Disruption Opportunity
DARPA-PA-24-04-05
Higher-Order Composite Resonators for Extra resilience (HORCREX)

I. Opportunity Description

The Defense Advanced Research Projects Agency (DARPA) Defense Sciences Office (DSO) is issuing a Disruption Opportunity (DO), inviting submissions of innovative basic or applied research concepts in the technical domain of novel micromechanical oscillators for applications toward precision positioning and navigation systems. This DO is issued under the Program Announcement for Disruptioneering, DARPA-PA-24-04. All awards will be made in the form of an Other Transaction (OT) for Prototype project. The total award value for the combined Phase 1 base (Proof-of-concept) and Phase 2 option (Prototype) is limited to $2,000,000. This total award value includes Government funding and performer cost share if required or proposed.

To view the original DARPA Program Announcement (PA) for Disruptioneering, visit SAM.gov under solicitation number DARPA-PA-24-04: https://sam.gov/opp/cb7a935d59bb4ceeb62b9515f7d9f9b0/view.

A. Introduction

The last two decades have seen technology innovation, development, and maturity of microelectromechanical systems (MEMS) for positioning and navigation applications. Despite rapid advances toward technological maturity of MEMS-based inertial sensors for commercial applications, in the defense realm the core technology has not achieved an important goal – providing precise navigation for an individual warfighter or a small vehicle in GPS-denied turbulent environments. A key limitation is the inability of inertial sensors to operate in extremely dynamic scenarios, such as executing precise maneuvers in contested airspace and during vehicle launch and landing.

For example, reusable air vehicles launch at extreme speeds with high revolutions per minute, slow down upon reaching a target, and then return to base. This range of behaviors means their navigation sensors must have sufficient dynamic range, survive shock and vibration in turbulent environments, and operate precisely through all those conditions. The current practice is to use an array of sensors with different bandwidths and dynamic ranges, but this adds unnecessary size, weight, and power (SWaP) burdens on those platforms. HORCREX will exploit the nonlinearities in mechanical sensor and suspension design using mechanical frequency combs to develop a single inertial sensor with dramatically increased dynamic range, enabling resilience to shock and vibration while maintaining functionality across a broad range of velocity and acceleration.

B. Objective/Technical Scope

Systems that rely on high-frequency signals, such as those used for precise measurements or communication, are often compact, but inertial sensors tend to be larger and operate at low frequencies so that they can measure very small signals that vary over long times and distances. High-frequency MEMS sensors with good shock resilience have been demonstrated, but at the cost of poor sensitivity. While an array of sensors with different dynamic ranges can extend operational capabilities, there are drawbacks that reduce the overall effectiveness of the approach. These include SWaP scaling linearly with the number of sensors, as well as issues like mechanical crosstalk and unintentional mode-locking due to acoustic energies exchanged

through the common substrate. Solutions that use arrays of sensing elements and their electronics are out of scope for this effort, as the design space for such methods has been well characterized and they do not address HORCREX's core challenges.

HORCREX aims to advance the development of high-performance inertial sensors by addressing the challenges of achieving both excellent sensitivity and resilience to shock and vibration in a single sensing proof-mass. The concept of mode-locking provides a possible pathway to achieve a spectrum of operational frequencies, including low-frequency modes which can then be used to demonstrate extended dynamic range (low noise and shock and vibration resilience). DARPA is interested in exploring a variety of methods, including different methods for transducing multiple vibration modes of a sensing proof-mass and for managing frequency variation and relative phase fluctuations across the full dynamic range of operational conditions. Regardless of chosen approach, each performer should fully explore the design space through modeling, characterization, and experimentation of mode families, materials, transducers, and locking mechanisms to stabilize a multiple-mode mechanical sensing platform. HORCREX will thus improve sensor survivability and ensure sensor operation through extremes of dynamic range, such as pinpoint landing of an unmanned aerial vehicle (UAV) in a turbulent weather system.

C. Structure

Proposals submitted in response to this DO must be unclassified and must address two sequential project phases: Phase 1 demonstrates operation of a locked mechanical frequency comb, and Phase 2 scales the design and provides a possible launch test opportunity for successful performers. Program metrics are detailed in Table 1 below. The periods of performance for these phases are 12 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 DO should not exceed 24 months. The Phase 1 (base) award value is limited to $1,000,000. The Phase 2 (option) award value is limited to $1,000,000. Both Phase 1 and Phase 2 award value limits include performer cost share, if required or if proposed. The total award value for the combined Phase 1 and Phase 2 is limited to $2,000,000. This total award value includes Government funding and performer cost share, if required or if proposed.

