BAA number HR001117S0025

Lead Organization University of Florida

Type of organization Other Educational

Proposers internal reference number

Other team members :

Changzhi Li Texas Tech University

YK Yoon University of Florida

Jenshan Lin University of Florida

Proposal title Biomimetic microfabricated magnetic gradiometer

Administrative PoC :

Technical PoC :

Casanova, Joaquin

1064 Center Dr, 565 NEB, Gainesville, FL 32611

352-246-9649, jcasa@ufl.edu

Total funds requested

Submitted XX/YY/2017

The transmittal letter should identify the BAA number, the proposal by name, and the organizations proposal reference number (if any), and should be signed by an individual who is authorized

to submit proposals to the Government.

Statement of Work (SOW)

The project’s aim is to develop a minaturized high-sensitivity, low-noise magnetic gradiometer.

Our approach is to mimic the mechanism found in magnetosomes, the specialized cells four from

bacteria to higher vertebrates such as fish and birds (see 2). This is comprised of four main tasks:

modeling and simulation, microfabrication process design, circuit design, and device manufacture

and testing. Each Phase (I,II,III) will include these four tasks.

1.1

Phase I

AMBIIENT Phase 1 will demonstrate sensor functionality and performance in a laboratory setting

meeting the performance metrics as indicated in Table 1.

1.1.1

Modeling and simulation

• The objective in this phase is to simulate the MEMS device, taking into account geometry,

material properties, and multiphysics interactions, in order to determine the range of acceptable design options. In addition, scaling laws will be derived, such that a scale model of the

sensor could be fabricated from COTS components.

• Our approach here is to initially specify geometry and physical properties by hand calculation,

the investigae more deeply in a finite-element multiphysics solver.

• This task will be accomplished at UF by Joaquin Casanova.

• Completion of this task is specified by successful simulation of the MEMS device that meets

the physical requirements specified in the BAA.

• Deliverables include successful simulation results and design parameters.

• No government equipment is required.

• To reduce risk of later failure due to non-manufacturability, this task will be accomplished

within fabrication constraints specified by the MEMS team at UF. This ensures the design is

physically realizable. In parallel, other sensing modalities could be explored in the case that

the MEMS cantilever is not practical.

• This task will be accomplished at UF.

1.1.2

Microfabrication

• The objective in this phase is to develop a microfabrication strategy (materials, deposition,

patterning) that can meet the requirements found from simulation.

• Our approach here is to find a range of dimensional constraints and material types that could

be physically realizable.

• This task will be accomplished at UF by Dr. YK Yoon.

the sensor described by the simulation results.

• Deliverables include successful microfabrication plan.

• No government equipment is required.

• To reduce risk of later failure due to non-manufacturability, this task will be accomplished

with paralel investigating of alternative MEMS sensing modalities.

• This task will be accomplished at UF.

1.1.3

Circuit design

• The objective in this phase is to develop a circuit which amplifies and digitizes the the voltage

produced by the MEMS elements.

• Our approach here is to ...

• This task will be accomplished at TTU by Dr. Changzi Li.

• Completion of this task is specified by successful design of a circuit capable of amplifying and

digitizing MEMS output voltage with input-referred voltage noise low enough to meet the

overall sensitivity requirement.

• Deliverables include successful design and prototype of the circuit, usable with the scale

model, using COTS components.

• No government equipment is required.

• To reduce risk of later failure due to excessive noise, this task will investigate only specifically

low-noise designs.

• This task will be accomplished at TTU.

1.1.4

Manufacture and testing

• The objective in this phase is to construct a scale model of the MEMS design using COTS

components, according to the scaling law developed in 1.1.1.

• Our approach here is to mimic the MEMS structure with COTS materials (ie, commercially

available piezo elements and magnetic sheets)

• This task will be accomplished at UF by Dr. Joaquin Casanova.

• Completion of this task is specified by successful construction and testing of a scale model,

which satisfies Table 1 after application of scaling laws.

• Deliverables include successful scale model prototype of the sensor.

• No government equipment is required.

• This task will be accomplished at UF.

