A Real-time Vertical Plane Flight Anomaly Detection System for a Long Range Autonomous Underwater Vehicle

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Abstract— **For autonomous underwater vehicles (AUVs) to be successful in long duration deployments, they must be reliable in the face of subsystem failure and environmental challenges. The ability to detect performance anomalies and unexpected events in real time, especially in the vertical plane, is critical for the vehicle's survivability (the AUV must surface for recovery) and important for planning and vehicle operations. To this end, we have developed a vertical plane flight anomaly detection algorithm capable of comparing observed vehicle performance to references of expected behavior onboard the *Tethys* class long-range AUV in real time. The detection algorithm operates based on statistical characterization of training datasets that represent normal vertical plane performance. These datasets are taken directly from previous long-range AUV field operations. From this analysis we have derived a series of conditional tests that monitor representative components of the vehicle state (e.g., depth rate, pitch angle, and stern plane angle). In the months of January, February and March 2015, we conducted a series of tests in Monterey Bay, CA. The *Daphne* long-range AUV ran the algorithm to detect and flag vertical plane performance anomalies in real time. The AUV was successful in discriminating between expected vertical plane flight performance and anomalies during long-duration deployments lasting more than 11 days.**

Keywords—Autonomous underwater vehicle (AUV), Anomaly detection, Vertical plane flight

I. Introduction

In recent years the use of autonomous underwater vehicles (AUVs) has increased significantly as their value has been demonstrated in industry, science and defense applications. As the capabilities of these vehicles are improving, the missions are becoming longer, riskier, and more complex. For AUVs to be successful in long duration deployments, they must be reliable in the face of subsystem failure and environmental challenges. The ability to detect performance anomalies and unexpected events in real time, especially in the vertical plane, is critical for the vehicle's survivability (the AUV must surface for recovery) and important for planning and vehicle operations. The long-term goal of our project is to give the vehicle the ability to mitigate problems autonomously by developing an onboard fault protection system that responds automatically to performance anomalies by: 1) detecting the anomaly, 2) diagnosing the source, 3) identifying possible responses, and 4) executing best response. Here we focus on the recent development of a model-free vertical plane flight anomaly detection algorithm that we have implemented on board the *Tethys* class long-range AUV and added to its existing fault detection and failure prevention system.

A. Tethys Long-Range AUV

Tethys-class long-range AUVs (LRAUVs) are developed, assembled, and operated at the Monterey Bay Aquarium Institute (MBARI). They are 2.3 m long (standard short-nose configuration) and 0.3 m (12 inches) in diameter at the midsection, with about 110 kg mass. The propeller-driven vehicle can run effectively from 0.5 m/s to 1 m/s and is designed to carry out long duration scientific missions (on the order of weeks) over large distances (hundreds to thousands of kilometers) [1]. Propulsion power consumption is minimized through a careful design of a low-drag body and a high-efficiency propulsion system [2]. The AUV controls its position in the vertical plane by means of traditional elevators (i.e., stern plane control surfaces), a moving internal mass, and buoyancy engine. The vehicle shifts its mass by actuating its battery pack (about 1/3 of the vehicle's total weight) forward and aft. In combination these allow the AUV to adjust ballast and trim at sea and to fly at zero angle of attack with no elevator angle at a range of pitch angles, and thus minimize drag [3]. In addition, the AUV is capable of ballasting to neutral buoyancy and drifting in a lower power mode by using its buoyancy engine. The *Tethys* LRAUV thus combines the merits of propeller-driven and buoyancy-driven vehicles.

LRAUVs navigate by dead reckoning with a magnetic compass and Doppler velocity log (DVL), surfacing periodically to get a Global Positioning System (GPS) fix and to communicate with operators on-shore via Iriduim satellite or cellular modem. LRAUVs are used to search for chlorophyll patches and upwelling fronts [4], [5], and to collect contextual data as part of a larger field campaigns. The vehicle's sensor suite includes Neil Brown temperature and conductivity sensors, a Keller depth sensor, a WET Labs ECO-Triplet Puck fluorescence/backscatter sensor, an Aanderaa dissolved oxygen sensor, and an In Situ Ultraviolet Spectrophotometer (ISUS) nitrate sensor.

