Final Report to Supergen ORE Hub

Project Title:

Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection

Keywords:

Biomimetic Robotics; Autonomous Underwater Vehicles, Offshore Wind Farm

Duration of project:

September 2019 – December 2020

Date report submitted for publication:

January 29, 2021

Academic Project Team:

Dr. Mark A. Post[1], Dr. Qing Xiao[2], Dr. Wael Gorma[1], Mr. Marvin Wright[2], Mr. Yang Luo[2]

[1] University of York, Heslington, York, YO10 5DD

[2] University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ

Contact details:

mark.post@york.ac.uk

qing.xiao@strath.ac.uk

wael.gorma@york.ac.uk

Industrial Project Partners:

Mr. Lee Richards, Supergen ORE Hub

Mr. Andrew Durrant, PicSea Ltd

Mr. Bodhi Sarkar, EC-OG Ltd

Mr. Alex Louden, ORE Catapult

2020

Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection
Final Report to Supergen ORE Hub

By Dr. Mark A. Post Dr. Qing Xiao & Dr. Wael Gorma

University of York, Heslington, York, YO10 5DD

University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ

1. Introduction

This report is the final report of the "Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection" project funded by the Supergen ORE hub project through the Flexible Funds program. Known as RoboFish, shown in Fig.1, this project is concerned with the development of an Autonomous Underwater Vehicle (AUV) prototype. The project started in September 2019 with a clear plan, timetable and objectives. The aim of the project is to build a robotic fish that mimics the motion of a fish to navigate its motion control around complex underwater structures and closely inspect underwater assets. The objectives of the project were achieved through the following four Work Packages:

- WP1 - Project kick off and integration into existing work
- WP2 - Construction and initial testing of AUV components
- WP3 - Compact RoboFish design with navigation and inspection capabilities
- WP4 - Summary and exploration of future research activities

WP1 and WP2 roceeded on schedule in the pre-COVID19 stage, and the modelling and design of the first RoboFish prototype was completed in summer 2020. Hardware construction using 3D printing technologies, electronic board fabrication and software development activities of WP3 were done during the COVID19 time with an inevitable delay due to closure of the Universities.

Fig. 1: First assembled RoboFish protype

With a three-month no-cost project extension, the first RoboFish prototype was accomplished in December 2020 and had minimal field trials. WP3 and WP4 are largely completed and the foundation of visual inspection, acoustic communication and navigation capabilities are well laid, but field tests will have to wait until the public facilities (York East Campus and ORE Catapult in Blythe) are fully accessible. To allow time and resources for testing, the consortium has applied for further EPSRC Impact Accelerator Account funding, in addition to the White Rose Collaboration Fund that has been secured to enable field testing at the ORE Catapult, two journal papers that are approaching readiness for submission, and a series of interdisciplinary outreach and collaboration meetings. This will achieve continuing impact though continued collaboration with our industrial partners PicSea Ltd and EC-OC Ltd and an impact case study is being pursued in collaboration with the Supergen ORE Hub.

2. Project Management

Despite lockdowns, restrictions on travel and closure of labs, work on RoboFish continued with relatively manageable disruption. Preliminary mechanical design of model was started at Strathclyde University in the first 3 months before the knockdown started in the late of March 2020. During the period of lockdown, general organisation of the project has been facilitated greatly by the use of Skype messaging and tele-conferencing for general meetings and day-to-day communication, and the use of G Suite cloud storage and document editing for access to project resources. Courier services have been used to move RoboFish prototype components between partners' homes for testing, and testing activities were mainly done in bathtubs and kitchens. Significant changes to the project include the cancellation of face-to-face meetings and outreach activities, though as all planned meetings were held virtually with minimal impact on progress. Significant impact occurred because of COVID-19. A set of contingency plans were put in place to work under lockdowns. In June 2020, a new timetable, shown in Fig. 3, was created based on the present circumstance and the approved project extension. Field testing of RoboFish is essential to success, but access to the York East Campus lake was limited. Efforts were made and one functionality/watertightness trial at the lake took place. The planned three-day field testing for RoboFish at the ORE Catapult testing site in Blyth will occur later in 2021 as it is funded by the White Rose universities, and use of the funding has been delayed to facilitate testing and outreach after the pandemic has hopefully eased. An EPSRC IAA funding application has been submitted to support more work on RoboFish docking and dissemination of results, and a large-scale proposal to support the use of RoboFish for inspection of water infrastructure is now underway with the university of Leeds. Also, funding was obtained over the summer to support an internship for a talented student who developed underwater visual inspection and SLAM capability for RoboFish based on a single camera, and two MEng students are now working to improve the buoyancy control and actuator design for RoboFish in their final year projects..