1.2

Phase II

AMBIIENT Phase 2 will develop and demonstrate an integrated sensor head meeting the performance and SWaP metrics of Table 1, and including all vacuum, photonic, and thermal control

components.

1.2.1

Modeling and simulation

1.2.2

Microfabrication

1.2.3

Circuit design

1.2.4

Manufacture and testing

1.3

Phase III

AMBIIENT Phase 3 will demonstrate a fully integrated gradiometer comprising all control electronics, power conditioning, and packaging, meeting all performance metrics of Table 1

1.3.1

Modeling and simulation

1.3.2

Microfabrication

1.3.3

Circuit design

1.3.4

Manufacture and testing

2

Innovative Claims

Our approach is to design a sensor based on a magnetoreceptive mechanism used in nature magnetite crystals torqued by external magnetic fields open ion channels in the cell wall. To mimic

this, we propose a microfabricated MEMS sensor, with a layer of magnetic material on top of piezo

electric cantilevers. When forced with an exernal field, torque induced on the magnet create stress

in the piezo, and thus a voltage is produced. There are three advantages to this approach. First,

microfabrication allows for a small size. Second, by orienting individual sensing elements in antiseries order, the output is natively a gradiometer. Third, by selecting the resonant frequency of the

cantilever carefully, we can create a gradiometer which outputs a spectrogram directly. Though

fluxgates can be microfabricated and function as gradiometers, they suffer a size/sensitivity tradeoff.

Microfabricated atmonic magnetometers are sensitive but don’t function natively as gradiometers.

Other micro-scale magnetometers, namely Lorentz-type, which operate on a similar mechanism,

are not yet sensitive enough and haven’t been used as frequency-domain gradiometers, as in the

proposed design.

Detailed Technical Approach

Magnetometers serve an important role in investigating biologically generated electromagnetic

fields, such as those created by neuronal currents, or geological magnetic fields. Typically, magnetometers are unable to achieve high sensitivity in an ambient, unshielded environment - getting to

femtotesla level sensitivity requires magnetic shield and cryogenic sensors, such as SQUID [13].√The

novel spin relaxation free magnetometer has been minaturized and achieves less than 10 fT/ Hz,

but still requires shielding and lacks directional sensitivity [18]. Fluxgates have achieved pT level

resolution at small size, but this is insufficient for biomagnetic field measurement [16, 17, 23]

Figure 1: Fundamental-mode orthogonal fluxgate gradiometer [17].

Lorenz-type magnetometers (which translate magnetic fields into mechanical actuation of a

magnet or current carrying wire) have been built in MEMS substrates, but are as yet insufficiently

sensitive and require shielding [11, 12, 20, 22]

In nature, many organisms have a sense of magnetoreception used for navigation, from magnetotactic bacteria to birds. Two mechanisms have been proposed: a spin-selective (and thus

field-sensitive) chemical reaction rate, or magnetite crystals which are actuated by external fields

and activate ion channels in the cell membrane [5, 9, 10]. Measurements of these magnetosomes

show a magnetic dipole moment of up to 100fA/m2 [7, 8].

Our approach is to mimic the approach found in magnetosomes, with some key modifications

so that is frequency-selective and functions inherently as a gradiometer and thus does not require

shielding. The closest biomimetic sensor is a flow sensor which uses ferromagnetic cilia to detect

microfluidic flow rates [1].

To acomplish this, we propose layering single-domain magnetic crystals on top of piezoelectric

~ is:

cantilevers. The moment M induced on the magnetic layer with moment µ

~ and field B

~

M =µ

~ ×B

Interpreted as a point load at the cantilever tip, this moment causes a stress distribution on a

cantilever of length L, thickness t, second moment I, piezoelectric constant g31 , and modulus E, at

point x, of

σ=

M t(L − x)

2I

and n in series generates a voltage

L

M t(L − x)

g31 ndx

2LI

0

Two features are possible from the cantilever design: frequency selection and gradiometery.

As in [19], a cantilever has a resonant frequency, which can be modifying through geometrical

parameters. Peak response will be achieved at this frequency. By selection many cantilevers

of different dimensions, each corresponding to a separate output, the magnetometer output is a

spectrometer. Many cantilevers at the same resonance in series generate a largeer voltage; in antiseries, the difference is taken, thus functioning as a gradiometer with very high spatial resolution.