B. Tethys Fault Detection and Failure Prevention

Onboard *Tethys*-class LRAUVs fault detection and failure prevention operations occur within various components of the main vehicle application (MVA) [6]. Of these the most involved is the Continuous Built in Test (CBIT), which is responsible for

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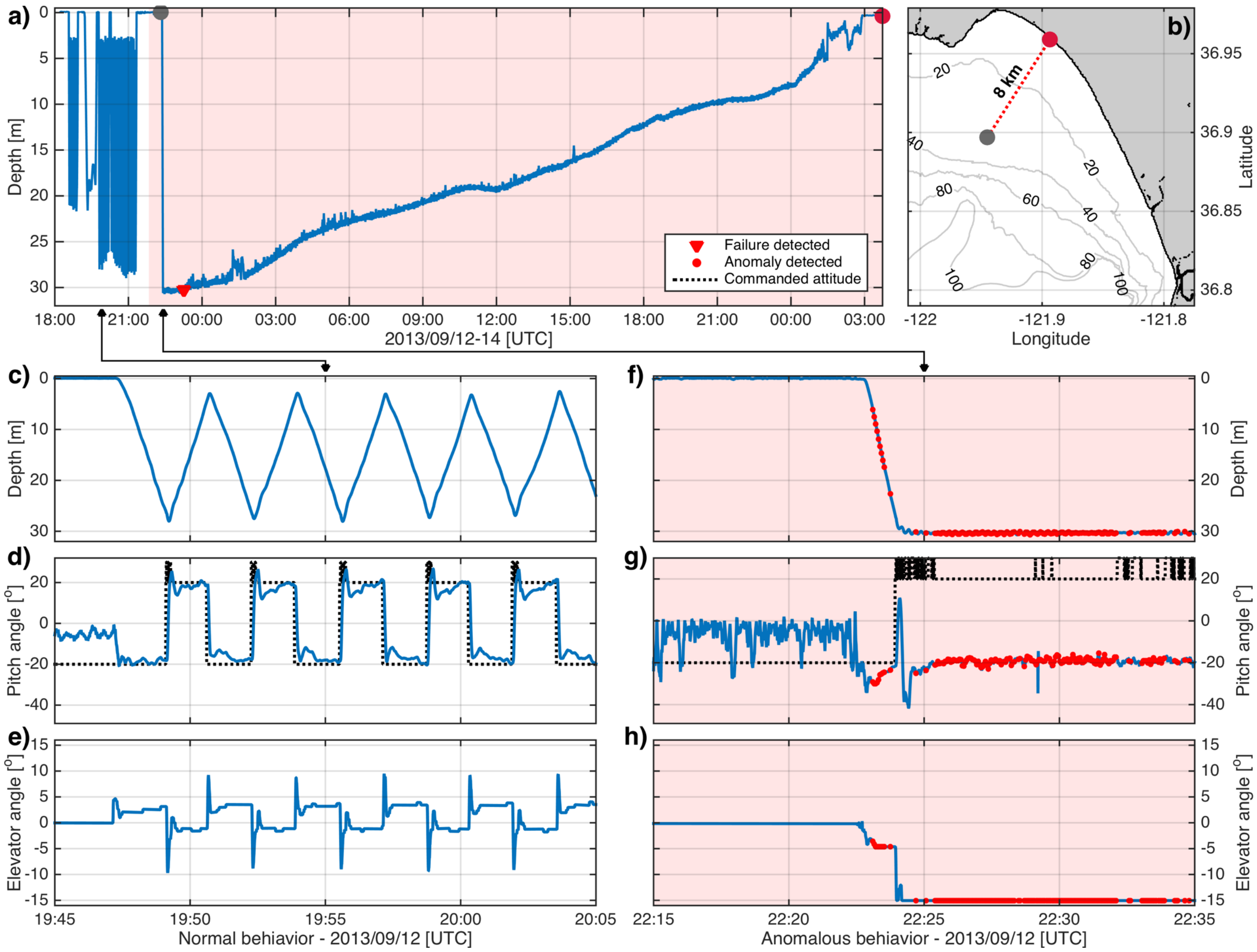