D. Detailed Technical Description

Making inertial sensors that are resilient to shock and vibration in highly dynamic environments is challenging. For example, MEMS inertial sensors, while operating at kilohertz frequencies with good sensitivity, have large mechanical compliance that makes them vulnerable to undesirable signals, such as shock and vibration from axes other than the sensing axis. This significantly limits their performance in turbulent conditions and dynamic operations.

HORCREX performers will address this challenge by exploiting a different and unique property of micromechanical systems. Due to their chip-scale size, these microresonators have multiple vibration modes, including harmonic modes from the same mode family and from different mode families. Inspired by recent breakthroughs[1,2] in low-noise optical frequency combs enabled by exquisite dispersion control and frequency locking, HORCREX performers will aim to produce and demonstrate similar micromechanical frequency combs.

[1] Park, M., & Ansari, A. (2019). Journal of Microelectromechanical Systems, 28(3), 429-431.
[2] Ganesan, A., Do, C., & Seshia, A. (2017). Physical review letters, 118(3), 033903

Industry and academic approaches today involve multiple sensors or multiple modes to achieve O(√N) scaling in sensitivity and stability and corresponding O(N) scaling in SWaP and electronic complexity. Recent research at academic institutions[2] has demonstrated mechanical frequency combs using a single transducer element, but there was insufficient back-action and a lack of strong coupling between the harmonics or different vibration modes. One approach may be to develop the mechanical equivalent of a frequency comb "lock" to prevent low-frequency mode from deviating or becoming unstable, enabling operation in high-shock environments. While mode locking is one approach, proposals are encouraged to explore alternative methodologies to achieve the program's goals, supported by robust analysis and validation.

HORCREX seeks to achieve its program goals through coherent codesign, encouraging innovative approaches to integrate transducers, vibrating element and mode families, and adaptive transducer control circuits. While the initial demonstration will focus on operation under shock and vibration, it does not constrain the fundamental frequency, allowing performers the flexibility to explore different designs. Although using higher frequencies may make it easier to achieve shock/vibration resilience in a lab environment, higher harmonics are expected to exhibit low signal-to-noise ratio, which could make frequency locking more challenging. In Phase 2, performers will focus on scaling their designs to fundamental sensing mode frequency with an emphasis on large, effective proof-mass size and performance in turbulent, real-world conditions.

Table 1: Program Metrics Summary

	Metric	Phase 1 (12 months)	Phase 2 (12 months)
Operation in Shock/Vibration Environment	Resilience	Shock/Vibration immunity	Fundamental mode
	Sensitivity	Maintain frequency lock during 10-g, 50-Hz vibration on a shaker table along most sensitive axis	<8 kHz
	Demonstration	Video imaging using laser Doppler vibrometry	Demonstration of operation (data log) during high-g test

This DO does not provide SWaP metrics for the HORCREX system. However, proposals should estimate the SWaP for their architecture and outline potential scaling pathways toward an autonomous system. Proposals must include a clear justification for how the approach has the potential to meet the program's performance metrics. The justification must be based on data, projections, calculations, or other relevant evidence.

Performers will be expected to report on operation through a shock/vibration test and conduct a comprehensive exploration of the design space. This includes explainable calculation and finite element analysis to evaluate their approach, with estimates on the accuracy of the simulation space and confidence levels.

E. Schedule/Milestones

Proposers must address the following fixed payable milestones in their proposals. Proposers must complete the "Schedule of Milestones and Payments" Excel Attachment provided with this DO to submit a complete proposal and fulfill the requirements under Volume 2, Price Volume. If

selected for award negotiation, the fixed payable milestones provided will be directly incorporated into Attachment 3 of the OT agreement ("Schedule of Milestones and Payments"). Proposers must use the Task Description Document template provided with the Program Announcement DARPA-PA-24-04, which will be Attachment 1 of the OT agreement.

