# Crab-like legged robot for accessing and classifying munitions in surf zones

Project Number : MR19-1369

Principal Investigator: Kathryn Daltorio

PI’s Organization : Case Western Reserve University

In-Progress Review Meeting

Presentation date: August 12, 2025

# Project Team

**Kathryn Daltorio**
*Case Western Reserve University*

with PhD students
Yifeng Gong
Mingyu Pan
Joshua Towns
John Grezmak

Undergrad/MS
Benjamin Poulin
Scuba Dive Team



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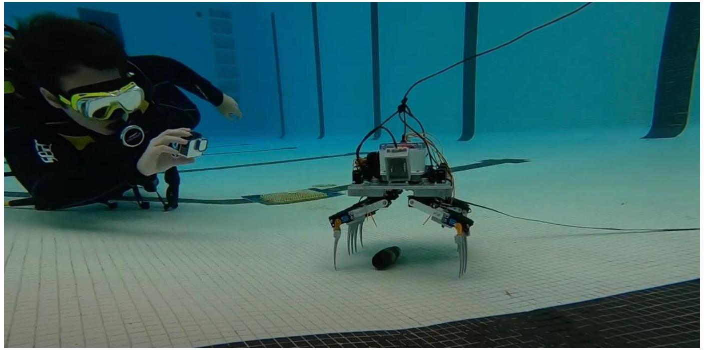
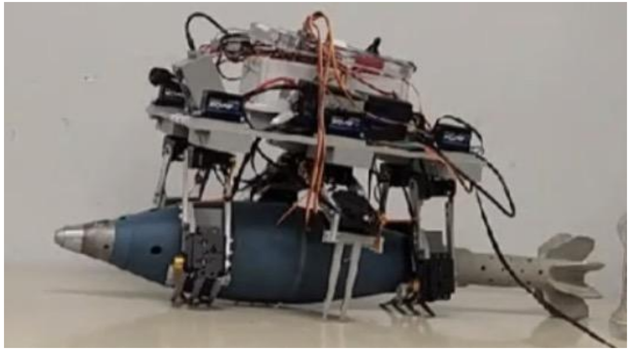
# Bottom Line Up Front

- Goal: mobile robotic handling of UXO.
- In 2024, published in Field Robotics on 13 lb (5.7kg) crab robot to pick up cylinders half the robot’s weight with one pair of legs.
- “Lab” prototype tested in lake, learned a lot about sensorization
- Now “gearing up” for more extensive outdoor testing Summer 2026





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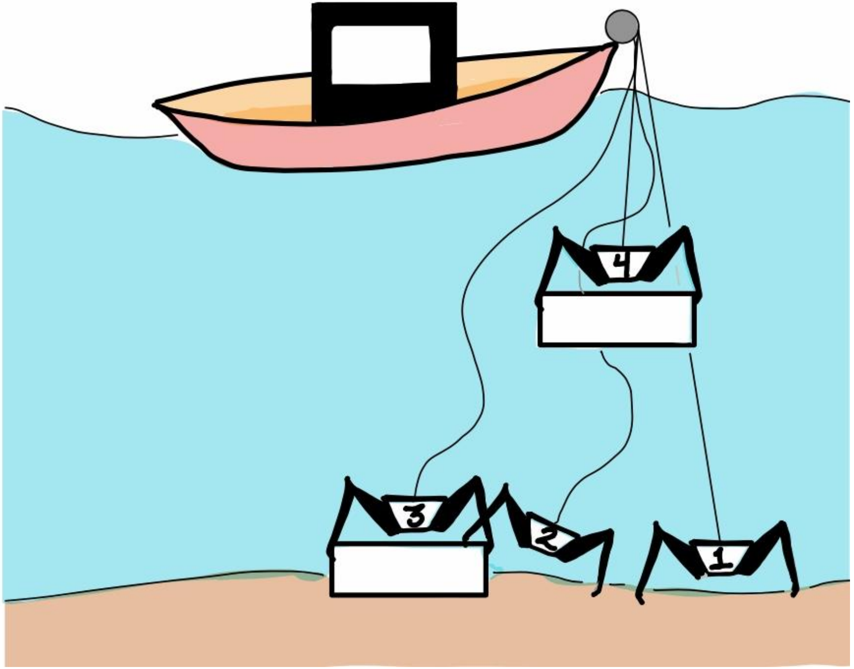
# After Seed Project and ONR YIP

# Technical Objectives




Can we make a robot that moves objects like UXO without a human diver?

* Search 5m radius spiral in less than an hour

* Grasp UXO when found tightly enough to lift or secure blow in place

# Technical Objectives

**Approach:** Our preliminary SEED project has identified three fundamental hypotheses that, if validated, will enable new types of crab-like robots for various munitions responses.

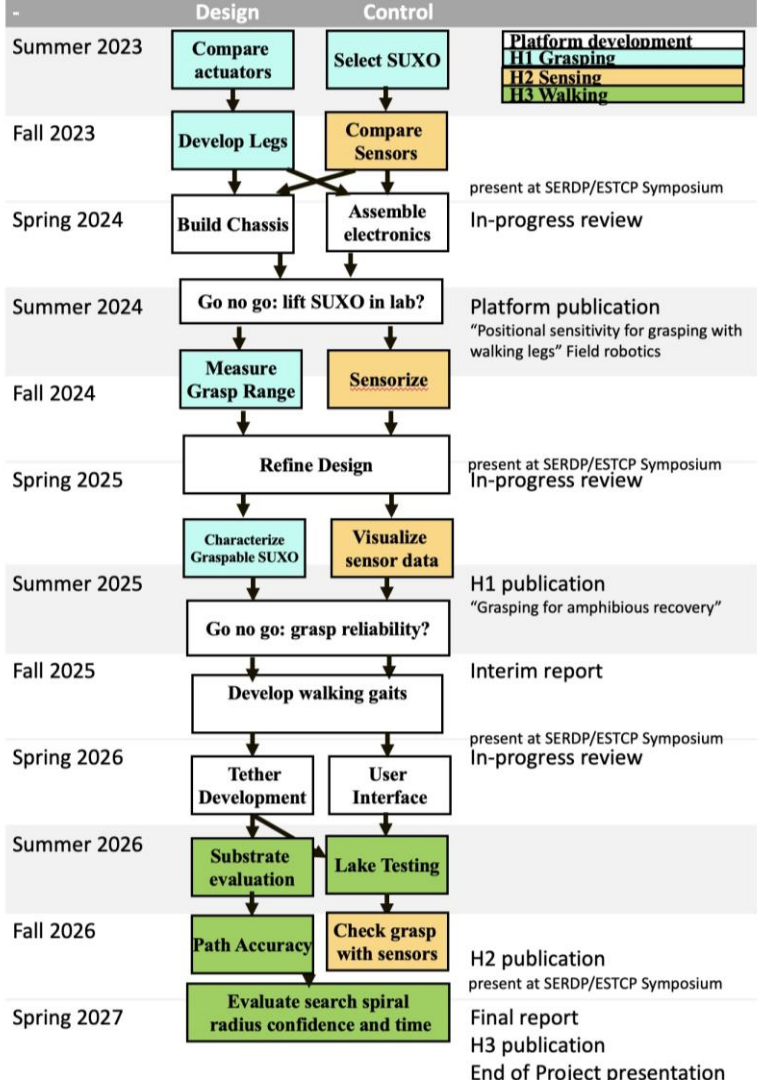
- **Hypothesis 1 (H1): Walking legs can securely grasp cylindrical UXO.** Using the same appendages for locomotion and grasping UXO builds redundancy into the system and simplifies the robot for robust use. We will convert our previous walking claw for use on cylindrical simulated UXO in the 40 mm to 60mm diameter range.
- **Hypothesis 2 (H2): Robust leg sensors can augment vision to increase grasp success.** Tactile exploration mitigates two underwater challenges, localization and vision in turbid waters. To demonstrate this on our robot, we will embed contact sensors within the legs, which we have previously used to detect hydrodynamic forces and to classify soft vs hard terrain.
- **Hypothesis 3 (H3): Walking-grasping legs are suitable for systematic exploration.** How far and how accurately can the robot walk? Downward facing and on-board cameras will be used to validate behaviors.

# Technical Approach

Hypothesis 1 (H1): Walking legs can securely grasp cylindrical UXO.

Hypothesis 2 (H2): Robust leg sensors can augment vision to increase grasp success.

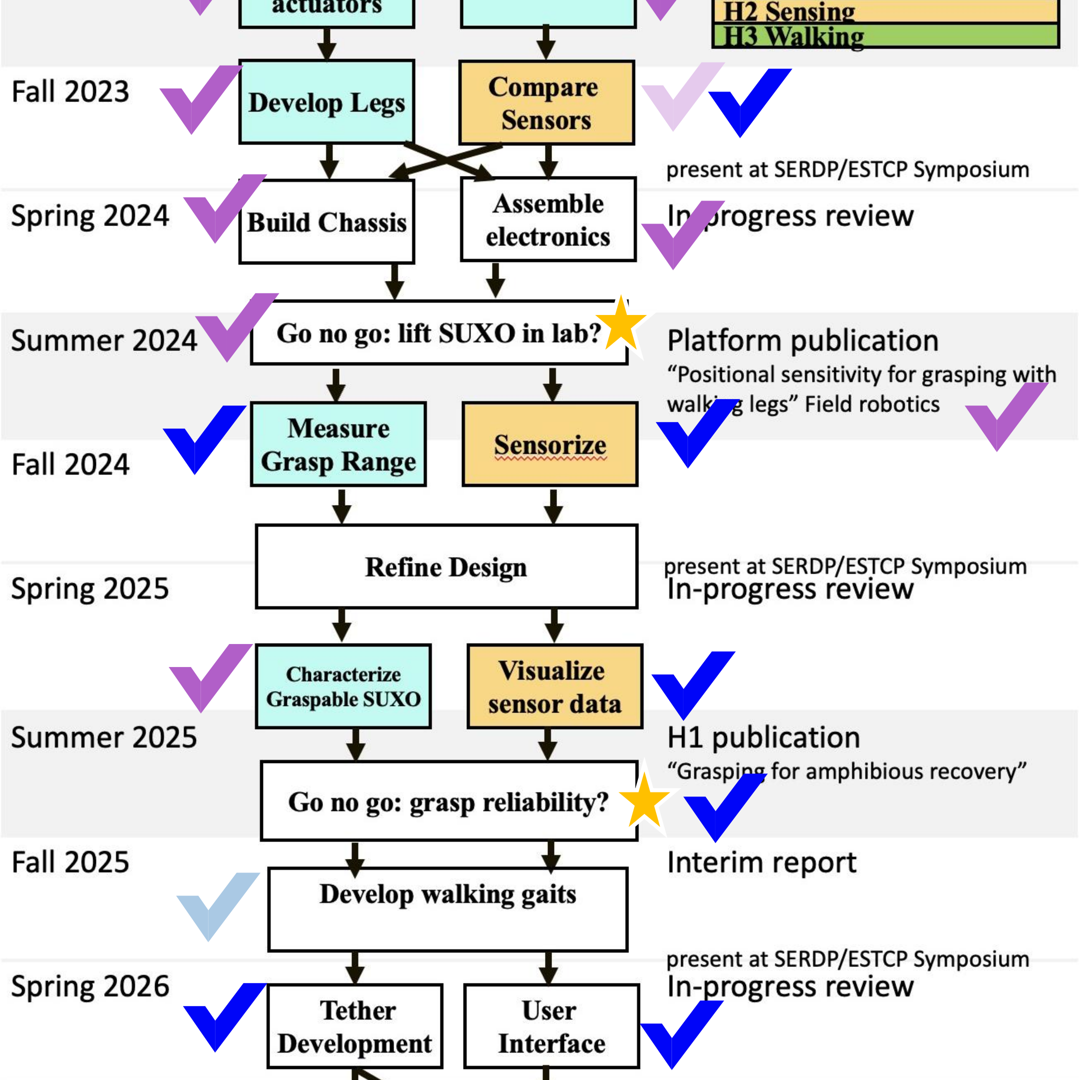
Hypothesis 3 (H3): Walking-grasping legs are suitable for systematic exploration.