Fig. 1. Depth (panels a, c and f), pitch angle (d and g), and elevator angle (e and h) measurements from the *Tethys* LRAUV bottoming incident that took place on September 12 to September 14, 2013 in Monterey Bay. The grey circle in panels a and b mark the time and location of the AUV's last decent before bottoming. The AUV descended at extream pitch angles and was unable change its attitude (bottom right panels f-h). After bottoming the AUV's fault detection and failure prevention system identified the problem as a vertical control failure at 23:15 UTC (red triangle in panel a). The AUV remained underwater for 27 hours until recovered on the beach 8 km away from its original position (red circle in panels a and b). In post-processing tests the newly developed detector identified the anomaly ~1 minute after the AUV began its final decent (red dots in bottom right panels f-h) . An exmple of the AUV's expected vertical plane performance recorded prior to the bottoming incident is also shown (bottom left panels b-e).

routine health monitoring (e.g., arming watchdog timers, ground fault scans, etc.) and detecting and responding to failed subsystems and software components. For example, if sensor data from a component continues to be erroneous beyond allowable limits, CBIT will respond by reinitializing the component a number of times and eventually, if the problem persists, retiring it. In some cases, the LRAUV can be preconfigured to continue its mission in a degraded state or using a redundant subsystem even though a component has failed, however in most cases, failure of a component requires operator intervention and so the vehicle will terminate its mission and drive to the surface to communicate with shore. If the vehicle is unable to reach the surface, it releases an emergency drop weight.

The developers are continuously improving CBIT based on accumulated operational experience. During the thousands of hours the team has operated LRAUVs at sea, we have encountered numerous anomalies and failures ranging form unanticipated hardware malfunctions to an attack by Great White Shark [7]. While in most cases the existing fault detection and failure prevention system is capable of handling problems before the vehicle is at risk, we have also experienced catastrophic failures that led to temporary loss of the vehicle. Of those incidents, roughly 50% were related to failures in components that support vertical plane flight.

Such a catastrophic failure occurred during the fall 2013 Controlled, Agile, and Novel Observing Network (CANON) field experiment, where the *Tethys* LRAUV bottomed due to a mechanical failure and remained underwater for 27 hours until recovered on the beach 8 km away from its original position (Fig. 1a-b). During the experiment the *Tethys* LRAUV was tasked with collecting contextual environmental data along a survey box near a buoy-mounted Environmental Sample Processor (ESP) in northern Monterey Bay. On September 09, 2013 between 21:20 and 22:20 UTC a hardware failure in the lead screw responsible for shifting the battery mass occurred while the vehicle was on the surface. The damage to the lead screw contributed to a change in the vehicle's trim. On the following dive (22:22 UTC) the vehicle was extremely nose heavy and descended towards the bottom at pitch angles exceeding -30 degrees (Fig. 1f-g). The vehicle attempted to correct its attitude by actuating the elevator control surfaces to their maximum range (-15 degrees; Fig. 1h), however, the AUV was unable to generate sufficient lift in order to maintain an upward pitch angle and eventually hit the bottom.

While on the bottom, the vehicle remained pitched downwards due to the large separation between the vehicle's center of buoyancy (the buoyancy pack is located in the aft) and center of gravity (now shifted forward). The vehicle's fault detection and failure prevention system identified the problem as a vertical control failure at 23:15 UTC (~53 minutes after the initial decent; Figure 1a) and triggered the AUV's safety behaviors, which included inflating the buoyancy package and dropping the emergency drop-weight. However, the vehicle's propulsion and pitch angle were such that these actions failed to bring the vehicle to the surface. The AUV continued its attempt to return to the surface for the following 27 hours until finally it washed up on the beach near Rio Del Mar, California [36.96°N, 121.89°W] and transmitted its position (GPS) via Iridium satellite.

To better handle the unexpected and improve the vehicle's survivability we have recently developed a vertical plane flight anomaly detection algorithm capable of comparing observed vehicle behavior to references of expected behavior onboard *Tethys*-class LRAUVs in real time. The detector has been implemented in the onboard vehicle code and added to the existing fault detection and failure prevention system.

