Final Research Performance Progress Report

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

ONR Award: N00014-18-1-2543

Project Title: Online Summary Mapping for Executing Commanders Intent with UUVs

PI: Dr. Jeffrey W. Kaeli

1. MAJOR OBJECTIVES AND GOALS

The major goals and objectives of this project were to explore and simulate frameworks that allow Unmanned Underwater Vehicles (UUVs) to adaptively execute a "commander's intent" during an unscripted mission scenario. A key attribute of this work is to allow exploration within some definable bounded space or within some definable bounded time such that the autonomous decisions made by the UUV are tractable and trustable by a commanding human authority.

UUV missions must transition from scripted lists of objectives to frameworks that enable them to make decisions autonomously and based on real-time data streams. This desired shift is motivated by platform endurances that have steadily increased from hours to days to weeks, and moreover by the relative lack of communication bandwidth underwater. Such autonomy in decision-making has analogs in the submarine fleet where officers are tasked with executing their commander's intent in the absence of consistent information flow up and down the chain of command. Defining high-level objectives rather than step-by-step instructions gives missions a higher probability of success because the autonomous agent is acting on the most up-to-date information about its dynamic environment.

2. ACCOMPLISHMENTS TOWARDS GOALS

Several simulated models were developed that encoded mission intent in different ways. The primary mission scenario was passive monitoring for marine mammals in a specified operations area. Figure 1 illustrates this concept in one dimension. The behavior of the animals was governed by some underlying probability distribution unknown to the UUV. The mission "intent" was to use adaptive UUV behaviors to estimate this underlying probability.

The probability of detection can be written:

$$PoD = \frac{2R}{D}\left(1 + \frac{U}{V}\right)N$$

where R is the detection range, D is the channel width, U is the UUV speed, V is the marine mammal speed, and N is the number of UUVs (assuming uniform spacing). Intuitively, the probability of detection can be increased by increasing the detection range, the vehicle speed, and the number of UUVs used. The probability of detection decreases for large channel widths and higher marine mammal speeds.

The first simulation was for a UUV traveling at a constant speed while transiting back and forth across a channel. Successful detections were determined by the UUV coming within a detection range of the marine mammal. The detection range, UUV speed, marine mammal speed, and channel width are all adjustable parameters. Figure 2 shows an example of the results from a constant-speed simulation with a detection range set to 10% of the channel width. The longer the channel is monitored, the closer the estimated distribution comes to approximating the true distribution.

The second simulation was for a UUV traveling at an adaptive speed as a function of the estimated underlying probability distribution. Between the minimum and maximum vehicle velocities, the speed goal was scaled linearly as a function of the estimated probability distribution. Thus, the vehicle traveled faster where there were less detections and slower where there were more detections. Figure 3 shows an example of the results. Figure 4 plots the relative detection rates between the constant and adaptive speed simulations. Improvements were typically small but definitive for certain parameter values.

Initial work was accomplished to transition this simulation into two dimensions, where both the vehicle speed and the vehicle heading are variables. Building on the one-dimensional simulation, our goal was to optimize some performance metric, but with the added constraint of a limited amount of time (or energy) to monitor an operational area. This "scheduling" component created an elliptical region of accessibility where the current UUV position and the end goal are foci, illustrated in Figure 5. Combining this two-dimensional scheduling component with estimating an underlying probability distribution will be the next step in follow-on work.

3. OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT

One (1) Northeastern University co-op student worked closely with the Principal Investigator on this project.

4. DISSEMINATION OF RESULTS

The results were presented at multiple ONR CENCAP Program Reviews in Panama City, FL in December 2021 and April 2022.

5. HONORS DURING REPORTING PERIOD

Nothing to report.

6. TECHNOLOGY TRANSFER

Nothing to report.

7. PARTICIPANTS

The following individual worked one (1) person-month or more during the project reporting period:

Dr. Jeffrey W. Kaeli, Principal Investigator (Research Engineer)
seven (7) person-months worked
not a National Academy Member

8. STUDENTS

One (1) undergraduate STEM participant

9. PRODUCTS

Nothing to report.