# Technical Approach

Yifeng Gong, Mingyu Pan, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. Journal of Field Robotics, Nov 2024 https://doi.org/10.1002/rob.22482
(Platform Publication includes grasp)

Yifeng Gong, Ge Sun, Aditya Nair, Aditya Bidwai, Raghuram CS, John Grezmak, Guillaume Sartoretti, and **Kathryn A. Daltorio**. Legged Robots for Object Manipulation: A Review. *Frontiers in Mechanical Engineering*. Vol. 9 2023. https://doi.org/10.3389/fmech.2023.1142421
(H1 Publication)



# Approach … Continued

Hypothesis 1 (H1): Walking legs can securely grasp cylindrical UXO.

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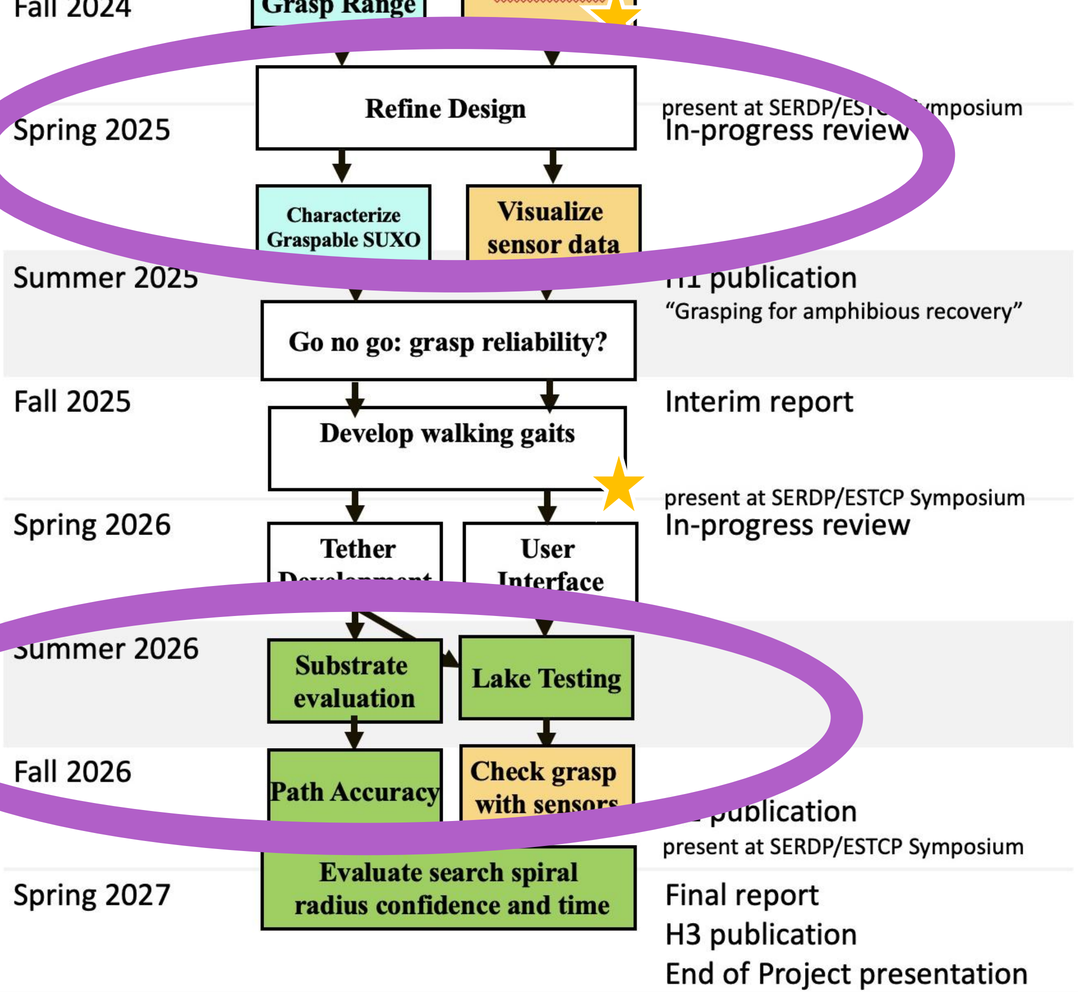
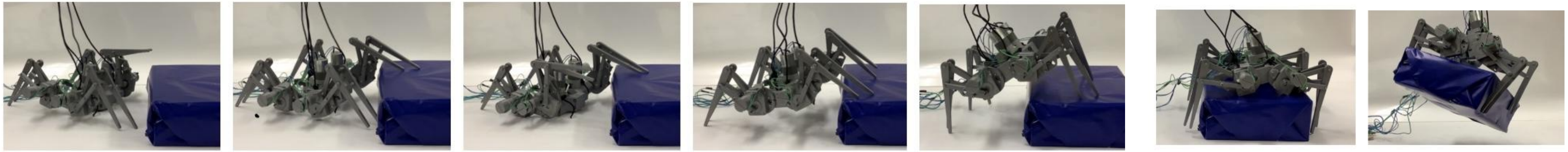


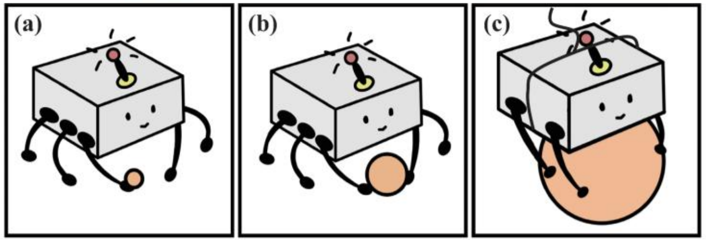
# Results to Date

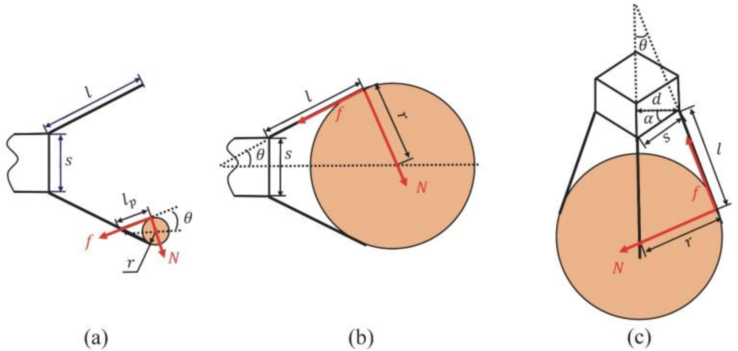
Yifeng Gong, Alexander M. Behr, Nicole M. Graf, Kaiyi Chen, Xiaoyue Xu, **Kathryn A. Daltorio***. A Walking Claw For Tethered Object Retrieval. Accepted Aug 2022 *ASME Journal of Mechanisms and Robotics*. (Impact factor 2.75).
https://doi.org/10.1115/1.4055812

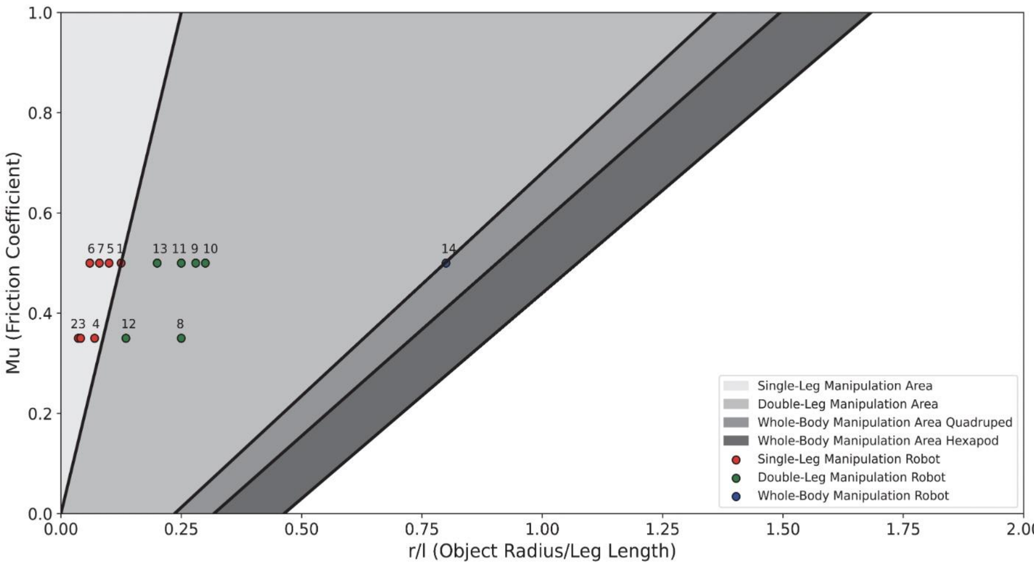


(a) Lift the 1st leg (b) Place the 1st leg (c) Lift the 2nd leg (d) Place the 2nd leg (e) Raise the body (f) Translation (g) Grasp and pull

# Ways to pick up objects with legged platforms




Yifeng Gong, Ge Sun, Aditya Nair, Aditya Bidwai, Raghuram CS, John Grezmak, Guillaume Sartoretti, and **Kathryn A. Daltorio**. Legged Robots for Object Manipulation: A Review. *Frontiers in Mechanical Engineering*. Vol. 9 2023. https://doi.org/10.3389/fmech.2023.1142421



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# Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response

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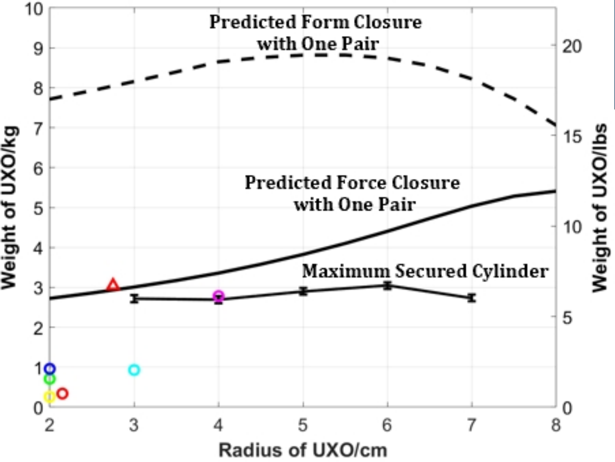
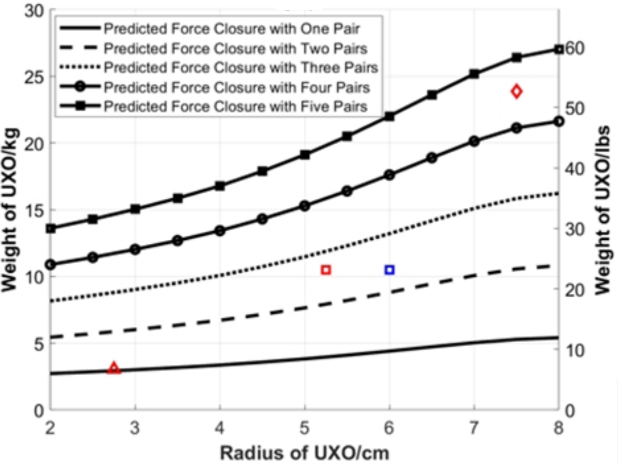
DOD ▪ EPA ▪ DOE

