1. Project Information

Proposal reference number[1]	21/1001599
Project Acronym (ID)[2]	FRONTIERS
Title of the project[3]	Fault detection, isolation and Recovery fOr uNderwaTer glIdERS
Host Research Infrastructure[4]	SOCIB, ES
Starting date - End date[5]	02/07/2021 - 19/07/2021
Name of Principal Investigator[6] **Home Laboratory** **Address** **E-mail address** **Telephone**	Enrico Anderlini, Marine Research Group, Department of Mechanical Engineering, University College London Roberts Engineering Building, London, WC1E 7JE, UK E.Anderlini@ucl.ac.uk +44 7450272675

2. Project objectives[7] (250 words max.)

The updated aim of the project is to validate methods for the smart anomaly detection and fault diagnostics for underwater gliders. The project outcomes will help increase the reliability of these platforms and help over-the-horizon pilots to monitor the conditions of these systems.
The project aim will be achieved through the following updated objectives:
O1 Introduction of data-driven methods for the anomaly detection and fault diagnostics of MAS (as part of project ALADDIN funded by the Assuring Autonomy International Programme, a partnership of Lloyds' Register Foundation and the University of York);
O2 Validation of the tools with the actual field test of an underwater glider for the following case studies:

- suddenly wing loss;

[1] Reference number assigned to the proposal by the TA-Office.

[2] User-project identifier used in the proposal.

[3] Title of the approved proposal. The length cannot exceed 255 characters

[4] Name of the installation/infrastructure accessed with this project. If more than one installations/infrastructures are used by the same project, please list them in the box.

[5] Specify starting and end date of the project (including eventual preparatory phase before the access).

[6] Fill in with the full contact of the Principal Investigator (user group leader).

[7] Write the short-term, medium and long-term objectives of the project. Use no more than 250 words.

- incorrect ballasting and trimming.

3. Main achievements and difficulties encountered (250 words max.)[8]

The project has successfully validated the introduced anomaly detection and fault diagnostics methods. The glider has been deployed, recovered and redeployed multiple times to simulate the loss of either wing, incorrect ballasting (through the addition or removal of weight pills) and incorrect trimming (through the addition or removal of the weight pills along the length of the vehicle as well as different settings of the internal battery position). Furthermore, the glider had additional intrinsic anomalies: slow leak in the thermal valve of the variable buoyancy device, a small offset in the CTD sensor readings and high energy consumption levels.

The simulated faults were correctly detected and identified, whilst the intrinsic smaller faults will provide additional training data to expand the system in the future. Validation of the diagnostics of these anomalies could be not completed as the training data available before the test from many other glider deployments did not present the same failures.

The main difficulties encountered concerned the global pandemic, which prevented the UCL team to travel to Mallorca due to the constantly changing travel rules. However, this problem was solved thanks to the professionalism of the SOCIB team, their user-friendly data exchange portal and regular email exchanges or calls. Bad weather before the project start meant that the project actually began a few days later than expected.

4. Dissemination of the results[9]

The project has been advertised on LinkedIn with two posts with 1,749 total views on 23/07/2021 and to the AAIP.
Further planned dissemination activities involve:

- Open-access publication of the collected data on the SOCIB data portal https://www.socib.eu/?seccion=observingFacilities&facility=glider, https://thredds.socib.es/thredds/dodsC/auv/glider/sdeep01-scb_sldeep001/L0/2021/dep0036_sdeep01_scb-sldeep001_L0_2021-07-02_data_dt.nc.html,

[8] Describe briefly the main achievements obtained and possible impacts, as well as possible difficulties encountered during the execution of the project. Use no more than 250 words.