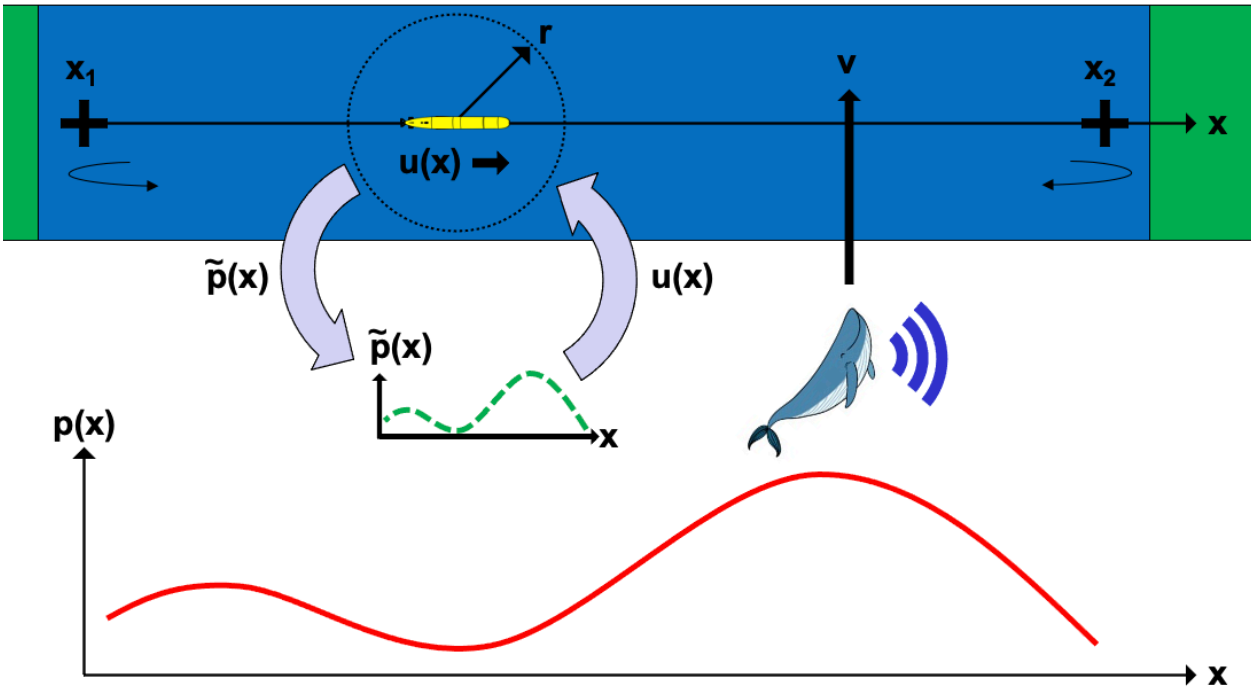

Figure 1. Experimental design of a 1-D simulation. An underlying distribution ***p(x)*** is used to generate targets which are detected if they transit within range ***r*** of the UUV moving at speed ***u***.