Yifeng Gong, Mingyu Pan, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. Journal of Field Robotics, Nov 2024
https://doi.org/10.1002/rob.22482

# How big of an object can we lift?




| Label | UXO | Weight/kg | Approx Volume/cm$^3$ | $\mu$ | Grasp Result |
|---|---|---|---|---|---|
| ○ (red) |  | 0.34 | 168 | 0.39 | Graspable with one pair. |
| ○ (yellow) |  | 0.26 | 100 | 0.37 | Graspable with one pair. |
| ○ (green) |  | 0.71 | 251 | 0.44 | Graspable with one pair. |
| ○ (blue) |  | 0.96 | 232 | 0.64 | Graspable with one pair. |
| ○ (cyan) |  | 0.93 | 359 | 0.40 | Graspable with one pair. |
| ○ (magenta) |  | 2.78 | 1276 | 0.42 | Graspable with one pair. |
| △ |  | 3.04 | 640 | 0.35 | Unstable upright grasp with one pair. Graspable with two pairs. |
| □ (red) |  | 10.5 | 5606 | | Graspable with three pairs. |
| □ (blue) |  | 10.5 | 8030 | | Graspable with three pairs. |
| ◇ |  | 23.9 | 14844 | | Predicted graspable with five pairs. |

Yifeng Gong, Mingyu Pan, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. Submitted March 2024.



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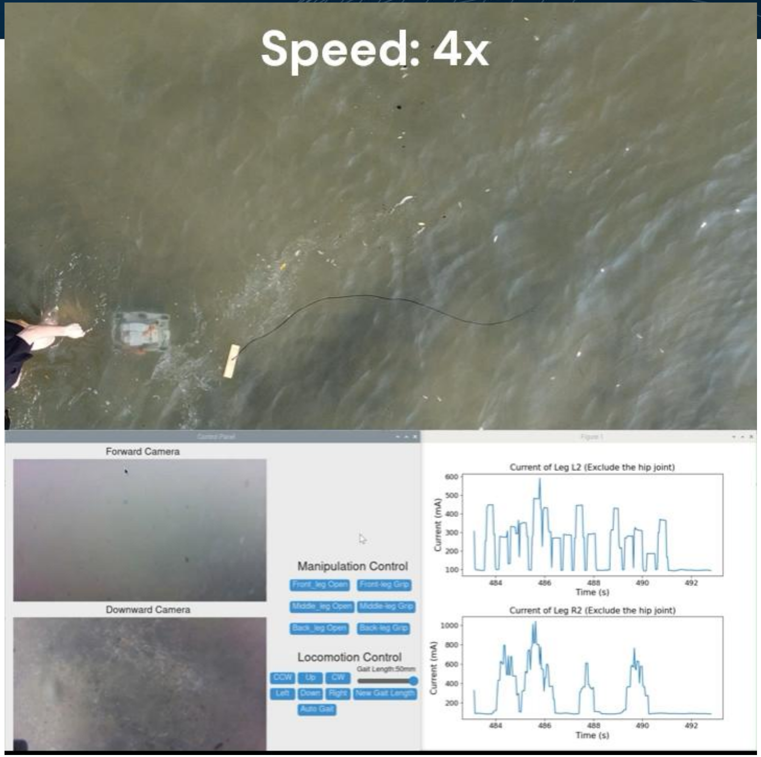
# Testing in Lake Erie Fall 2024

Windfinder.com

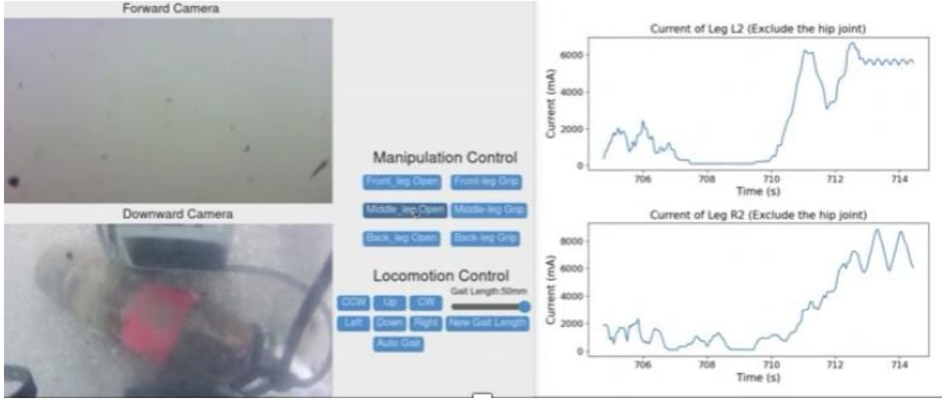

<u>Yifeng Gong,</u> <u>Mingyu Pan</u>, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. Journal of Field Robotics, Nov 2024 https://doi.org/10.1002/rob.22482

# Progress by Hypothesis

Hypothesis 1 (H1): Walking legs can securely grasp cylindrical UXO.

Hypothesis 2 (H2): Robust leg sensors can augment vision to increase grasp success.

Hypothesis 3 (H3): Walking-grasping legs are suitable for systematic exploration.



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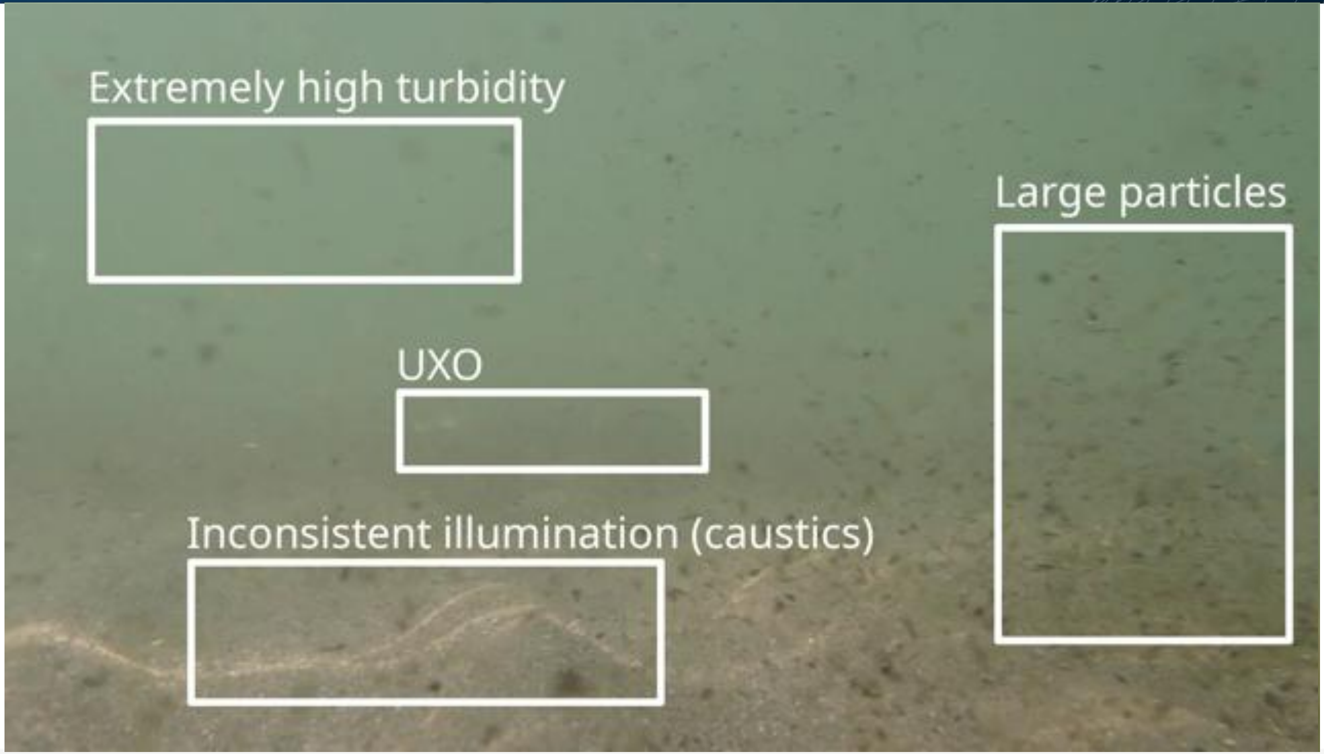
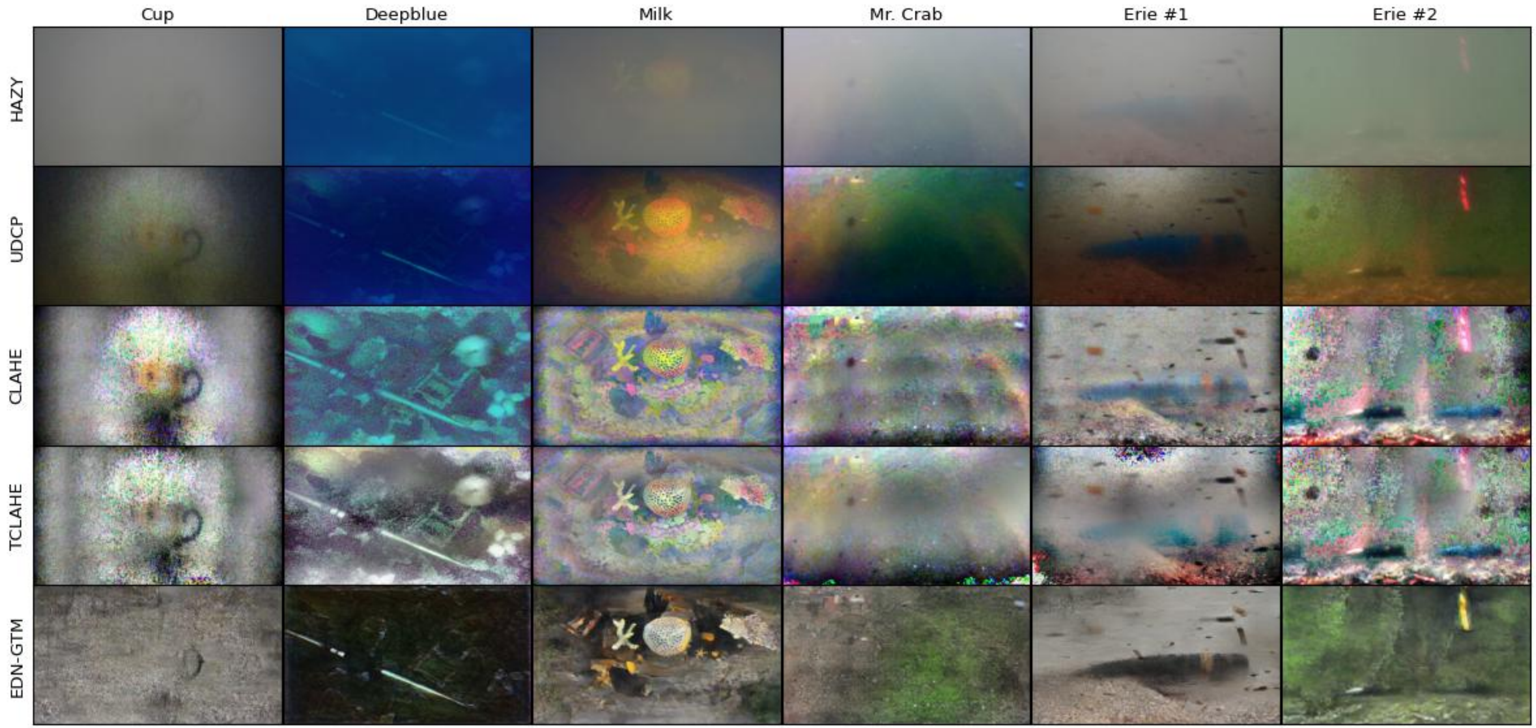
# H2 Sensing – Vision in Benthic Areas