Even though biological magnetoreception is limited to nT sensitivity, our design will allow us to

surpass this. First, by careful selection of materials (such as Co-Pt or rare-earth magnets) [2, 4] we

can have much higher magnetic dipole moment, and thus higher moment. Second, by careful selection of geometery, we can employ parametric resonance [24]. Finally, using two banks of cantilevers

in series in anti-series, we both boost the voltage and create a high resolution gradiometer.

Z

V =

The noise floor of magnetic materials is governed by Barkhausen noise - the random flipping

of magnetic domains [3]; this noise is characterized as a flux noise level. The flux noise can be

converted into a magnetic moment noise, and thus moment noise. Piezo noise floor is largely

a function of piezo losses [14]. Additionally, there is the input-referred noise of any amplifier.

With conservative estimates for all of these, and two anti-series banks of 30 cantilevers each with

dimensions 400x40x3 µm, the sensitivity level is less than 10 fT/cm/sqrtHz.

An alternative design, should magnetic/piezo integration prove infeasible, is to measure the tilt

of magnetic cilia by some other means. One way would be to affix micromirrors to the magnetic cilia

and measure the change in reflected angle of a laser beam [6]. Instead of a laser, millimeter-wave

radar could detect changes in tilt angle, similar to the techniques used in vital-signs radar [15].

MEMS fabrication processes are capable of constructing the above-described sensor. This consists of two main fabrication tasks: piezo cantilever construction, and magnetic material integration.

The process described in [19] can be used for our task, with an additional step to apply the magnetic layer. PZT has a high voltage coefficient and is highly suitable for the piezo elements [21]

and can be deposited with pulsed laser deposition or solution-based deposition and patterned with

chemical etching or ion etching. Rare-earth magnetic materials, such as alloys of Sm-Co, offer high

magnetic energy product at room temperature and can be integrated into MEMS using sputtering

or pulsed laser deposition [2]. However, patterning of these materials is slow, using wet etching or

ion-beam milling.

Circuit description?

To test, in Phase I, it may be more feasible to test a scale model which can be built from COTS

components. An appropriate scaling law and set of nondimensional parameters can be used to

appropriately choose materials and dimensions for the scale model.

Metric

Power consumption

Sensor Volume

Control Electronics Volume

Ambient Magnetic Field

Ambient Operating Temperature

Gradient Full-scale Range

Gradient Sensitivity

Gradient Accuracy

Total Field Range

Total Field Sensitivity

Total Field Accuracy

Data Rate

3 dB Bandwidth

Phase 1

150 mW

3x3x10 cm

N/A

± 100 µT

N/A

1 nT/cm

√

10 fT/cm/ Hz

100 fT/cm

100 µT

√

100 pT/ Hz

1 nT

100/s

200 Hz

Phase 2

50 mW

1x1x7 cm

N/A

± 100 µT

0◦ C to 50◦ C

1 nT/cm

√

3 fT/cm/ Hz

30 fT/cm

100 µT

√

30 pT/ Hz

500 pT

200/s

400 Hz

Phase 3

100 mW

1x1x7 cm

¡ 20cm2

± 100 µT

0◦ C to 50◦ C

1 nT/cm

√

1 fT/cm/ Hz

10 fT/cm

100 µT

√

10 pT/ Hz

100 pT

500/s

1000 Hz

Table 1: Design objectives, by phase.

4

Risk Analysis and Mitigation Plan

Identify the major technical and programmatic risks in the program. Include a risk matrix. For

each risk, assign a probability of occurrence on a scale of 1-10, where 10 indicates a high likelihood

that the risk will impact program success, as well as an assessment of impact, also on a scale of 1-10,

where 10 indicates that this risk would maximally limit the program from delivering prototypes

on schedule or meeting performance objectives. For each item with total risk (likelihood impact)

exceeding 40, include a plan for mitigating the risk and assessing risk reduction. Where necessary,

parallel risk reduction tasks may be proposed, e.g. concurrent development of redundant techniques

or components. The proposal must differentiate the primary technical path from risk reduction

Phase

1

1

1

1

2

2

2

2

3

3

3

3

Milestone

Cantilever simulation and design

Fabrication plan

Circuit design

Scale model design and testing

Cantilever simulation and design

Fabrication plan

Circuit design

MEMS fabrication and testing

Cantilever simulation and design

Fabrication plan

Circuit design

MEMS fabrication and testing

Date

Table 2: Milestones schedule

tasks, which should be uniquely identified in the SOW and separately costed as optional tasks in

Volume II.