Phase 1 fixed milestones for this program must include, at a minimum, the following:

- Month 1:
    - Phase 1 kickoff meeting presentation including preliminary description of proposed HORCREX microsystem platform with suitable justification in modeling, simulation, and prior theoretical or experimental results.
    - All supporting positions identified in the proposal are assigned to personnel, and names are provided to the Government.
- Month 4:
    - Theoretical analysis and computational/FEA simulations to engineer HORCREX frequency-locked oscillator.
    - Estimates of SWaP.
    - All proposed personnel must be working on the effort at the planned level of effort.
- Month 10:
    - Measurement results from the HORCREX proof-of-concept system, with independent assessment using available laser Doppler vibrometry resources, with corresponding video data or datasets provided to evaluate its potential to meet program metrics.
- Month 12:
    - Complete the laboratory-scale evaluation of the microsystem, including independent assessment using available laser Doppler vibrometry resources, and generate a report summarizing the results.
    - Integrate and document insights from HORCREX, consolidating data-backed projections of SWaP requirements, design space exploration, and simulation accuracy confidence estimates.

Phase 2 fixed milestones for this program must include, at a minimum, the following:

- Month 14:
    - Complete the iterative scaled-design, simulation, and fabrication process of the microsystem focusing on optimizing toward a fundamental sensing mode frequency target of <8kHz, and propose mode-locking scheme based on measured experimental parameters in Phase 1.
    - All proposed personnel must be working on the effort at the planned level of effort.
- Month 16:
    - Complete the experimental assessment and validation of HORCREX material properties, transducers, fabrication, and control system to refine the design and improve system performance based on findings.
- Month 21:
    - Perform detailed performance assessments of the HORCREX system to evaluate capabilities, focusing on achieving a mode frequency of <8kHz.
- Month 24:

- Complete a comprehensive analysis of HORCREX system progress toward meeting program metrics, with a focus on multi-axis, multi-mode-family operation, scalability, and overall system performance.
- Integrate and document insights from the HORCREX system, consolidating system designs, performance summaries, comparison to existing state of the art, discussion of scalability analysis, SWaP consumption, design space exploration, and simulation accuracy and confidence estimates.

For planning and budgetary purposes, proposers should assume a program start date of April 14, 2025. Schedules will be synchronized across performers as required and monitored/revised as necessary throughout the program's period of performance.

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 virtual Principal Investigator (PI) meeting will be held approximately every six months.
- Regular quarterly teleconference meetings will be scheduled with the Government team for progress reporting, video demonstrations of experimental progress, and risk 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 toward agreed-upon milestones.

Proposals should not include conference travel or publications costs.

F. Deliverables

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

- Negotiated deliverables specific to the objectives of the individual efforts. These may include registered reports, experimental protocols, publications, intermediate and final versions of documentation and user manuals, and/or a comprehensive assemblage of design documents, models, modeling data and results, and model validation data.
- Demonstrate packaged microsystem operating under test parameters verified using independent optical metrology such as laser Doppler vibrometry systems or similar at the end of Month 10 of Phase 1 and Month 22 of Phase 2.

II. Award Information

Selected proposals that are successfully negotiated will result in the award of an OT for Prototype project. See Section 4 of DARPA-PA-24-04 for information on awards that may result from proposals submitted in response to this announcement.

Proposers must review the model OT for Prototype agreement provided as an attachment to DARPA-PA-24-04 prior to submitting a proposal. DARPA has provided the model OT 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 120 calendar days from idea inception. The model OT is representative of the terms and conditions that DARPA intends to include in all DO 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. DARPA may not accept suggested edits. The Government reserves the right to remove a proposal from award consideration should the parties fail to reach an 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 model OT agreement provided as an attachment, indicating agreement (in principle) with the listed terms and conditions applicable to the specific award instrument.

DARPA's goal for this DO is to achieve an award within 118 calendar days from the posting date (December 18, 2024) of this announcement. To ensure that, 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 15, 2025.

III. Eligibility

See Section 7 of DARPA-PA-24-04 for information on who may be eligible to respond to this announcement.

IV. Disruption Opportunity Responses

A. Proposal Content and Format

All proposals submitted in response to this announcement must comply with the content and format instructions in Section 5 of DARPA-PA-24-04. All proposals must use the templates provided as Attachments to DARPA-PA-24-04 and the "Schedule of Milestones and Payments" Excel Attachment provided with this DO and follow the instructions therein.