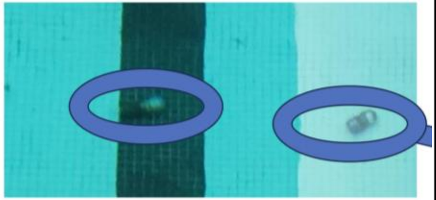


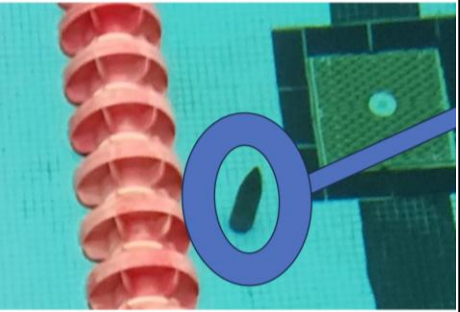
# H2 Sensing - Exploring Vision Filters

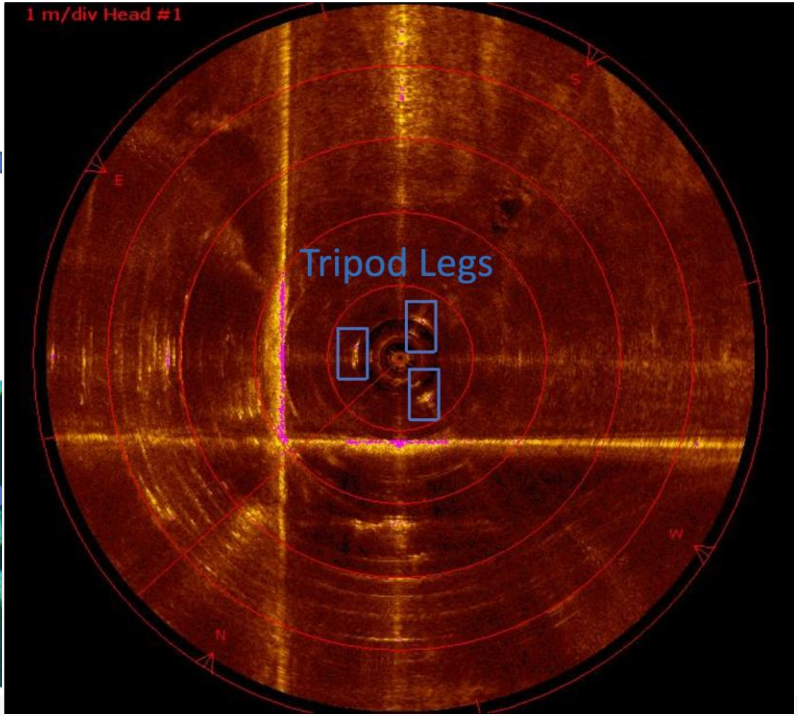



Ben Poulin
MS project

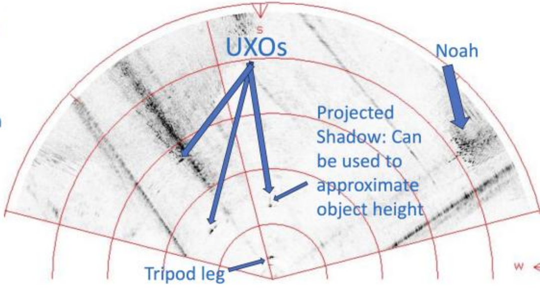
# H2 Sensing – Sonar Fall 2024







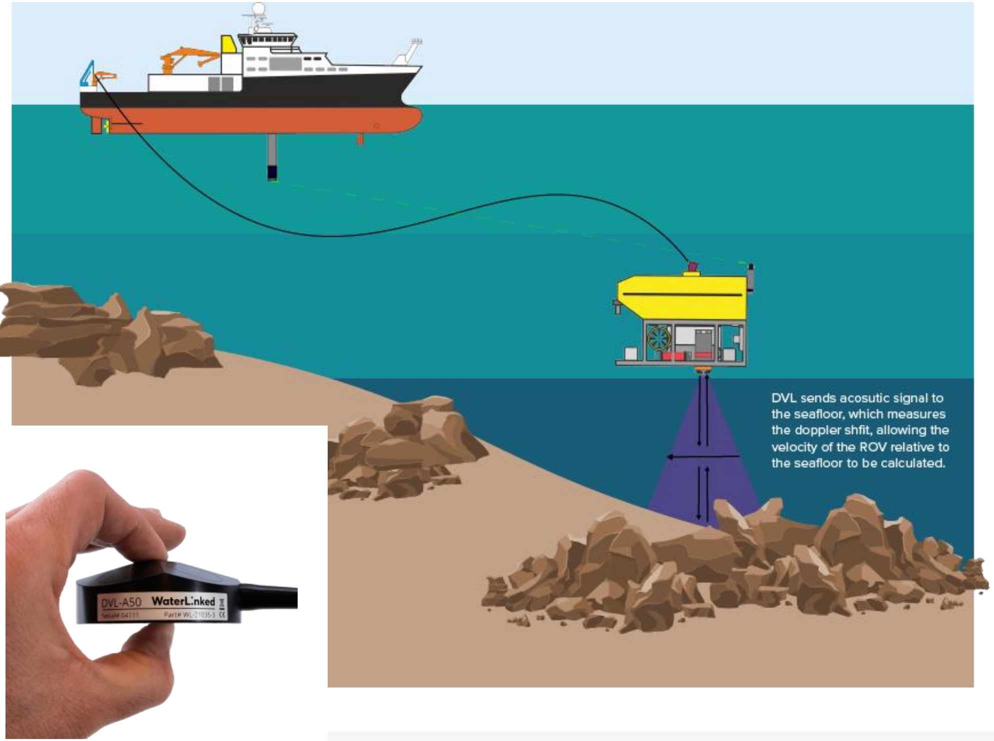

Different view options and adjusting Gain can make metallic objects standout much more clearly from the background



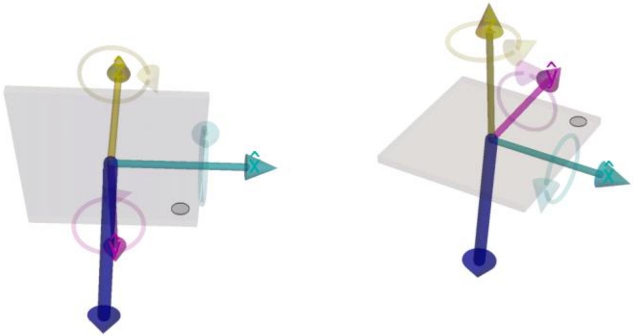

Tripod sonar systems
“very annoying to set up”

Thanks to Chef Bender and Brendan McNamara, Cleveland Fire Department

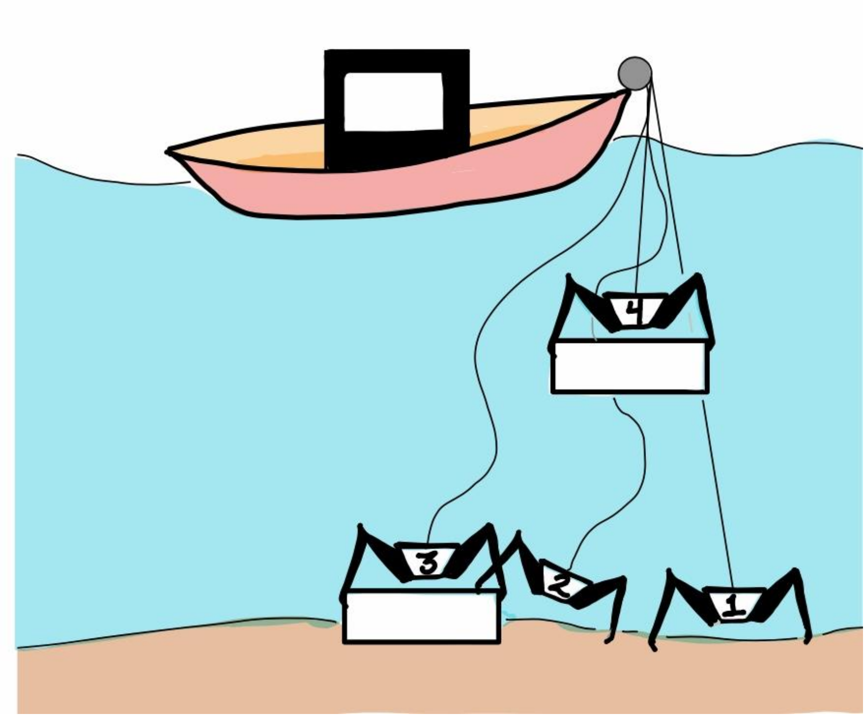
# Sensing for Localization – acoustic vs reckoning




IMUs



# H3 Systematic Exploration




**Hypothesis 3 (H3): Walking-grasping legs are suitable for systematic exploration.**

* Search 5m radius spiral in less than an hour



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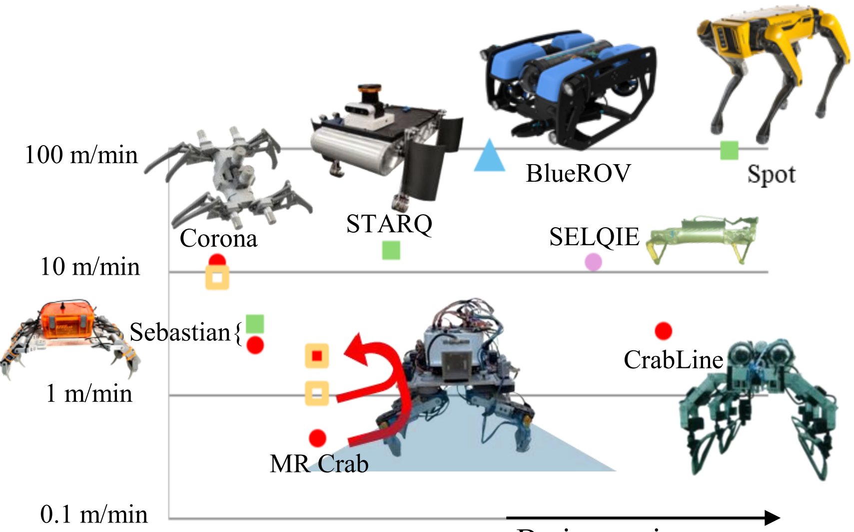
# Locomotion Speed (m / min)