II. Vertical Plane Flight Anomaly Detection

The vertical plane flight anomaly detection algorithm is specifically designed to detect deviations from expected vertical plane flight performance for an AUV in flight mode (on a yo-yo trajectory; see Figure 1c for an example). When in flight mode, the vehicle transits between defined waypoint while vertically profiling the water column at a constant velocity of 1 m/s. In each yo-yo profile (descent-ascent) the vehicle alters its attitude from a -20 degree pitch angle (when going down) to a 20 degree pitch angle (when going up; Figure 1d). The yo-yo profile is terminated either at a predefined depth or by altimeter reading to avoid collision with the ground. The transitions between yo-yo profiles are enforced by issuing a new commanded attitude to the control system, which in turn maintains that attitude by issuing commands to the elevator control surfaces (or mass shifter; Figure 1e).

A. Elevator Angle Offset

When the AUV enters flight mode, it initializes the anomaly detection algorithm by approximating the offset angle of the elevator control surfaces ($\delta_{E_{offset}}$) over a specified training period as follows:

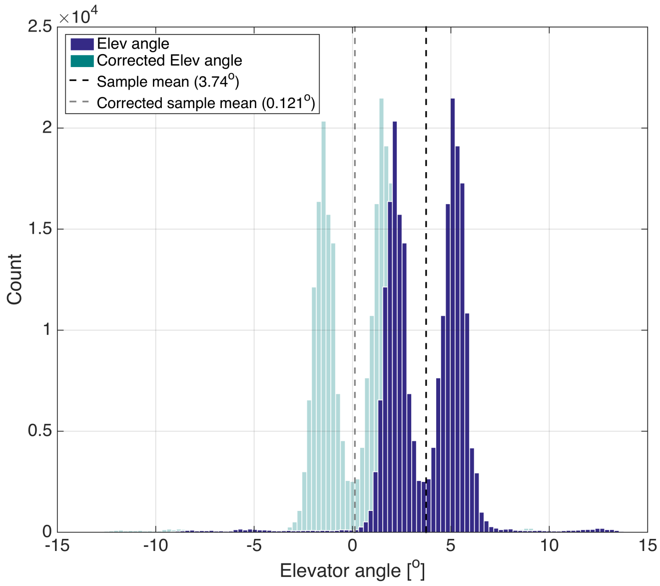

Fig. 2. Histogram of elevator angles recorded by the *Daphne* LRAUV in February 2015 while on a yo-yo trajectory (in flight mode; shown in dark blue). The repediteive descent-ascent cycles of the yo-yo profile yeild a symmetric bimodal distribution. The elevator offset $\delta_{E_{offset}}$ is approximated as given in (1) (dark dashed line). The corrected data (offset removed) is shown in light blue.

$$\delta_{E_{offset}} = \frac{1}{N}\Sigma_{i=1}^{N}\delta_{E\_i} \quad (1)$$

where i is the measurement index, and N is the total number of elevator angle measurements included in the training period. δ_{E_i} is the elevator angle measurements of index i and $\frac{1}{N}\Sigma_{i=1}^{N}\delta_{E\_i}$ is the average angle of those measurements. The ability to approximate the elevator offset angle by calculating a simple mean is rooted in the symmetric bimodal distribution that typically results from a yo-yo trajectory (Fig. 2).

The calculated offset is indicative of the correction that is enforced by the AUV's controller to counter any hydrostatic pitch moment that the AUV might experience as a result of the combined effects of the vehicle's weight and buoyancy. Different offset values may result from changes in the AUV's configuration and variations in the AUV's ballast and trim settings. Throughout the deployment the elevator offset is updated sporadically as defined in (1) every time the sample size requirement is satisfied. The offset value is reported back to shore for operator evaluation as an additional measurement of the vehicle's state that represents the condition of the AUV's hydrostatic balance. Since the offset is expected to remain constant throughout the duration of a deployment (or at least while ballast and trim settings are maintained), it can be used to track anomalous changes in the AUV's ballast and trim that may result from internal hardware failures (e.g., failure of the mass shifter) as well as external interferences (e.g., kelp caught on the vehicle's tail, mud picked up from the sea floor, etc.).