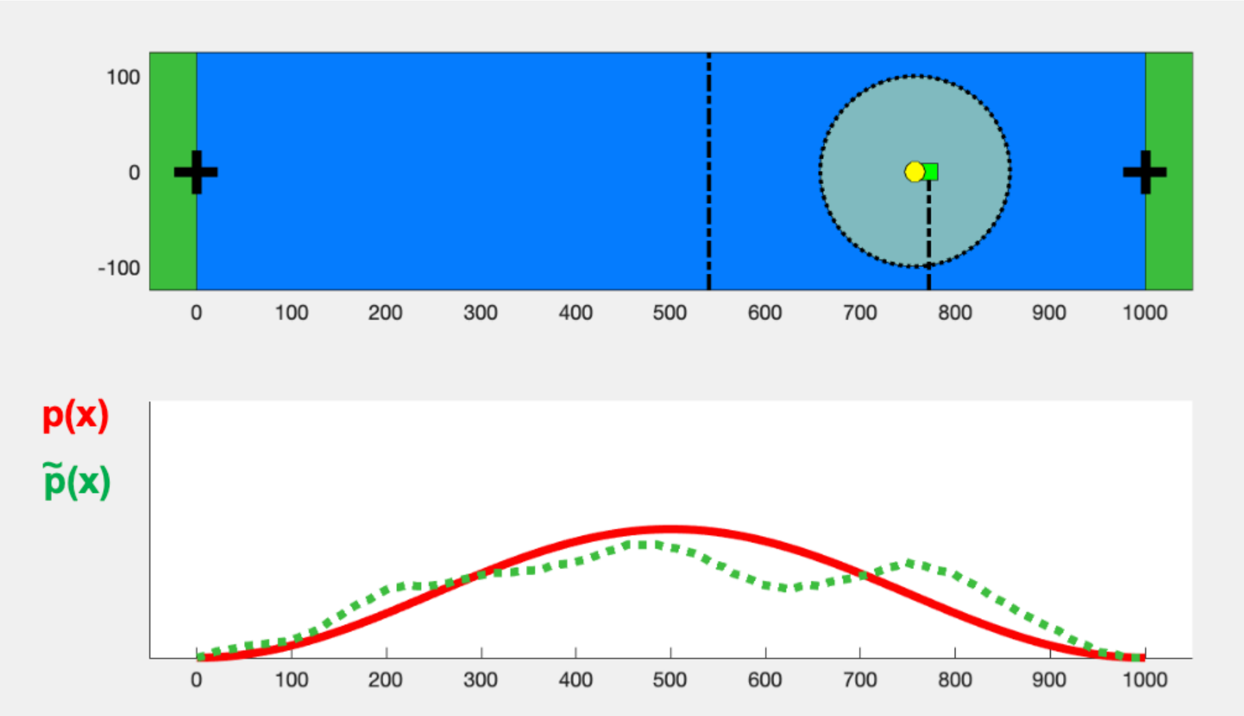

Figure 2. Screen shot from the 1-D simulation where the UUV transits at constant speed ***u***.

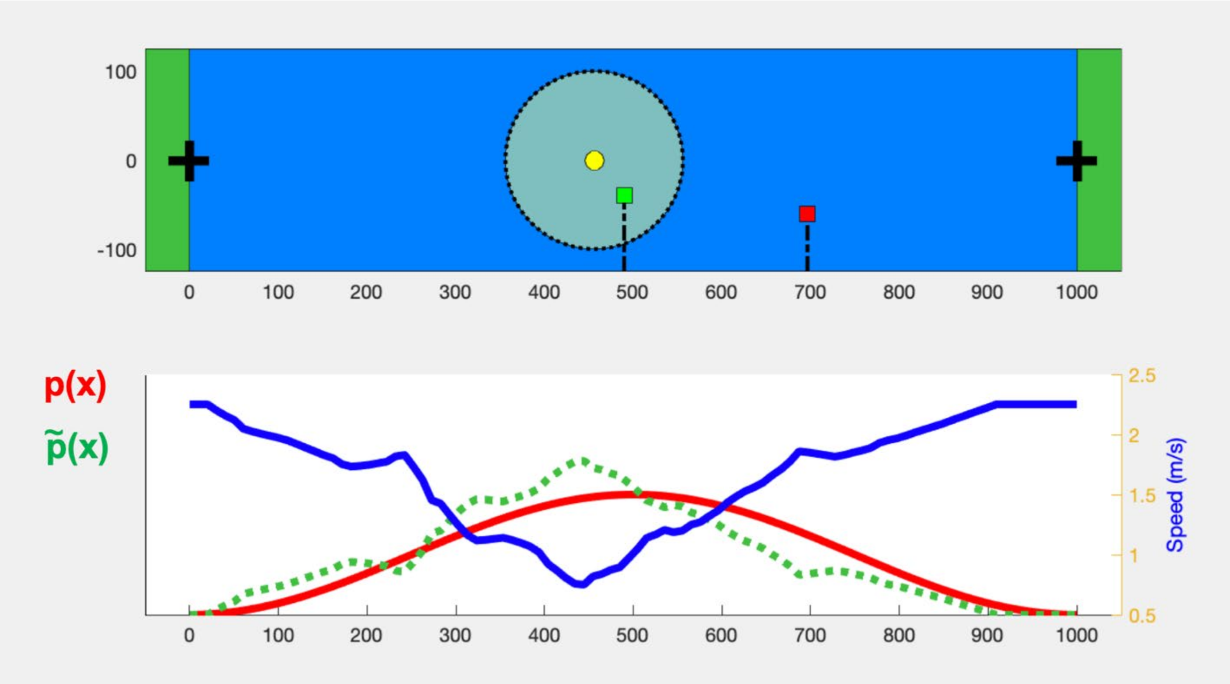

Figure 3. Screen shot from the 1-D simulation where UUC speed is adapted as a function of an estimation of the underlying probability distribution.