Log-Log axes

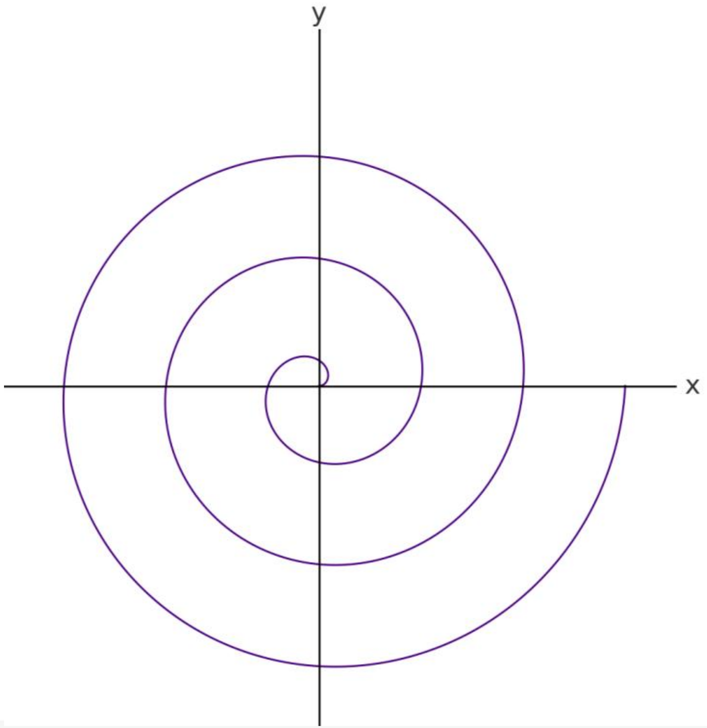
New dactyls increased speed ~x4

| Robot Name | Velocity (cm/s) | Length (cm) | Mass (kg) | Speed (m/min) | |
|---|---|---|---|---|---|
| BlueROV2 | 150 | 45.7 | 12 | 90.00 | Swimming |

(Our robots)

**Current fastest speed:** 2 m/min
**Goal:** Cover a 5 m radius spiral area (~158 m path length) in < 1 hour
**Detection range:** 0.5m
**Required speed:** ~2.6 m/min to finish spiral in < 1 hour.

# H3 – Spiral Search




$$s(t) = \frac{1}{2}a\left(\sqrt{t^2 + 1}\,t + \sinh^{-1}(t)\right)$$

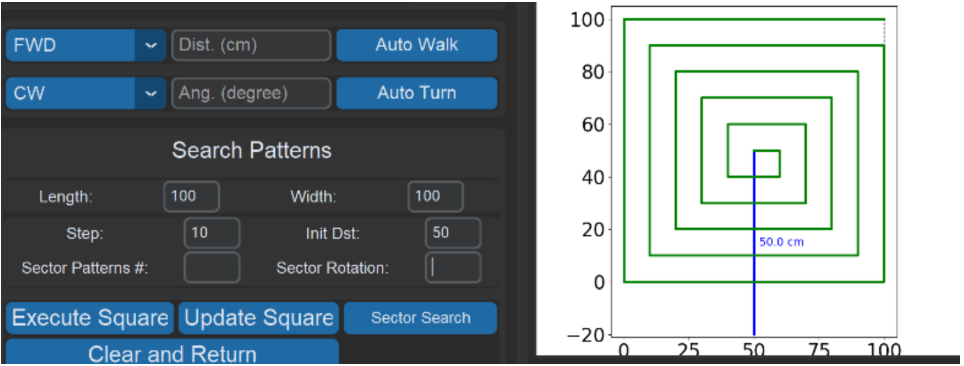
$$r(\theta) = a\,\theta$$

For spacing 1m, to get radius of 5 m
t = 0 to 10pi, a = .16, = path length 79m

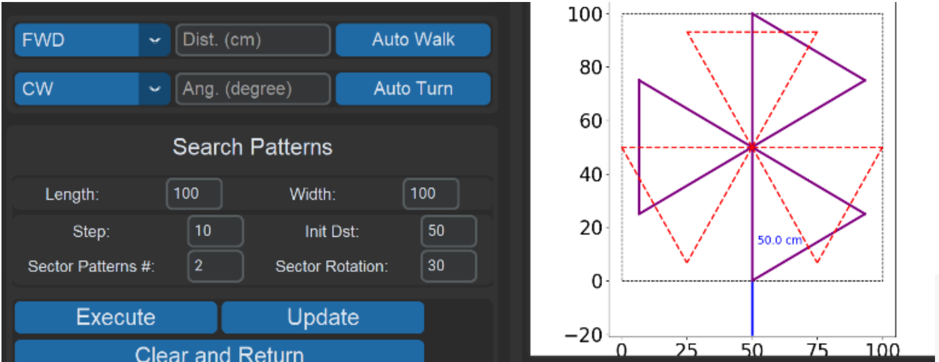
For spacing .5m, to get radius 5m,
t = 0: 20pi a = 0.08 = path length 158m

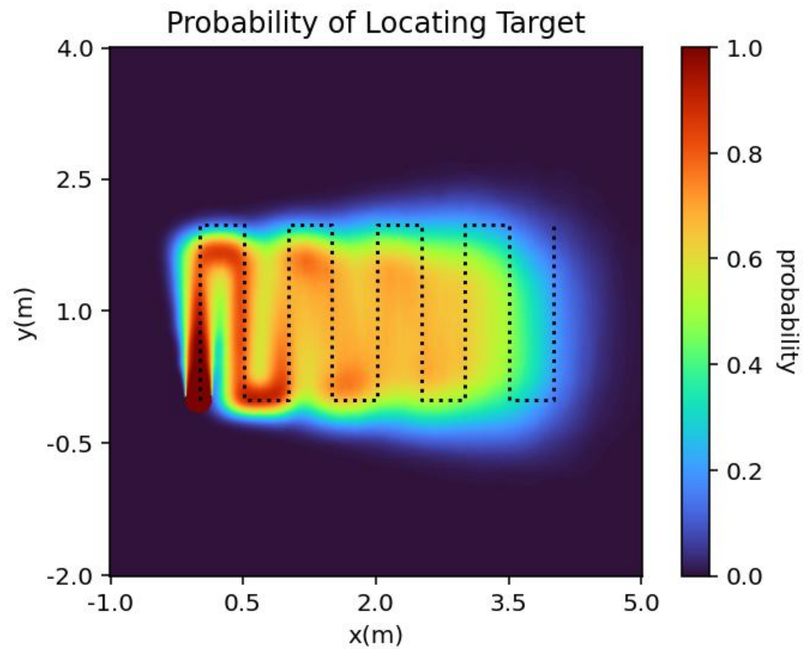
# H3 Patterns for Systematic Exploration

## Expanding Square




## Sector Search



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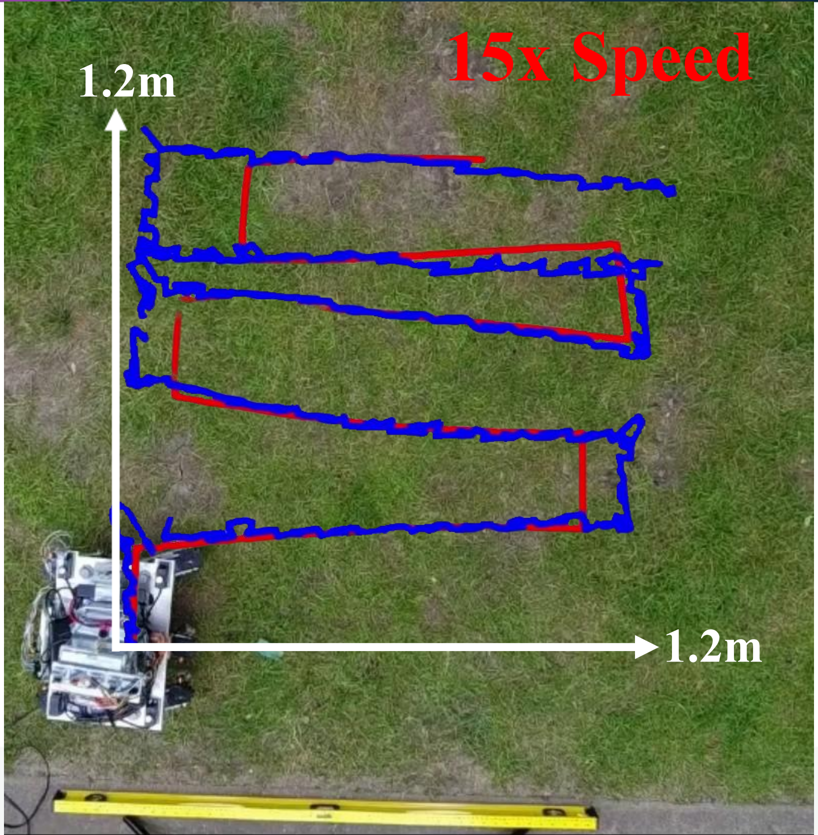
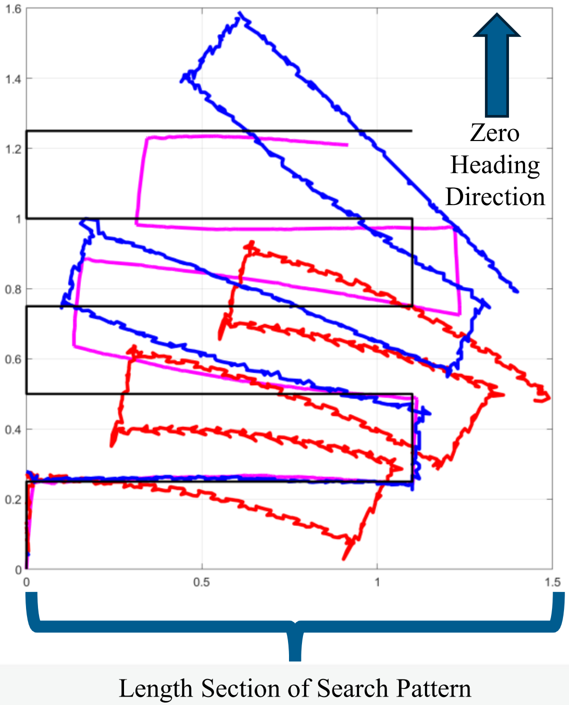
# H3 The Robot Follows a Trajectory




## Challenges of localization

- Overhead
- Onboard estimate

# H3 – Getting the best trajectory out of the robot




Ladder trajectory

1) **Forward walking** on longest part of ladder

2) **Sideways walking** on longest part of ladder

3) **Sideways walking with heading correction** after each ladder segment.