Information not explicitly requested in DARPA-PA-24-04, its Attachments, or this announcement may not be evaluated.

B. Proposal Submission Instructions

Responses to DARPA-PA-24-04-05 shall be submitted electronically to DARPA's Broad Agency Announcement (BAA) Portal (https://baa.darpa.mil).

DARPA will acknowledge receipt of complete submissions via email and assign identifying numbers that should be used in all further correspondence regarding those submissions. If no confirmation is received within two (2) business days, please contact HORCREX@darpa.mil to verify receipt.

When planning a response to this DO, proposers should take into account the submission time zone and that some parts of the submission process may take from one (1) business day to one month to complete (e.g., registering for a SAM Unique Entity ID (UEI) number or Tax Identification Number (TIN)).

Electronic Upload

First-time users of the DARPA BAA Portal must complete a two-step account creation process. The first step consists of registering for an extranet account by going to the URL above and selecting the "Account Request" link. Upon completion of the online form, proposers will receive two separate emails; one will contain a username, and the second will provide a temporary password. Once both emails have been received, the second step requires proposers to go back to the submission website and log in using that username and password. After accessing the extranet, proposers may then create a user account for the DARPA Submission website by

selecting the "Register your Organization" link at the top of the page. Once the user account is created, proposers will be able to see a list of solicitations open for submissions, view submission instructions, and upload/finalize their proposal.

Proposers who already have an account on the DARPA BAA Portal may log in at https://baa.darpa.mil, select this solicitation from the list of open DARPA solicitations and proceed with their proposal submission. Note: proposers who have created a DARPA Submission website account to submit to another DARPA Technical Office's solicitations do not need to create a new account to submit to this solicitation.

All full proposals submitted electronically through the DARPA Submission website must meet the following requirements: (1) uploaded as a zip file (.zip or .zipx extension); (2) only contain the document(s) requested herein; (3) only contain unclassified information; and (4) must not exceed 100 MB in size. Only one zip file will be accepted per full proposal. The DARPA Submission website will reject full proposals not uploaded as zip files. Technical support for the DARPA Submission website is available during regular business hours, Monday – Friday, 9:00 a.m. – 5:00 p.m. Requests for technical support must be emailed to BAAT_Support@darpa.mil with a copy to HORCREX@darpa.mil. Questions regarding submission contents, format, deadlines, etc., should be emailed to HORCREX@darpa.mil. Questions/requests for support sent to any other email address may result in delayed/no response.

Since proposers may encounter heavy traffic on the web server, DARPA discourages waiting until the day proposals are due to request an account and/or upload the submission. Note: Proposers submitting a proposal via the DARPA Submission site MUST (1) click the "Finalize" button for the submission to upload AND (2) do so with sufficient time for the upload to complete prior to the deadline. Failure to do so will result in a late submission.

C. Proposal Due Date and Time

Proposals in response to this announcement are due no later than 4:00 p.m. on February 14, 2025. As described in Section 5 of DARPA-PA-24-04, full proposal packages must be submitted per the instructions outlined in this DO *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 announcement, proposers should consider that some parts of the submission process may take from one (1) business day to one (1) month to complete.

V. Proposal Evaluation and Selection

Proposals will be evaluated and selected in accordance with Section 6 of DARPA-PA-24-04. Proposers will be notified of the results of this process as described in Section 8.1 of DARPA-PA-24-04.

VI. Administrative and National Policy Requirements

Section 8.2 of DARPA-PA-24-04 provides information on Administrative and National Policy Requirements that may be applicable for proposal submission and performance under an award.

VII. Point of Contact Information

Sunil Bhave, Program Manager, DARPA/DSO, HORCREX@darpa.mil

VIII. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this announcement must be emailed to HORCREX@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 the name, email address, and telephone number of a point of contact. DARPA will attempt to answer questions publicly in a timely manner; however, questions submitted within seven (7) calendar days of the proposal due date listed herein may not be answered.

DARPA will post an FAQ list under the DO on the DARPA website. The list will be updated on an ongoing basis until one (1) week before the proposal due date.

For those new to DARPA or national security, DARPA makes available a free, comprehensive resource via DARPAConnect on how to do business with the agency. In addition to DARPA 101 materials, relevant preparatory modules includes "Understanding DARPA Broad Agency Announcements." Registration and access are free at www.darpaconnect.us.