In addition, the offset value is used to adapt δ_{E0}, a fixed user predefined threshold, to new thresholds that are used by the detector and are compatible with the AUV's configuration and ballast and trim settings. The adapted thresholds δ_{E_neg} and δ_{E_pos} are calculated onboard the AUV such that:

$$\delta_{E_{neg}} = \delta_{E_{offset}} - \delta_{E_0} \quad (2)$$

and

$$\delta_{E_{pos}} = \delta_{E_{offset}} + \delta_{E_0} \quad (3)$$

where δ_{E_neg} is a offset-corrected negative threshold used to monitor negative elevator angles, and δ_{E_neg} is a offset-corrected positive threshold used to monitor positive elevator angle.

Throughout the deployment the detector's thresholds are re-adapted using the latest offset value. This greatly improves the detector's ability to avoid false detection during transitions between yo-yo profiles, where the AUV uses a sharp elevator angle to change its attitude from negative to positive and vice versa (e.g., signal spikes in Figure 1e).

B. Conditional Tests

The detector operates based on statistical characterization of training datasets that represent normal vertical plane performance of the LRAUV. These datasets are taken directly from previous LRAUV field operations. For reference, the short data segment collected prior to the to the *Tethys* LRAUV bottoming incident on September 09, 2013 (Fig. 1c-e) and the illustrations in Fig. 3a-b provide a good example of "normal" vertical plane performance of the AUV in flight mode.

From this analysis we have derived a set of conditional tests that provide an intuitive representation of the relationship between performance anomalies in the vertical plane and their symptoms. To differentiate between expected performance and anomalies, we monitor a metric of the vehicle's "intention" (i.e., elevator angle measurements, δ_E) versus metrics of the vehicle's "response", or in our case, measurements of the vehicle's performance in the vertical plane (i.e., depth rate and pitch angle, Δz and θ, respectively). The AUV records the state parameters δ_E, Δz and θ continuously and validates the data against the conditional tests in 5 second time bins.

The conditional tests are comprised of predefined thresholds that are based on the characterization of training datasets and that depict the expected "response" given the AUV's "intention" (as shown in Fig. 3).

Suppose an AUV flies on a yo-yo trajectory. If the vehicle attempts to modify its pitch upwards by applying a negative elevator angle δ_E that falls below the threshold value δ_{E_neg} and simultaneously experience's a depth rate value Δz or a pitch angle θ that are below thresholds Δz_{neg} or θ_{neg} (respectively) for a number of consecutive time bins, the AUV determines that it is experiencing a vertical plane flight anomaly (see Fig. 3c). Similarly, if the vehicle attempts to modify its pitch downwards by applying a positive elevator angle δ_E that rises above the threshold δ_{E_pos} and also observes a depth rate value Δz that rises above Δz_{pos} for a number of consecutive time bins, the AUV determines that it is experiencing an anomaly (see Fig. 2d). To avoid false detection due to measurement noise or isolated disturbances, the algorithm only sets the detection flag when the parameters exceed the thresholds for 3 consecutive time bins.

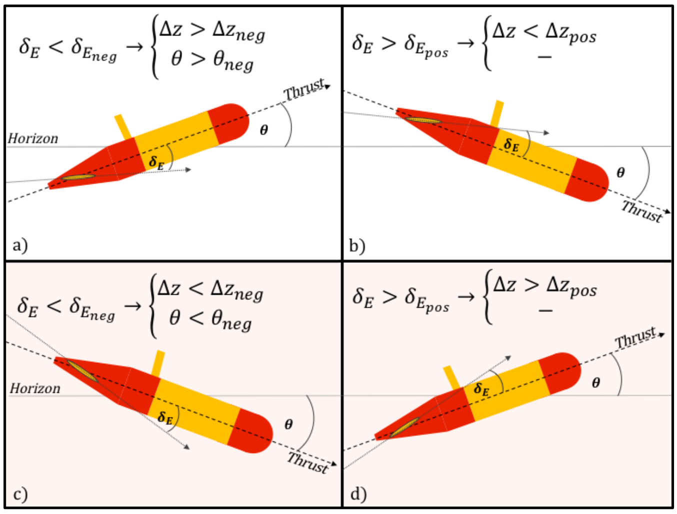

Fig. 3. Illustration of an LRAUV in flight mode. The top panels a, and b provide an example of "normal" vertical plane performance; in both panels the state parameters δ_E, Δz and θ do not violate the conditional tests, or in other words, the "response" mattches the AUV's "intention". Conversely, panels c, and d dipict anomuolos performance where the state parameters δ_E, Δz and θ violate the conditional tests. For example, in (c) the vehicle has set its elevators to pull up, but remaines nose down.