[9] Describe any plan you have to disseminate and publish the results resulting from work carried out under the Transnational Access activity in JERICO -S3: scientific articles, books - or part of them -, patents, as well as reports and communication to scientific conferences, meetings and workshops. Highlight peer-reviewed publications. **Note that any publications resulting from work carried out under the JERICO -S3 TA activity must acknowledge the support of the European Commission – H2020 Framework Programme, JERICO -S3 under grant agreement No. 871153.**

- Publication of one collaborative journal article in the Journal of Field Robotics or IEEE Journal of Oceanic Engineering,
- Use of the results in up to three additional journal article publications as part of project ALADDAIN, https://www.york.ac.uk/assuring-autonomy/projects/unmanned-marine-systems-safety/,
- Inclusion of the project outcomes within the AAIP's Body of Knowledge entries 2.2.4.1 – Verification of sensing requirements, 2.2.4.2 – Verification of understanding requirements, https://www.york.ac.uk/assuring-autonomy/body-of-knowledge/,
- Advertisement on SOCIB's twitter account, https://twitter.com/socib_icts/status/1417784285264760833,
- Further advertisement on the principal investigator's LinkedIn account once the results are postprocessed.

5. Technical and Scientific preliminary Outcomes (2 pages max.)[10]

Figure 1. Summary of the glider deployment for the FRONTIERS project.

The project mission is summarised in Figure 1, which shows the GPS coordinates of the glider during the deployment, the number of days spent at sea, the number of profiles undertaken, the distance covered, the maximum depth reached and the average surge speed.

[10] Describe in detail results and main findings of your experiment at the present stage.

