.A of BAA HR001117S0040.

VI. Administrative and National Policy Requirements

Section VI.B of BAA HR001117S0040 provides information on Administrative and National Policy Requirements with which proposers may have to adhere for proposal submission as well as performance under an award (e.g., Representations and Certifications, Intellectual Property, Data Management).

VII. Point of Contact Information

Jan Vandenbrande, Program Manager, DARPA/DSO, FUNDESIGN@darpa.mil

VIII. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this notice must be emailed to FUNDESIGN@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=name. The list will be updated on an ongoing basis until one week prior to the proposal due date.
IX. Additional Information

What is the program trying to do?

Establish conceptual design building blocks to enable exploration and discovery of novel & optimized designs

Enable generation of new designs

Combine best of designs

The goal of this program is to determine whether we can develop or discover a new set of building blocks to describe conceptual designs, and use the building blocks to explore, optimize or combine ideas from different designs to create novel designs. For example, a carburetor and a fuel injector both perform the same function (control power of a combustion engine), but do so using very different configurations. Can we come up with a set of building blocks and a scheme to combine them that could represent the designs and investigate alternative combinations of these building blocks to discover other solutions, e.g., other means of distributing fuel? Likewise, how do you combine the best of two ideas (aircraft and helicopter) and create a new concept (e.g., a V22)?
Design is typically accomplished in several stages. Conceptual design is the ideation phase where a set of mission requirements are decomposed into a set of behaviors that manipulate physical phenomena that when combined achieves the desired functionality. The result of conceptual design are configurations which describes the basic layout and combination of behaviors that may achieve the function. For example, air transport can be accomplished with many different configurations as shown to the right of the figure. Conceptual design is perhaps the most critical phase of design because the majority of risk, life-cycle cost are locked in at this stage. Preliminary design takes a configuration, and based on trade studies, determines the sizing, positioning and shaping to get the best performance given all the constraints. Finally, detailed design decomposes a preliminary design into a set of manufacturable components, usually subject to minimizing build time and cost. The FUN DESIGN program is focused on conceptual design.

How is conceptual design done today?

There exists no general computational framework to generate new design ideas

- Human Insight
- Historical Data
- Hard coded solutions

Inspiration from SciFi & Art

The geometry and layout is still human generated.

Conceptual design is currently a human artisan activity tapping experience accumulated over many years of practice frequently leveraging historical data or inspiration from other empirical sources such as nature, art and SciFi. Specialized codes exist that synthesize solutions in narrow domains, but they typically lack generality and unable to explore beyond their intended solution space. Ultimately determining what combination of shapes can implement a function is still a human activity. This limits designers’ ability to generate radical new ideas that realize the potential of attainable design possibilities, and restricts the agility to adapt a design to evolving requirements.
For example, to achieve air transport we need to find a combination of physical behavior to accomplish lift and propulsion. The main sets of physics that drive these behaviors are buoyancy, fluid flow, electro magnetics, anti-gravity, Newton’s 3rd law, and thermodynamics. To realize these behaviors we can employ lighter than air structures, airfoils, thrust, and electro-magnetics. When combined into a configuration to describe candidate solutions, which includes relative positioning of behaviors, can we generate the necessary information to synthesize the shaping, sizing and positioning to understand the trade space associated with each candidate for conceptual design?

One of the fundamental insights of the FUN DESIGN program is that locking down specific geometry early in the design process is unnecessarily restrictive and hinders adaptability as
design requirements evolve. Another insight is that hand coded approaches in other domains such as image recognition and language translation having given way to deep learning techniques that have achieved much higher success rates than the hand coded solutions. For example, can we use ideas derived from deep learning and artificial intelligence (AI) to discover the building blocks? Can we leverage compositional mathematics and evolutionary techniques to combine these building blocks and generate math or computer code to feed a preliminary design synthesis processes to determine shaping, sizing and positioning?

Can we discover the building blocks of design?

**DARPA**

**FUN DESIGN Question:**
- What are the right mathematical and algorithmic descriptions of Function, Behavior & Structure to form a new basis to describe and generate conceptual designs?
- Can we generate novel and optimal configurations by exploring various combinations of these design building blocks?

**FUN DESIGN Results:**
- Radical new designs that achieve best in class performance.
- Agility to adapt to evolving design requirements.
- Thorough understanding of trade-offs early in the design process.

What this program is not about!

**DARPA**

**Combining Commodity Components**
- No path to embodiment

**Specialized Solutions**
- Materials or manufacturing

**Lack of practicality**
- Solutions restricted to single physics