Detections made by the algorithm are reported back to shore for operator evaluation.

In post-processing tests we conducted using historical LRAUV datasets containing known anomalies, the detector was consistently successful in discriminating between expected vertical plane flight performance and anomalies. In most cases, as in the bottoming incident of September 09, 2013 discussed above (see Fig. 1 f-g), adding the detector to the existing fault detection and failure prevention system improved its ability to identify performance anomalies in the vertical plane and could have provided earlier notice of failures in components that support vertical plane flight.

III. Field Performance

We have recently implemented the detector in the onboard vehicle code and added it to the existing fault detection and failure prevention system to detect and flag performance anomalies onboard the vehicle in real time. In the months of January, February and March 2015, we conducted a series of tests on the *Daphne* LRAUV in Monterey Bay, CA. The AUV was performing scientific tasks while the presented vertical plane flight anomaly detection algorithm was running in the background and reporting back to the shore.

From January 31 to February 10, the *Daphne* LRAUV was deployed in the Monterey Bay and tasked with collecting environmental data on a 50 km survey line over the Monterey Canyon between a waypoint located at the canyon head (~5 km from Moss Landing, CA) [36.797°N 121.847°W] and MBARI's M2 buoy [36.690°N 122.410°W]. The AUV flew at a speed of 1 m/s, on a yo-yo trajectory between the surface and 90 m depth. Based on characterization of previous deployments we set the threshold values such that: δ_{E0}=10°, $-\Delta z_{neg} = \Delta z_{pos}$= 0.1m/s, and θ_{neg}= -30°. Once in flight mode, the AUV initialized the