Insufficient sensitivity in

simulation

Best available MEMS processes infeasible

Scale model inaccurate

method for initial testing

Fabrication time/window

exceeds deadlines

Circuit/sensor fails tests

Probability

3

Impact

10

Plan

Change to alternate design

4

10

Change to alternate design

3

5

3

5

Rely on MEMS fabricated

sensor for test

Extend project time

3

9

Identify points of failure for

next design

Table 3: Risk matrix

5

Schedule and Milestones

Include a high-level Gantt chart outlining major technical tasks and measureable milestones by

phase. At a minimum, the schedule should include each SOW task of Volume 1, Section II.A.

Where risk reduction tasks are proposed, the schedule should include a milestone for assessment

and removal of redundant tasks.

6

Test Plan

Describe how compliance with the proposed metrics and milestones will be demonstrated in each

phase of the program. The test plan should be structured so that compliant performance can be

verified prior to delivery of hardware for government test and evaluation.

6.1

Phase 1

6.2

Phase 2

6.3

Phase 3

7

Results and Technology Transfer

Description of the results, products, transferable technology, and expected technology transfer.

This should also address mitigation of life-cycle and sustainment risks associated with transitioning intellectual property for U.S. military applications, if applicable. See also Section IV.B.10,

Intellectual Property.

8

Ongoing Research

Comparison with other ongoing research indicating advantages and disadvantages of the proposed

effort.

Proposer Accomplishments

Discussion of proposers previous accomplishments and work in closely related research areas. In

this section, also include any ongoing research projects or pending proposal activity that technically

overlaps with the proposed effort, including funding source, administrative point of contact, and

the program management plan for combining and de-conflicting the efforts.

10

Facilities

Description of the facilities that will be used for the proposed effort.

11

Teaming

Description of the formal teaming agreements that are required to execute this program. Describe

the programmatic relationship between investigators and the rationale for choosing this teaming

strategy. Present a coherent organization chart and integrated management strategy for the program team. For each person, indicate: (1) name, (2) affiliation, (3) abbreviated listing of all

technical area tasks they will work on with roles, responsibilities, and percent time indicated, (4)

discussion of the proposers previous accomplishments, relevant expertise and/or unique capabilities.

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352-246-9649, jcasa@ufl.edu

Total funds requested

Submitted XX/YY/2017

Award instrument requested Cost-Plus-Fixed Fee (CPFF), Cost-contractno fee, cost sharing

contractno fee,or other type of procurement contract (specify) or Other Transaction

Place(s) and period(s) of performance

Total proposed cost separated by basic award and option(s), if any, by calendar year and by

government fiscal year

Defense Contract Management Agency (DCMA) administration office (if known) Name,

address, and telephone number

Defense Contract Audit Agency (DCAA) audit office (if known) Name, address, and telephone number

Date proposal was prepared

DUNS

TIN

Subcontractor Information

Proposal validity period (120 days is recommended)

Any Forward Pricing Rate Agreement other such approved rate information, or such documentation that may assist in expediting negotiations (if available). Attachment 1, the Cost

Volume Proposer Checklist, must be included with the coversheet of the Cost Proposal.