# H3 - on Sand: where we were last year

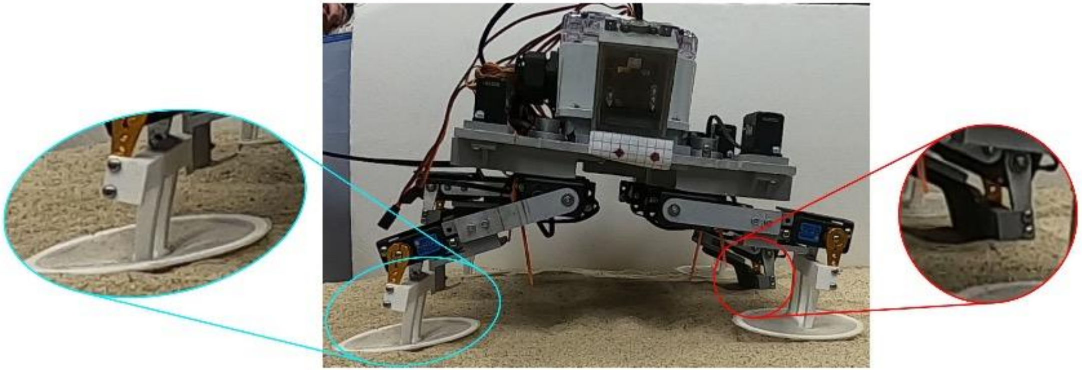
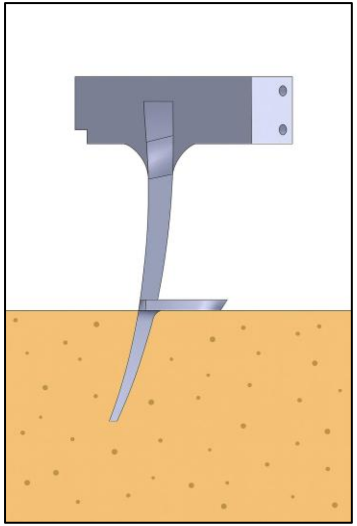
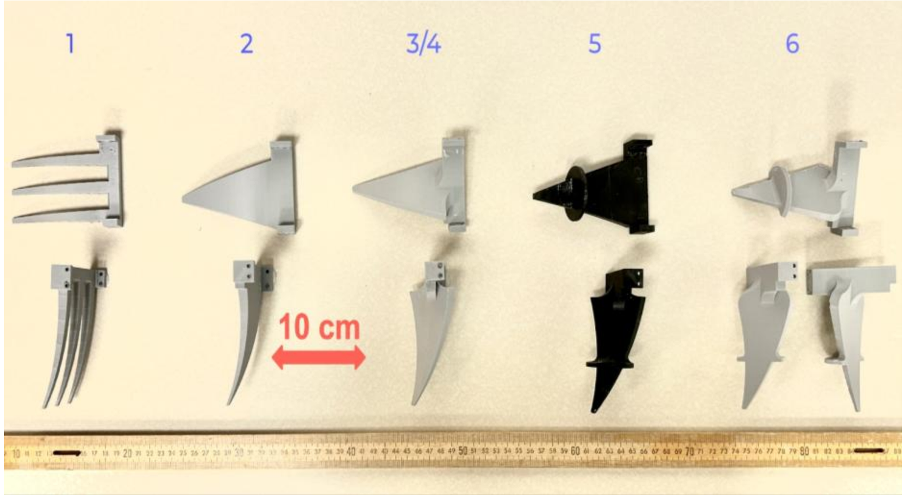


Figure 4.4: A frame from a side view video of the robot walking in its sideways gait. The blue detail shows how sand collects in a pile in front of the two piece fabric dactyl. The red detail shows the front middle leg of the robot anchoring itself in the sand, hindering the robot's forward motion.

MS Dexter Ethan Wood Compliant Webbing Between Robotic Crab Legs for UXO Probing, Excavation, and Removal

# H3 - Dactyl Design Improvements



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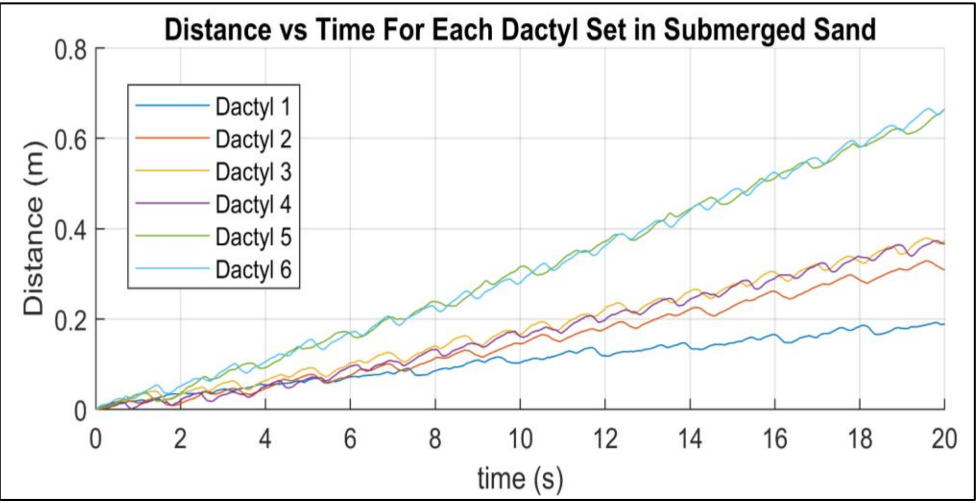
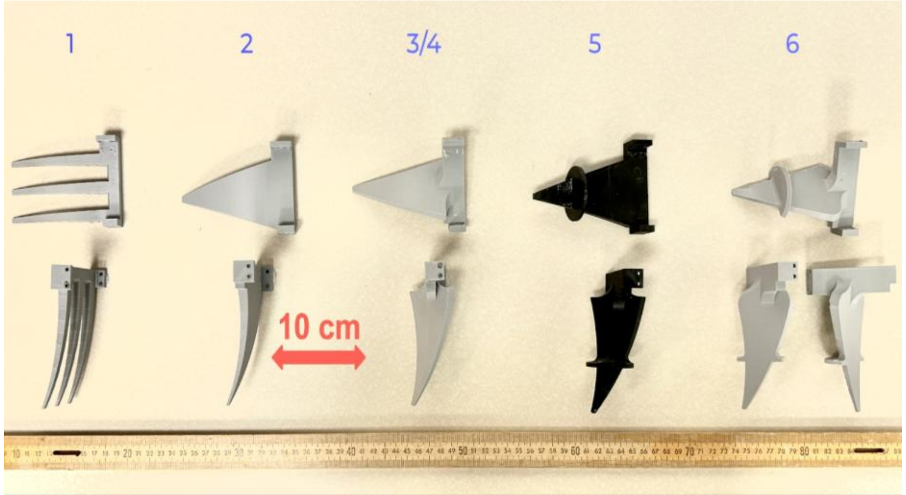
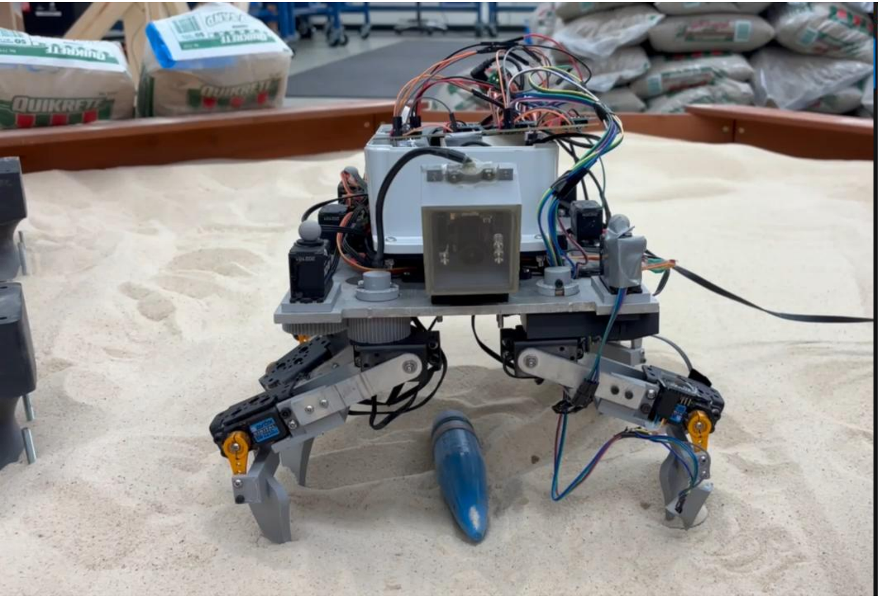
# Forward walking speed increased 2x in dry sand and 4.25 times in sand submerged in water.