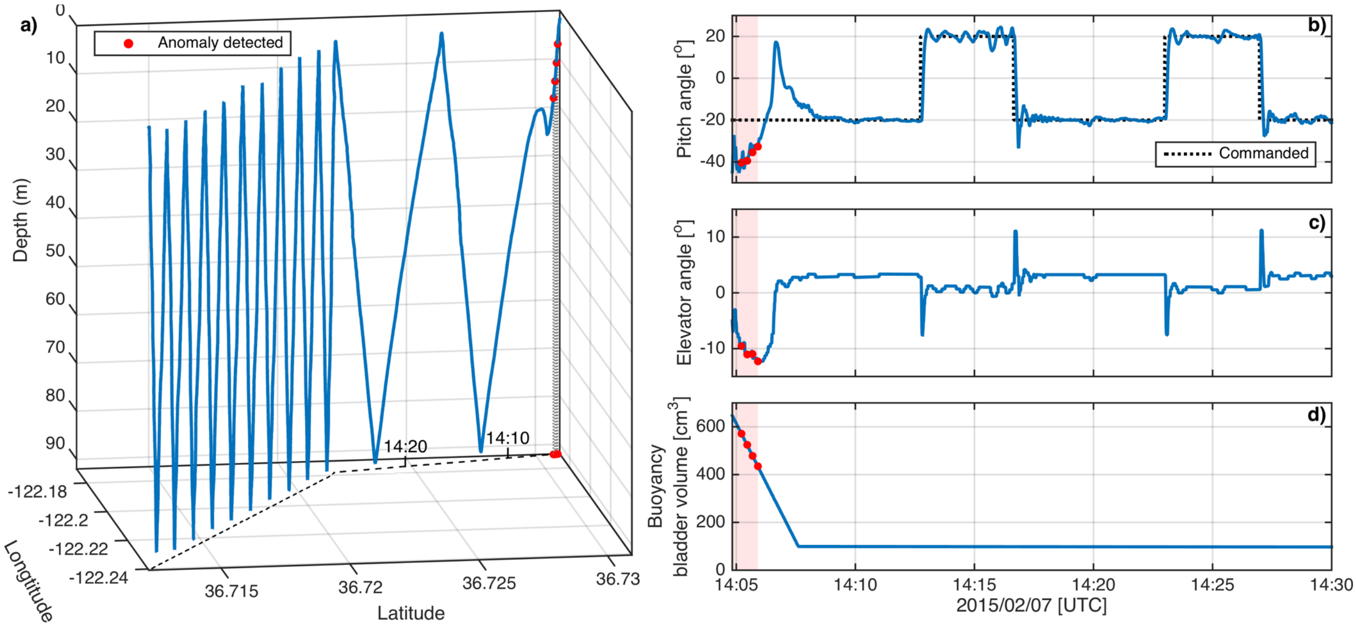

Fig. 4. (a) Depth record from a segment of the AUV's transect during February 2015 test in Monterey Bay. Also shown in close-up are the AUV's measurements of: pitch angle in (b), elevator angle in (c), and buoancy bladder volume in (d). The times and locations where the AUV determined it was experiencing a vertical plane flight anomaly are marked by red dots (over red background). After the buoyancy package was sufficiently emptied (~410 cm^3) the AUV regained vertical control and returned to normal performance.

anomaly detection algorithm autonomously and calculated $\delta_{E_{offset}}$ as in (1). On the following ascend to the surface the AUV reported to shore an offset angle $\delta_{E_{offset}} = 4.3°$, which indicated that the AUV was slightly tail heavy.

Over the course of 7 days (from January 31 to February 06) the AUV maintained a steady offset with low variability, which averaged to $\delta_{E_{offset}} = 4.42 \pm 2{\times}10^{-4}°$ (standard error to the mean at 95% confidence interval).

On February 06 at 16:54 UTC the AUV surfaced to communicate to shore. However, rough sea conditions interfered with the AUV's satellite reception and so at 18:55 UTC the AUV dropped the emergency drop weight in an attempt to increase its buoyancy and improve communications. After communications were restored we commanded the AUV to adjust its ballast and trim settings to accommodate the loss of the weight and continue its surveying mission.

When the AUV descended from the surface δ_E fell below the threshold δ_{E_neg} while simultaneously θ fell below the threshold θ_{neg} for more than 3 consecutive time bins, the AUV determined it was experiencing a vertical plane flight anomaly, and accordingly set the detection flag. A close-up side view of a segment from the AUV's transect that followed the weight drop is shown in Fig. 4.

The hydrostatic imbalance that the AUV experienced in the absence of a weight in its tail was the main contributing factor to the devotion from expected vertical plane performance. As illustrated in Fig. 4d, although the AUV's ballast and trim settings were corrected, the pumping rate of the buoyancy package was not sufficient to adjust the vehicle's buoyancy when transitioning from its surface volume of 740 cm^3 to the reduced diving volume of 100 cm^3 (instead of 560 cm^3 before weight was dropped). As such, the buoyant tail caused the AUV to pitch downwards in angles exceeding -40° without the ability to correct its attitude (via control surfaces). After the buoyancy package was sufficiently emptied (~410 cm^3) the AUV regained vertical control and returned to its normal performance patterns.

Although the vehicle was not at risk, the detector acted according to its design and successfully identified anomalous vertical plane performance that resulted from a change in the AUV's state. The detection of these anomalies informed an engineering decision to increase the pumping rate of the buoyancy system when the AUV is at the surface in future LRAUV deployments.

In an additional test we conducted from March 10 to March 13, the *Daphne* LRAUV was deployed in the Monterey Bay to collect environmental data and perform engineering trials. Like in previous deployments the AUV flew at a speed of 1 m/s, on a yo-yo trajectory between the surface and 90 m depth (Fig. 5a). Once again, the AUV initialized the anomaly detection algorithm and calculated $\delta_{E_{offset}} = 2.9°$ (Fig. 5b). However, in contrast to previous deployments where $\delta_{E_{offset}}$ remained steady, over the duration of the AUV's mission we noticed an upward trend in $\delta_{E_{offset}}$ at a relatively constant rate of 0.06° per hour (from 2.9° to 4.5° in a period of 24 hours). The increase in $\delta_{E_{offset}}$ was indicative of a growing separation between the AUV's centers of weight and buoyancy.