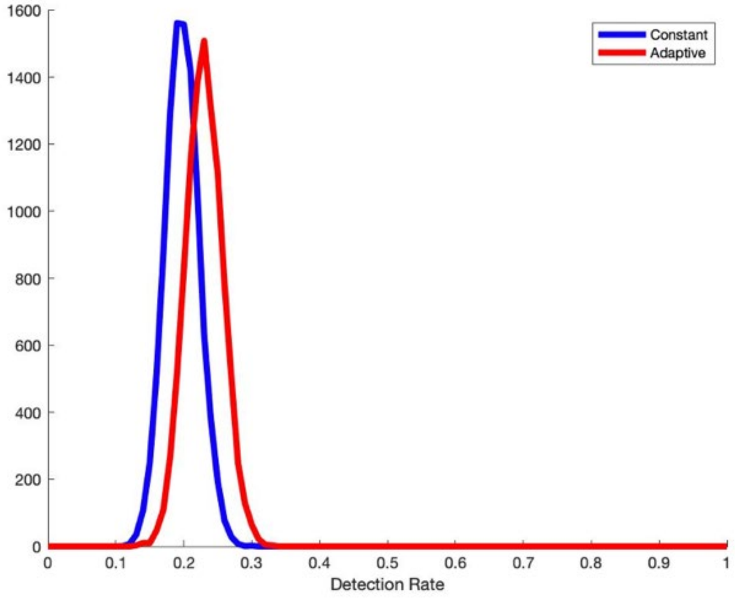

Figure 4. A 3-4% improvement in detection rate was achieved at higher target speeds.

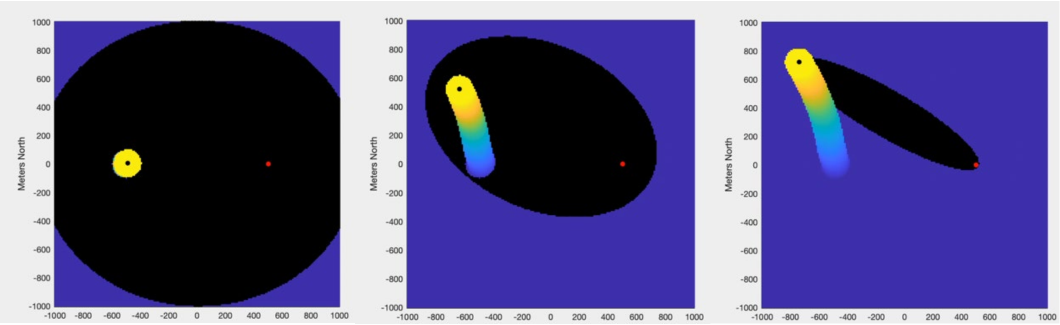

Figure 5. A 2-D simulation showing the elliptical region of accessibility given an end mission time goal. The UUV explores the region by optimizing some underlying parameter until it must transit to reach the goal at a prescribed time.

REPORT DOCUMENTATION PAGE

1. REPORT DATE 20240418	**2. REPORT TYPE** Final Research Performance Progress Report	**3. DATES COVERED** **START DATE** 20200501	**END DATE** 20221231

4. TITLE AND SUBTITLE
Online Summary Mapping for Executing Commanders Intent with UUVs

5a. CONTRACT NUMBER	**5b. GRANT NUMBER** N00014-20-1-2452	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Kaeli, Jeffrey W.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Woods Hole Oceanographic Institution
266 Woods Hole Road
Woods Hole, MA 02543-1535

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research, Ocean Sensing and Systems Applications Division
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We propose to develop and simulate a framework whereby a group of unmanned underwater vehicles (UUVs) can collaboratively and adaptively execute a “commander’s intent” during an unscripted mission scenario. UUV missions must shift from scripted lists of objectives to frameworks that enable them to make decisions autonomously and based on real-time data streams. This shift is motivated by platform endurances that have steadily increased from hours to days to weeks, and moreover by the relative lack of communication bandwidth underwater.

15. SUBJECT TERMS
Unmanned underwater vehicles, autonomy, decision-making, real-time data

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**C. THIS PAGE** U	UU	5

19a. NAME OF RESPONSIBLE PERSON Jeffrey W. Kaeli	**19b. PHONE NUMBER** *(Include area code)* 508-289-2671