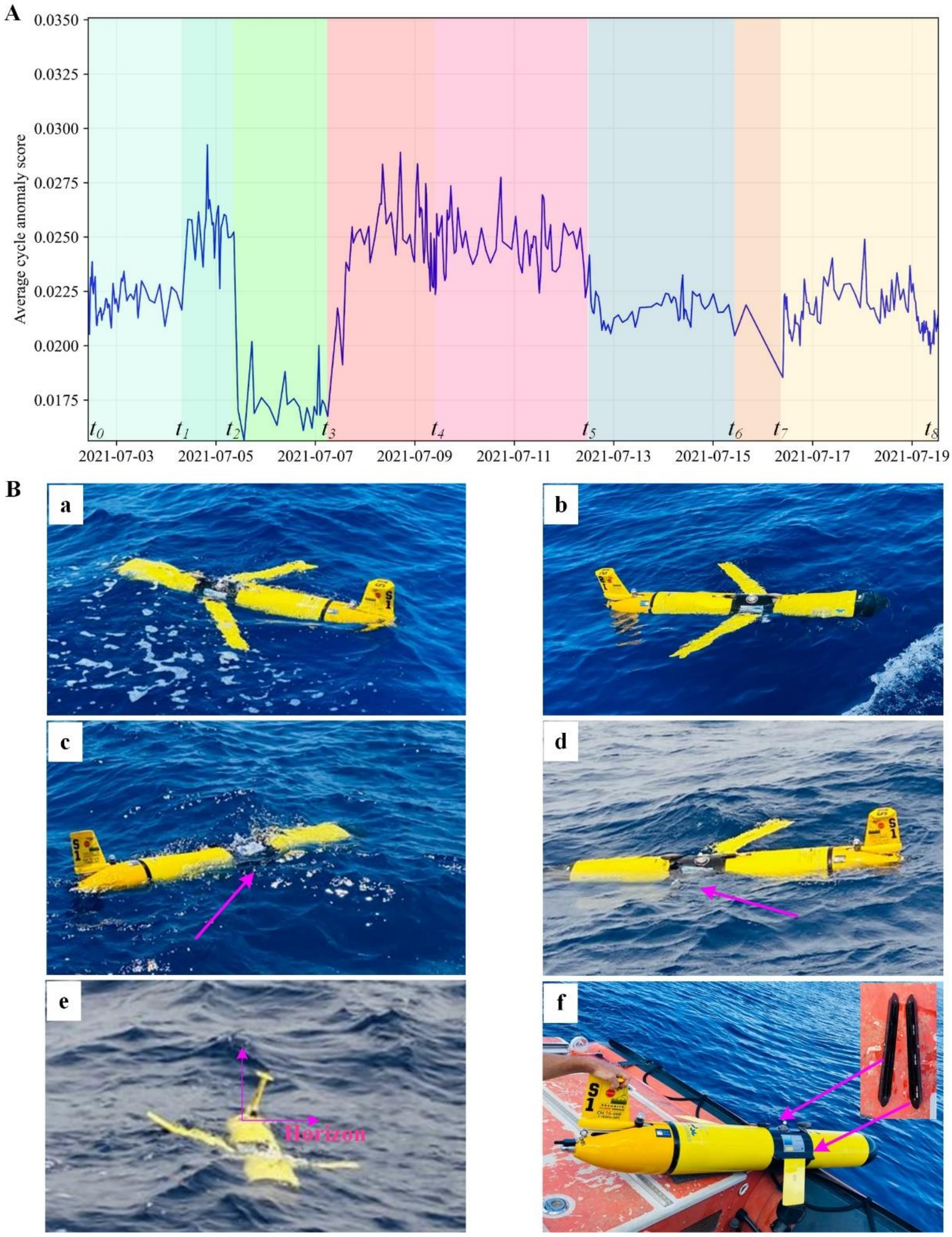

Figure 2. (A) anomaly scores over the test. (B) a: the glider at the beginning of the test, b: the glider before recovery at the end of the test, c: the glider with its starboard wing removed, d: the glider with its port wing removed, e: incorrectly ballasted glider, f: the balancing weight setting for the simulated trimming fault.

As shown in Figure 2A, the test started at t_0 (Figure 2B-a) and ended at t_8 (Figure 2B-b). The anomaly detection system based upon Bidirectional Generative Adversarial Networks (BiGAN) has successfully output anomaly scores over the test. The pitch angles for t_0-t_1, t_1-t_2, and t_2-t_3 were set as 30°, 18°, and 26°, respectively. The glider's starboard wing was removed at t_3 (see Figure 2B-c). At

t_4, the starboard wing was restored while the port wing was removed (see Figure 2B-d). At t_5, the port wing was restored while the balancing weight setting in the wing rails was adjusted from left-2 & right-5 to left-5 & right-2 (each pill is 15.5 g) (see the vehicle status in Figure 2B-e). At t_6, the wrong battery position was applied. At t_7, the battery position servo mode was set, and the balancing weight setting was changed to left-0 & right-3 (2 extra pills removed along the length of the vehicle in each wing rail, see Figure 2B-f). The glider was recovered at t_8.

A data-driven anomaly detection system based on a BiGAN architecture with added hints was trained with data from deployments from the British Oceanographic Data Centre and the SOCIB portal. The system uses the decimated semi-real-time data signals from each dive of the glider sent ashore to calculate an anomaly score that can be used to determine whether anomalies are present on board the vehicle. Once trained, the system was validated using the data stream from the JERICO deployment. As can be seen in Figure 2A, as the 30° and 18° pitch settings were not included in the training dataset, high anomaly scores have been incorrectly returned at the start of the deployment for normal behaviour. However, the system was able to clearly detect the loss of wing, as removing the starboard and port wings resulted in high anomaly scores of similar magnitudes. Additionally, relatively high anomaly scores can be observed from t_5 to t_8 for the incorrect ballasting and trimming. In conclusion, the simulated faults were correctly detected, validating the proposed anomaly detection solution, although further work is needed to address the false positive at the start of the deployment. This will be tackled through data augmentation.

Additionally, the BiGAN architecture is used as the first layers of a classification-based, data-driven fault diagnostics system currently being actively developed. Correctly labelling the individual faults is particularly challenging due to the sever class imbalance towards healthy baseline glider behaviour. The data collected during project JERICO will be critical to develop and demonstrate this system. Work is currently being undertaken to validate this fault diagnostics method.

___London, 23/07/2021___

Enrico Anderlini

Location and date | Signature of principal investigator