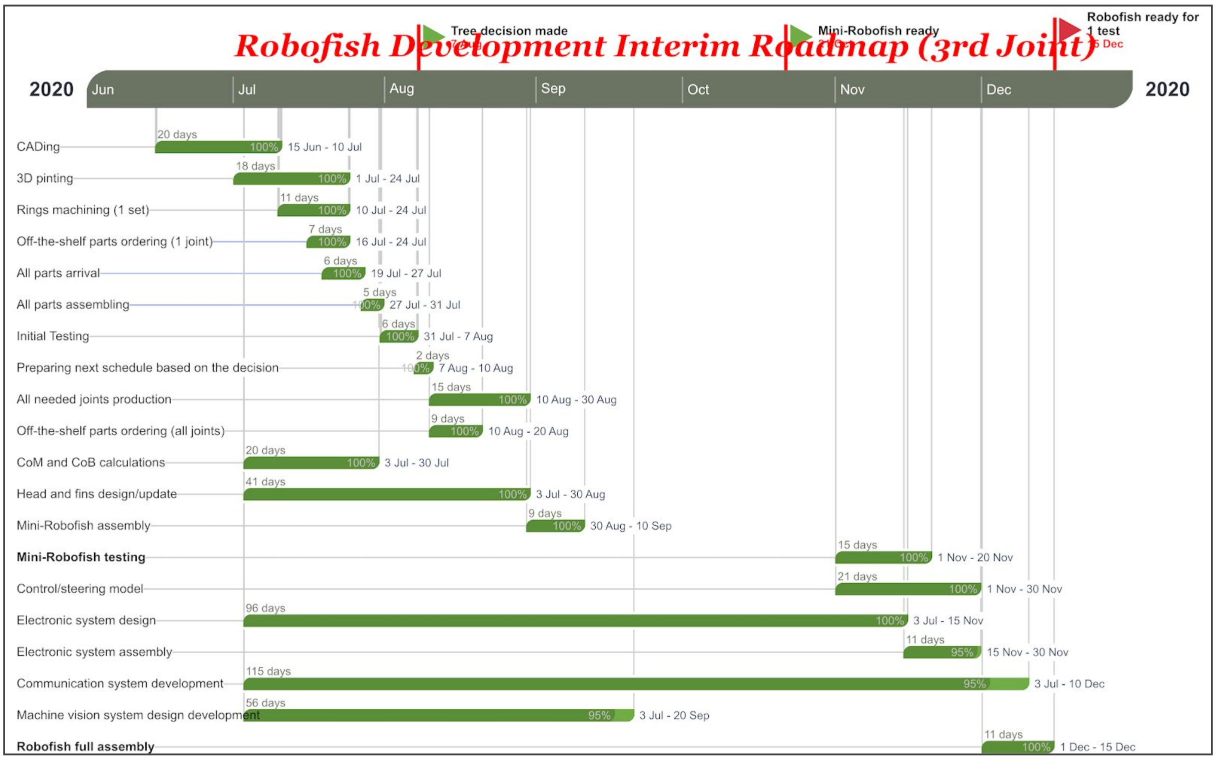


Fig. 3 Project COVID-19-Stage timetable

3. Impact

A case study on the impact of this project over the period of its first three quarters was conducted and submitted to Supergen ORE. The RoboFish project has established itself as a vibrant, dynamic, manufacturing collaborative endeavour, and is already delivering significant benefits that represent just a fraction of its long-term potential. It has brought together leading university researchers, graduate and undergraduate students, technological companies and future-focused businesses, attracted further funding both for the academic partners and industrial partners, and made contributions to knowledge and society in the form of publications and outreach activities. The benefits of the RoboFish project are not just an economical and efficient means of ORE infrastructure inspection; but also, the learned lessons that range from how to apply analytical and numerical modelling results to practical design, how to improve the quality of underwater 3D printing, and how to make modular robots that can navigate visually and acoustically underwater. The project outcomes include further development of numerical modelling methodology in fish swimming, new solutions for control of bio-inspired AUVs. Three conference papers and two relevant journal papers have been published so far. A series of outreach programs have started with a lecture to more than fifty students of Huntington School in York, and will continue with other schools in 2021. An online G Suite file repository is used to share all project resources, feeding a dedicated open-access RoboFish webpage (www.york.ac.uk/robot-lab/robofish/). The project has forged a very strong collaboration between the consortium members (University of York, University of Strathclyde, Supergen, PicSea, Catapult and EC-OG). Dr Mark Post and the consortium members have successfully obtained a White Rose Collaboration Fund Grant under the project title “Innovating the Future of Bio-Inspired Autonomous Robots for Offshore Renewable Energy Inspection”. This new fund will facilitate connections between the Yorkshire Universities of Leeds, Sheffield, and York with the RoboFish project partners for further collaboration. Furthermore, our eventful consortium Skype channel has created a think tank that has stimulated numerous useful ideas that helped us and some of our partners in securing further funds. For example, by being an effective member in the consortium, Andrew Durrant has found the outcomes of this project very useful and they have assisted him in securing new industrial funding for his company. Two research funding applications were also submitted by our partners