The proposers (to include FFRDCs and Government Labs) cost volume shall provide cost and

pricing information, or other than cost or pricing information if the total price is under the referenced threshold (See Note 1), in sufficient detail to substantiate the program price proposed (e.g.,

realism and reasonableness). In doing so, the proposer shall provide, for both the prime and each

subcontractor, a Summary Cost Breakdown by phase and performer fiscal year, and a Detailed

Cost Breakdown by phase, technical task/sub-task, and month. The breakdown/s shall include,

at a minimum, the following major cost item along with associated backup documentation: Total

program cost broken down by major cost items:

12

Direct Labor

A breakout clearly identifying the individual labor categories with associated labor hours and direct

labor rates, as well as a detailed Basis-of-Estimate (BOE) narrative description of the methods used

to estimate labor costs

13

Indirect Costs

Including Fringe Benefits, Overhead, General and Administrative Expense, Cost of Money, Fee,

etc. (must show base amount and rate)

14

Travel

Provide the purpose of the trip, number of trips, number of days per trip, departure and arrival

destinations, number of people, etc. See Section IV.B.13 for travel funding restrictions

15

Other Direct Costs

Itemized with costs; back-up documentation is to be submitted to support proposed costs

16

Material/Equipment

(i) For IT and equipment purchases, include a letter stating why the proposer cannot provide the

requested resources from its own funding. (ii) A priced Bill of Material (BOM) clearly identifying,

for each item proposed, the quantity, unit price, the source of the unit price (i.e., vendor quote,

engineering estimate, etc.), the type of property (i.e., material, equipment, special test equipment,

information technology, etc.), and a cross-reference to the Statement of Work (SOW) task/s that

require the item/s. At time of proposal submission, any item with a unit price that exceeds $1,000

must be supported with basis-of-estimate (BOE) documentation such as a copy of catalog price lists,

vendor quotes or a detailed written engineering estimate (additional documentation may be required

during negotiations, if selected). (iii) If seeking a procurement contract and items of Contractor

Acquired Property are proposed, exclusive of material, the proposer shall clearly demonstrate that

the inclusion of such items as Government Property is in keeping with the requirements of FAR Part

that title to all equipment purchased with funds available for research under any resulting contract

will vest in the acquiring nonprofit institution (e.g., Nonprofit Institutions of Higher Education

and Nonprofit Organizations whose primary purpose is the conduct of scientific research) upon

acquisition without further obligation to the Government. Any such equipment shall be used for

the conduct of basic and applied scientific research. The above transfer of title to all equipment

purchased with funds available for research under any resulting contract is not allowable when the

acquiring entity is a for-profit organization; however, such organizations can, in accordance with

FAR 52.245-1(j), be given priority to acquire such property at its full acquisition cost.

17

Consultants

If consultants are to be used, proposer must provide a copy of the consultants proposed SOW as

well as a signed consultant agreement or other document which verifies the proposed loaded daily

/ hourly rate and any other proposed consultant costs (e.g. travel);

18

Subcontracts

Itemization of all subcontracts. Additionally, the prime contractor is responsible for compiling

and providing, as part of its proposal submission to the Government, subcontractor proposals prepared at the same level of detail as that required by the prime. Subcontractor proposals include

Interdivisional Work Transfer Agreements (ITWA) or similar arrangements. If seeking a procurement contract, the prime contractor shall provide a cost reasonableness analysis of all proposed

subcontractor costs/prices. Such analysis shall indicate the extent to which the prime contractor

has negotiated subcontract costs/prices and whether any such subcontracts are to be placed on a

sole-source basis. All proprietary subcontractor proposal documentation (fully disclosed subcontract proposal), prepared at the same level of detail as that required of the prime, which cannot

be uploaded to the DARPA BAA website (https://baa.darpa.mil, BAAT) as part of the proposers

submission, shall be made immediately available to the Government, upon request, under separate

cover (i.e., mail, electronic/email, etc.), either by the proposer or by the subcontractor organization.

This does not relieve the proposer from the requirement to include, as part of their submission (via

BAAT), subcontract proposals that do not include proprietary pricing information (rates, factors,

etc.). A Rough Order of Magnitude (ROM), or similar budgetary estimate, is not considered a fully

qualified subcontract cost proposal submission. Inclusion of a ROM, or similar budgetary estimate,

may result in the full proposal being deemed non-compliant or evaluation ratings may be lowered;

19

Cost-Sharing

The amount of any industry cost-sharing (the source and nature of any proposed cost-sharing

should be discussed in the narrative portion of the cost volume); AND

Fundamental Research

Written justification required per Section II.B, Fundamental Research, pertaining to prime and/or

subcontracted effort being considered Contracted Fundamental Research.