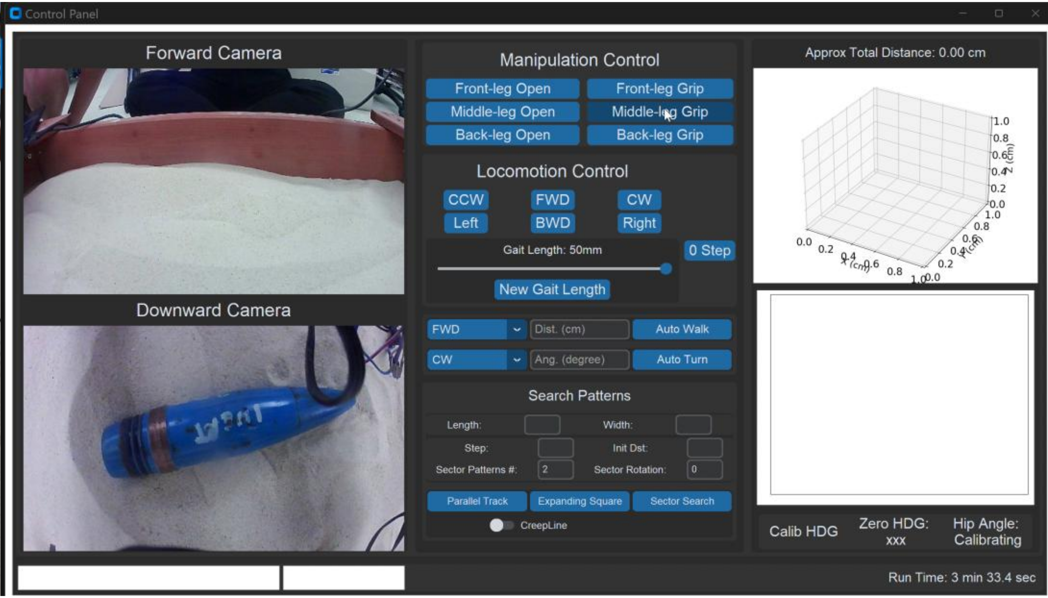



**Dactyl Designs**



# Checking : New Legs Still Grasp Object





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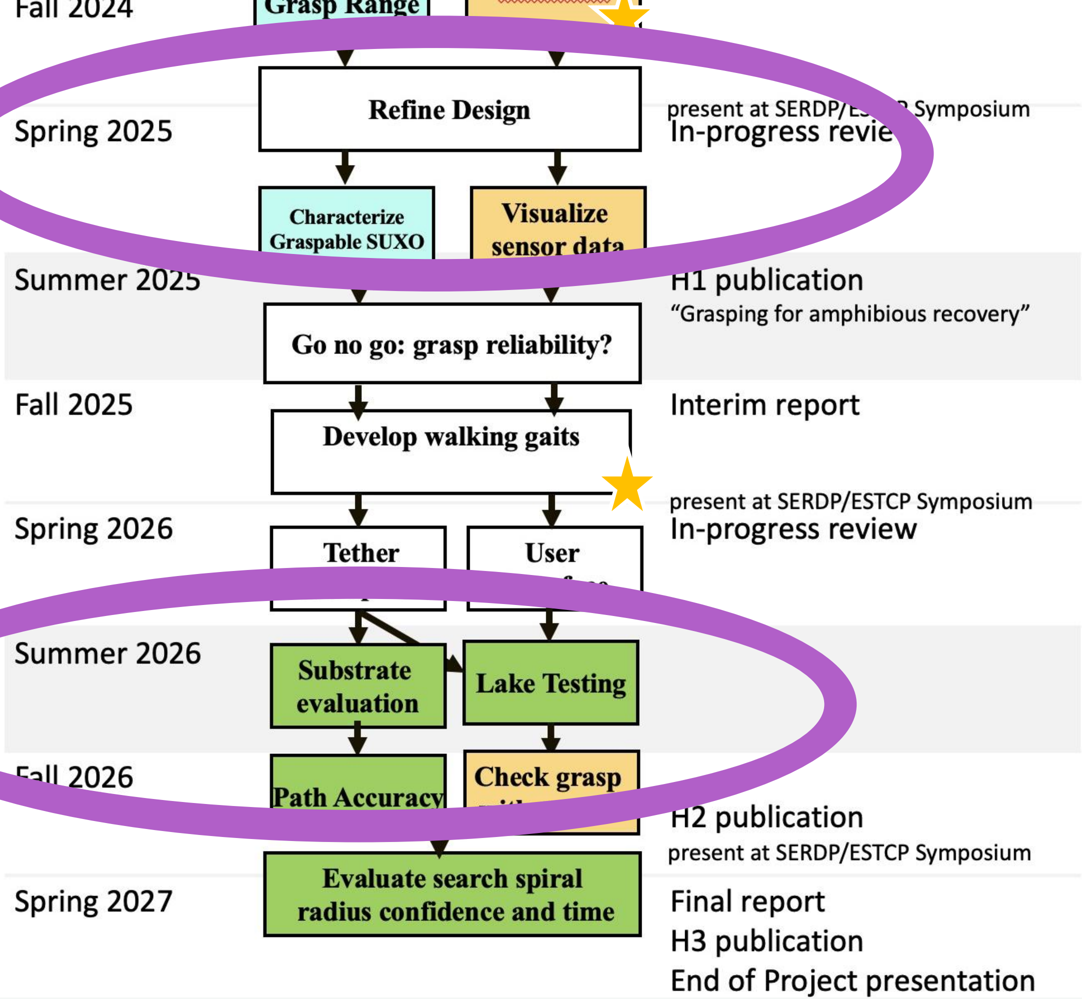
# Next Steps




After more than 30,000 steps, we are ready to make final design updates to get ready for outdoor testing next summer



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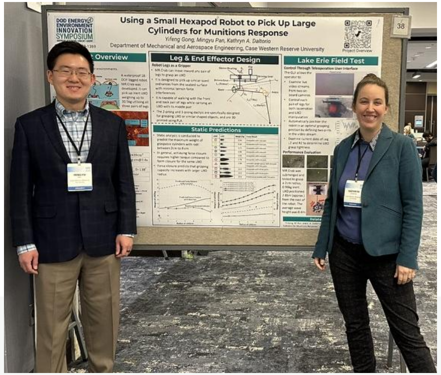
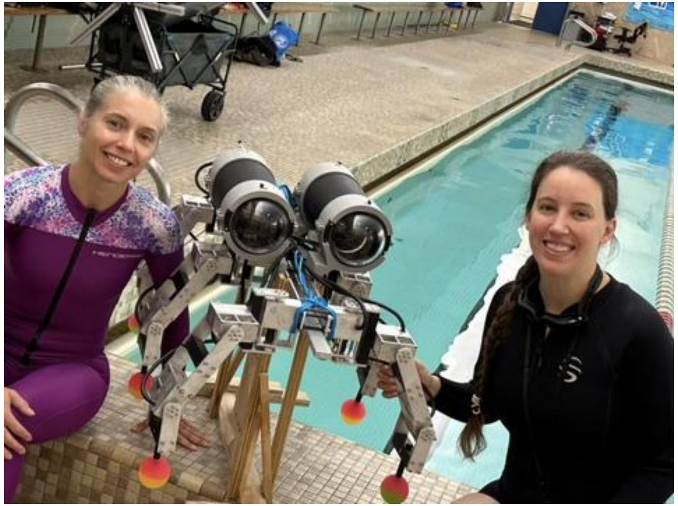
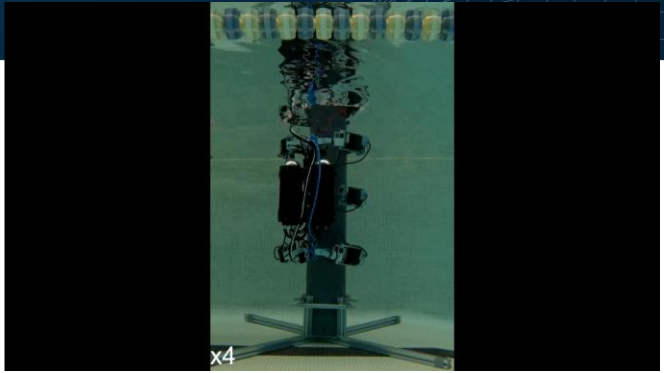
# Technology Transfer

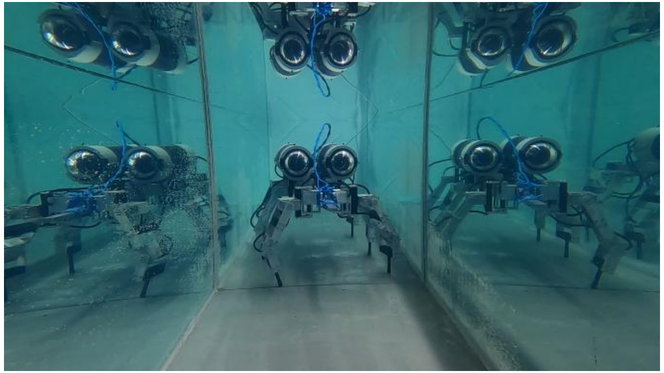
- Demo at SERDP Symposium
- Multiple Patents in Progress
- Publications and presentations for research audience
- Participation in UMST conference in 2024, 2025
- Ohio internships
- Start-up project in parallel, completed NSF Phase I,
- applied for Phase II

# CrabLine Robotics

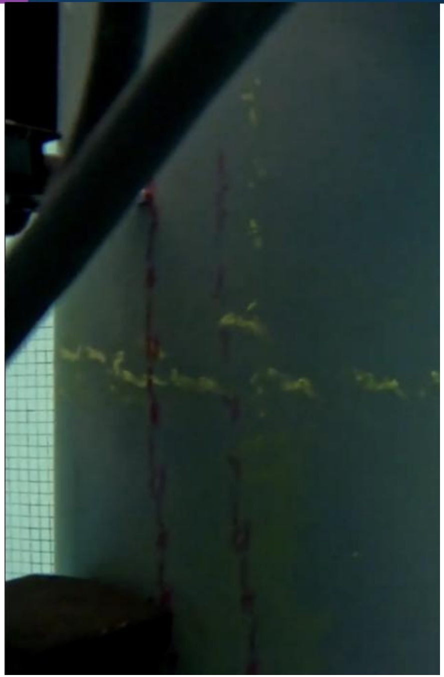




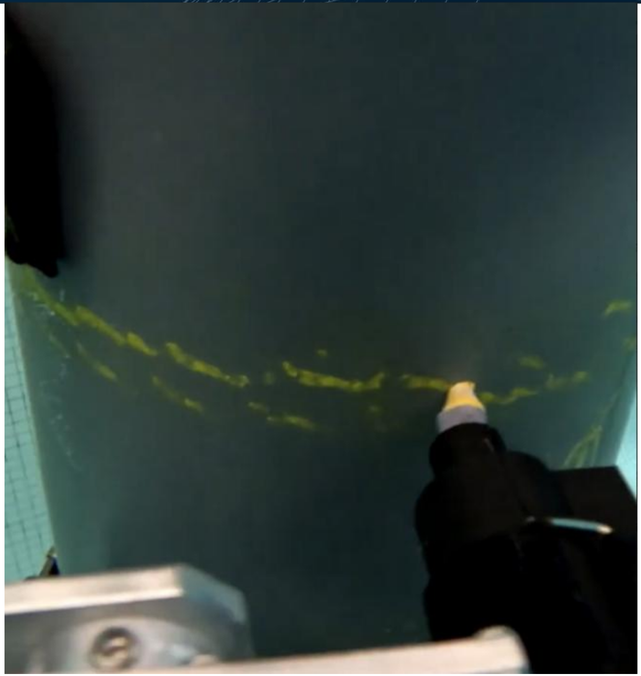
https://www.crablinerobotics.com/

# Tool path results



Vertical lines

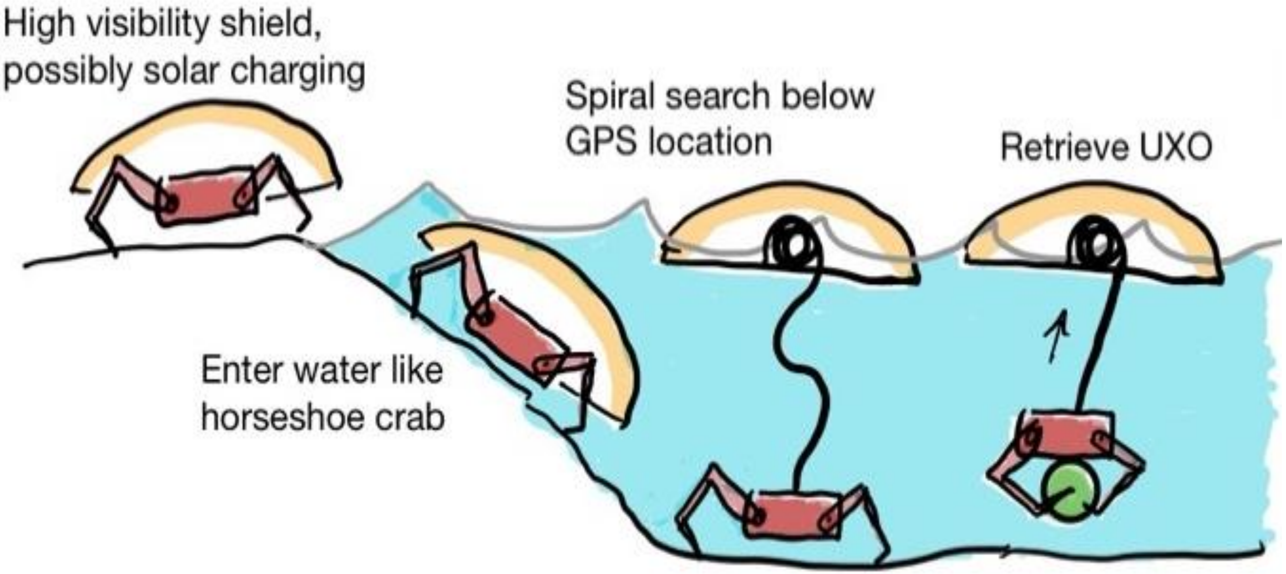
Fine closed shapes

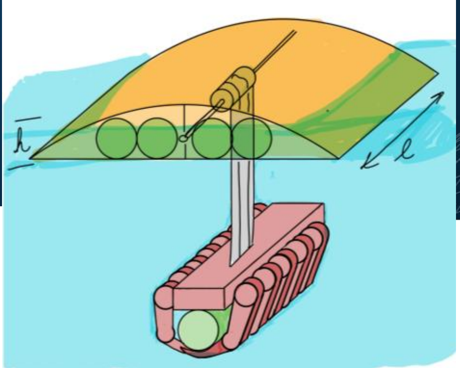


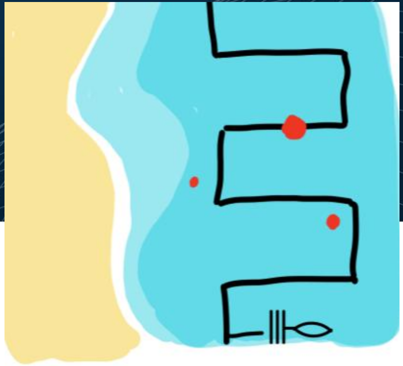
Circumferential closed

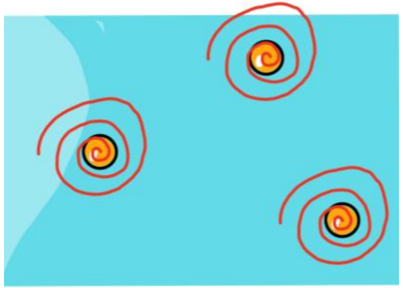
# Operational Concepts

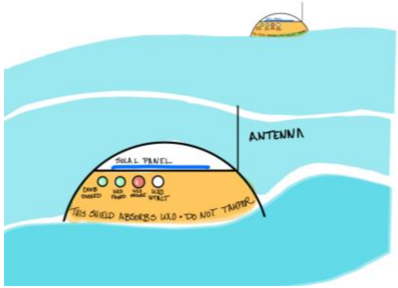
Safe, autonomous deployment









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# Issues

- Team turn over -> PhD student graduated, new team members started
- Actuators need gearbox replacement after over 30,000 steps -> good time to update design
- Magnetic fields disrupted indoor testing -> best to test outdoors for large areas