Based on this data, after the *Daphne* LRAUV was recovered we conducted a series of tests and uncovered mechanical degradation of the mass shifting actuating system. The drift in $\delta_{E_{offset}}$ resulted from incremental shifts in the position of the

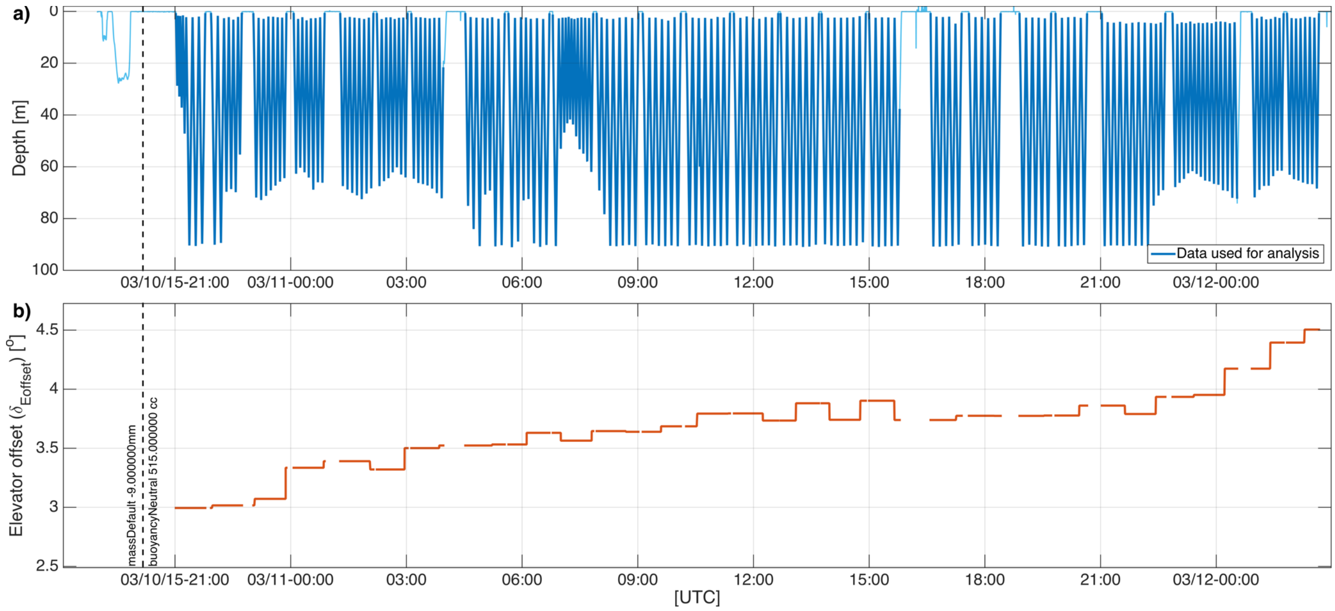

Fig. 5. (a) Depth record from the *Daphne* LRAUV test in Monterey Bay in March 2015. Only data collected during flight mode (shown dark blue) is considered for analysis. (b) Time series of the calculated offset angle of the stern plane control surface (orange). Once ballast and trim configuration is set (black dashed vertical line), the offset is expected to persist; in this dataset an upward trend can clearly be seen.

battery mass (backwards) that were not accounted for by the system (the system is powered off when inactive to conserve energy). Although the mass shifting actuating system is designed to prevent the mass from back-driving when it is powered off, accumulated mechanical wear of the actuator's lead screw and gear box, combined with a recently upgraded heavier battery pack, allowed the mass to back-drive.

IV. Conclusion and Further Work

We have developed a method for an AUV to autonomously detect and flag vertical plane performance anomalies in real time. The method is specifically designed to detect deviations from expected vertical plane flight performance for an AUV in flight mode, and relies on a series of conditional tests that are easy to implement and computationally cheap. During field tests conducted in the months of January, February and March 2015, the *Daphne* LRAUV ran the vertical plane flight anomaly detection algorithm, and was successful in discriminating between expected vertical plane flight performance and anomalies that resulted from changes in the AUV's physical state. The AUV produced high-quality data products that were consistent throughout long-duration deployments, informed engineering decisions, and led to the early discovery of mechanical degradation in a vital subsystem that would have otherwise been difficult to find. We are working on further development of model-based and data-driven anomaly detection methods and failure mitigation architectures.

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