Operational collision avoidance strategy for CANON-2012

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I. Introduction

During part of the September 2012 Controlled, Agile, and Novel Observing Network (CANON) experiment, at least six vehicles will be operating in close proximity:

- the environmental sample processor (ESP) drifter,
- the R/V *Western Flyer*,
- the long-range autonomous underwater vehicle (LRAUV) *Tethys*,
- the LRAUV *Daphne*,
- the R/V *Zephyr*, and
- the autonomous underwater vehicle (AUV) *Dorado*.

The drifter and *Western Flyer* operate on the surface, but extend several meters deep. The LRAUVs will usually be submerged, but must surface periodically for communications and navigation. The *Zephyr* and *Dorado* will also operate in the same area for several days. There is significant potential for collision between these vehicles operating at and near the surface – this document proposes an operational strategy to avoid such collisions.

For most of the deployment, the LRAUVs will be doing yo-yos in a large circle around the drifter. Unfortunately, we will have no way to estimate or communicate the position of either LRAUV while it is submerged. The LRAUVs will be driving up and down through the water column, and part of the operations will be at depths shallower than the draft of the *Western Flyer*.

The basic strategy is to command the LRAUVs to surface at known times, and update navigation estimates using global positioning system (GPS). These position fixes will then be sent to shore, and relayed to the *Western Flyer*. The operators aboard the *Western Flyer* will then be responsible for avoiding the LRAUVs. This is the lowest level plan for avoiding collisions.

Two higher level tools are also being considered *in addition to* this operational strategy.

1) Augment the operator display on the *Western Flyer* with a basic dead reckoning (DR) estimate of the submerged position and the next surfacing position for both LRAUVs. This would be done using a mathematical model running on shore.
2) Refine the DR position estimates to account for ocean currents.

These may or may not be tested and available at the time of the September CANON experiment.

II. Concept of Operations

During normal operations, the LRAUVs will circle the drifting ESP buoy at a nominal radius of 2 km. The vehicles will stay on opposite sides of the circle, running in the same direction. They will execute a yo-yo survey between depths of 3 m and 100 m, surfacing every hour, on the hour, for communications and navigation fixes. At a forward speed of $U = 1$ m/s (in the vehicle reference frame), each circle should take roughly 3.7 hours to complete, so the LRAUVs will surface about four times per circle. The center of the survey circle will be updated each time they surface.

The *Western Flyer* will stay at least 1 km away from the survey circle while the LRAUVs are submerged, as illustrated by the shaded gray exclusion zone in Figure 1. The *Western Flyer* may transit across the exclusion zone when the LRAUVs are on the surface and at a safe distance, or immediately after the

TABLE I

survey circle radius	2	km
nominal forward speed	1	m/s
nominal pitch angle	20	degrees
approximate circling period	3.7	hours
approximate surfacings per circle	3.7	-
approximate time at surface	> 6	minutes
minimum yo-yo depth	3	meters
maximum yo-yo depth	20	meters
closest approach distance	1	km
minimum transit distance	2	km
approximate time window for transit	37	minutes

LRAUVs submerge, while their positions are still relatively well-known. This will enable the *Western Flyer* to sample the water near the ESP drifter while avoiding possible collisions with the LRAUVs. Assuming the *Western Flyer* starts its transit over the 2 km exclusion zone directly from the West, while the LRAUVs are at North and South of the survey circle, the ship will have ~ 37 minutes to complete the transit before the closest LRAUV approaches within 1 km. This would require a transit speed > 0.9 m/s$(1.75$ knots$)$.

The *Zephyr* may be nearby, tending to *Dorado*, but must always stay outside the exclusion zone. The *Dorado* will be surveying along segments between the ESP buoy and several Surface Temperature Experimental Longitude Latitude Asset (STELLA) drifters, then executing triangle surveys around the ESP buoy and LRAUVs. Collisions between *Dorado* and the LRAUVs have been deemed improbable and low-risk, but the triangle surveys are currently planned to run outside the exclusion zone anyway.

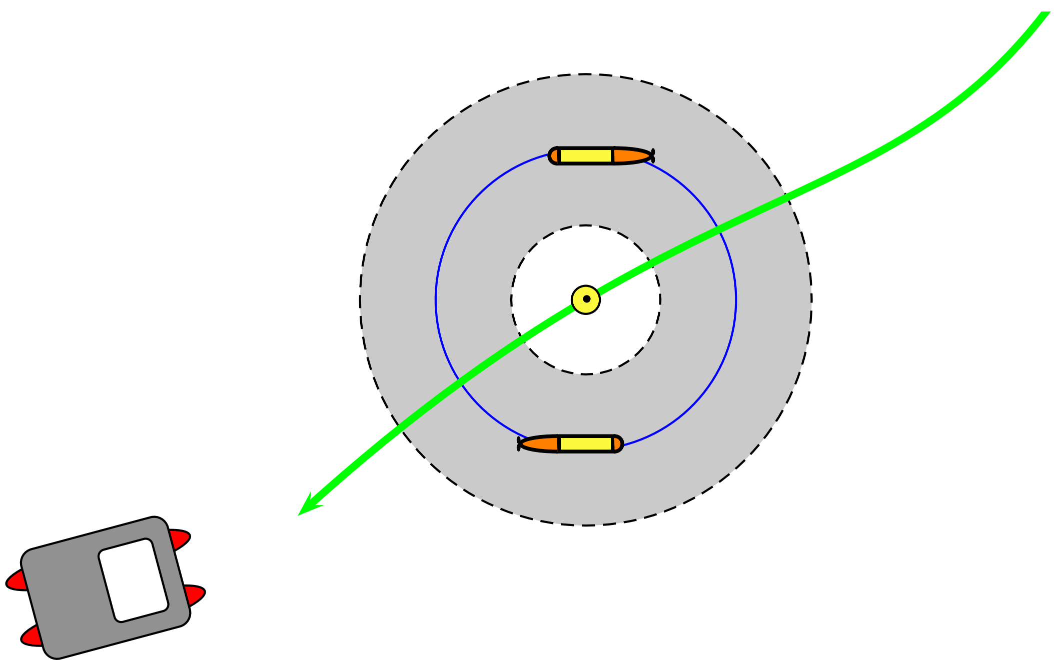

Fig. 1. Concept of operations for collision avoidance during September 2012 CANON experiment. This figure is drawn in the Lagrangian frame of reference, moving with the ESP buoy at the center – this is *not* a fixed geographic frame of reference. The LRAUVs circle the drifting ESP buoy at ~ 2 km radius – the *Western Flyer* stays at least 1 km away from submerged LRAUVs (i.e., outside the shaded gray exclusion area) during normal operations. The LRAUVs surface for communications and navigation every hour, on the hour. The *Western Flyer* can transit between the inside and outside of the exclusion area during and right after LRAUV surfacing, when vehicle position is known best.

APPENDIX

AUV autonomous underwater vehicle
LRAUV long-range autonomous underwater vehicle
ESP environmental sample processor
STELLA Surface Temperature Experimental Longitude Latitude Asset
GPS global positioning system
DR dead reckoning
CTD conductivity, temperature, and depth
CANON Controlled, Agile, and Novel Observing Network