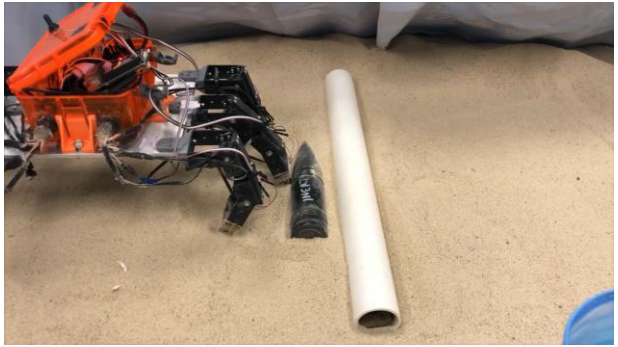
# Related ONR Projects

**Hands to Hexapods, Wearable User Interface Design for Specifying Leg Placement for Legged Robots**

Program Managers
Jean McGovern, Emily Medina

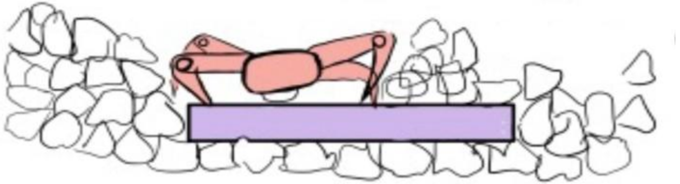

**Benthic Autonomy Gaits to Identify Munitions With Dactyl Sensors**

Program Manager
Tom McKenna



**Expendable Crab-like Robots, Increasing speed with thrust and autonomy with search and clean actions in rocky environments**

Program Manager
Joong Kim

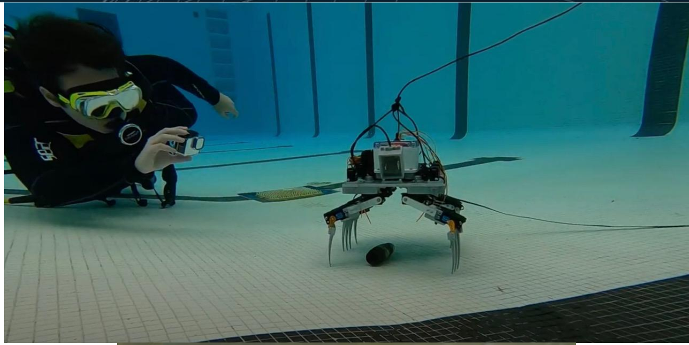


# BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

# MR19-1369: Crab-like Robots

**Performers:** *Kathryn Daltorio at Case Western Reserve University*



**Technology Focus**

- *Developing amphibious walking robots (crab robots) that can traverse benthic surfaces*

**Research Objectives**

- *Determine size of graspable objects, sensors required and walking requirements to be useful for this kind of work.*

**Project Progress and Results**

- *Robot grasps cylindrical objects in air or water at range of sizes (0.2 kg to 10.5kg), Completed first outdoor tests*

**Technology Transition**

- *Patents, ONR presentations, start-up*



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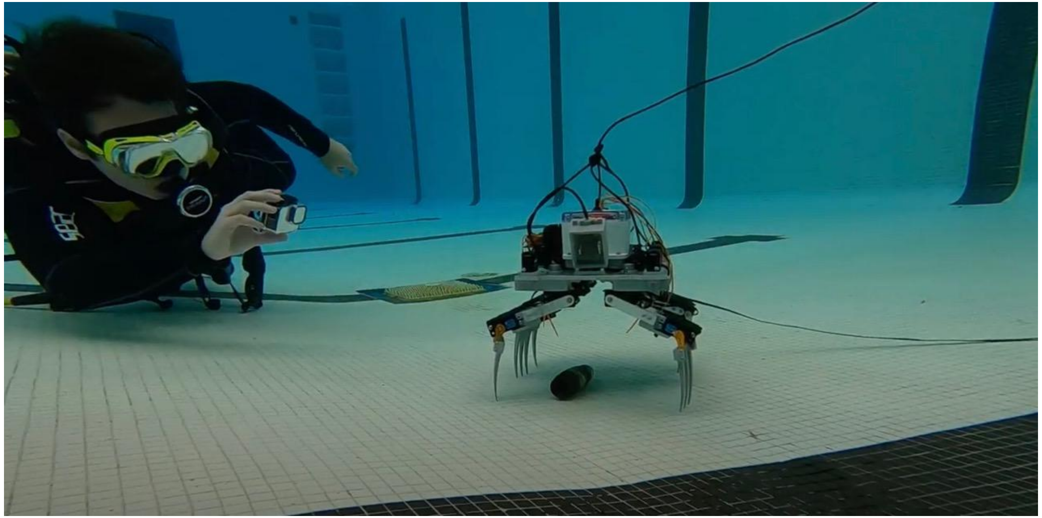
# Plain Language Summary

- UXO are a problem in shallow water areas where it is difficult to combine large scale scanning and remediation.
- We want to de-risk smaller robot designs that can help address this problem by walking on benthic floor (rather than operating in waves on surface).
- Our work will establish the mechanical grasping requirements, minimal sensing requirements, and localization requirements required for fine-searching for UXO in offshore areas.

# Impact to DoD Mission

Our demos in the pool and in the lake are showing the the robot can work, lifting objects at a range of sizes.

We now want to get the robot to a point of being able to be systematic with search. To our knowledge, this form factor of robot is novel for this application, potentially enabling expedited remediation of otherwise unusable environments.



# Action Items

# Publications

- Yifeng Gong, Mingyu Pan, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. Published Journal of Field Robotics.

1. Yifeng Gong, Ge Sun, Aditya Nair, Aditya Bidwai, Raghuram CS, John Grezmak, Guillaume Sartoretti, and **Kathryn A. Daltorio**. Legged Robots for Object Manipulation: A Review. *Frontiers in Mechanical Engineering*. Vol. 9 2023. https://doi.org/10.3389/fmech.2023.1142421
2. Nicole M. Graf, John Grezmak, **Kathryn A. Daltorio*.** Get a grip: inward dactyl motions improve efficiency of sideways-walking gait for an amphibious crab-like robot. *Bioinspiration and Biomimetics*. (Impact factor 2.965). Accepted Aug 2022. https://doi.org/10.1088/1748-3190/ac8710
3. Nicole M. Graf, Alexander M. Behr, **Kathryn A. Daltorio*.** Dactyls and Inward Gripping Stance for Amphibious Crab-like Robots on Sand. March 2021. *Bio-inspiration and Biomimetics*. (Impact factor 2.965). https://doi.org/10.1088/1748-3190/abdd94



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# Literature Cited


- Yifeng Gong, Mingyu Pan, **Kathryn A. Daltorio**. Using a Small Hexapod Robot To Pick Up Large Cylinders for Munitions Response. In revision with Journal of Field Robotics in due August 2024.

1. John Grezmak and **Kathryn Daltorio**. Probing With Each Step: How a Walking Crab-like Robot Classifies Cylinders in Sand with Hall Effect Sensors. IEEE Sensors 20*24* (5), 1579; https://doi.org/10.3390/s24051579
2. Yifeng Gong, Ge Sun, Aditya Nair, Aditya Bidwai, Raghuram CS, John Grezmak, Guillaume Sartoretti, and **Kathryn A. Daltorio**. Legged Robots for Object Manipulation: A Review. *Frontiers in Mechanical Engineering*. Vol. 9 2023. https://doi.org/10.3389/fmech.2023.1142421
3. Nicole M. Graf, John Grezmak, **Kathryn A. Daltorio*.** Get a grip: inward dactyl motions improve efficiency of sideways-walking gait for an amphibious crab-like robot. *Bioinspiration and Biomimetics.* (Impact factor 2.965). Accepted Aug 2022. https://doi.org/10.1088/1748-3190/ac8710
4. Yang Chen, Nicole M. Graf, Glenna Clifton, Jennifer Taylor, **Kathryn Daltorio***. Optimal Crab Leg Length Ratio in Robots and Animals. *Bioinspiration and Biomimetics.* (Impact factor 2.965). Accepted Aug 2022. https://doi.org/10.1088/1748-3190/ac8f04
5. Yifeng Gong, Alexander M. Behr, Nicole M. Graf, Kaiyi Chen, Xiaoyue Xu, **Kathryn A. Daltorio***. A Walking Claw For Tethered Object Retrieval. Accepted Aug 2022 *ASME Journal of Mechanisms and Robotics*. (Impact factor 2.75). https://doi.org/10.1115/1.4055812
6. Yang Chen, John Grezmak, Nicole M. Graf and **Kathryn Daltorio***. Sideways crab-walking is faster and more efficient than forward walking for a hexapod robot. *Bioinspiration and Biomimetics.* (Impact factor 2.965). April, 2022 https://doi.org/10.1088/1748-3190/ac6847
7. Jianfeng Zhou, Quan Nguyen, Sanjana Kamath, Yaneev Hacohen, Chunchu Zhu, Michael Fu, **Kathryn Daltorio***. Hands to Hexapods: User Interfaces for Specifying Leg Placement for Legged Robots. Accepted March 28, 2022. *Frontiers in Robotics and AI.* (Impact factor 4.33). vol 9. https://doi.org/10.3389/frobt.2022.852270
8. John Grezmak, Nicole M. Graf, Alexander M. Behr, **Kathryn Daltorio***. Terrain Classification Based on Sensed Leg Compliance for Amphibious Crab Robot. *IEEE Sensors*. (Impact factor 3.3) Sept 2021. https://doi.org/10.1109/JSEN.2021.3109864
9. Nicole M. Graf, Alexander M. Behr, **Kathryn A. Daltorio*.** Dactyls and Inward Gripping Stance for Amphibious Crab-like Robots on Sand. March 2021. *Bio-inspiration and Biomimetics*. (Impact factor 2.965). https://doi.org/10.1088/1748-3190/abdd94




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# Additional Slide(s) for High-Quality Photos

# Acronym List

ONR – Office of Naval Research
UXO – unexploded ordinance
SERDP – Strategic Environmental Research Development Program