at Strathclyde in relation to this project. They are Bionic Adaptive Stretchable Materials for WEC (BASM-WEC) EPSRC Marine Wave Energy and Simulation-based design and manufacturing of a novel underwater soft robot H2020-MSCA-IF 2020. Internal COVID-19 relief funding was secured from the University of York to extend the project a further two months, and an Impact Accelerator Account application was submitted within the University of York to extend testing and knowledge exchange activities and produce further impact of Robofish.

4. Development of RoboFish

Development of a modular bio-inspired autonomous underwater vehicle for close subsea asset inspection is a task of extraordinary challenges. Splitting a protective, watertight 3D printed enclosure into jointed segments, and mimicking the motion of a fish poses many hardware and software challenges. To overcome this, innovative mechanical and electronic modular designs were created as this section introduces.

4.1. Mechanical Design

Robofish is composed of several separate body segments with a head at one end and a caudal fin at the other end. The segments are joined together using an innovative magnetic-coupling joint. This allows it to have the required multiple degrees of freedom in its agility in order to move very precisely by aiming its head and undulating its body. With this kind of locomotion and the absence of any peripherals, RoboFish features greater agility in close proximity to structures compared to ROVs and conventional AUVs. The current RoboFish prototype is developed using off-the-shelf parts and an accessible 3D printing process. The prototype currently consist of three sections due to testing space constraints, but being modular, five sections have been created and will be assembled in further testing to produce longer operation, more efficient movement and higher agility.

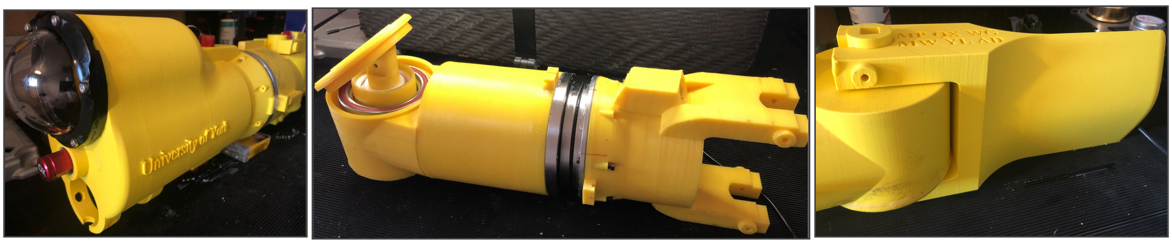


Fig. 3: Body Segments with Magnetic Joints, head and caudal tail fin

- **Body Segment:** this enables modularity as the RoboFish body is composed of several of these FDM-ASA 3D printed body segments. The most part of a segment takes the form of cylindrical enclosure of 93cm internal diameter and 23.3cm length, as shown in Fig. 3. The total length of a segment is variable to any modifications that are made, but the length with the current configuration is 42.2cm. To reach the inside of the enclosure, O-ringed stainless steel rings with male-to-female fit are used to hold the two parts of the enclosure together. This allows convenient disassembly while keeping the system watertight under high pressure. The enclosure is designed with a fork at one end to interlock with the rotor of the following enclosure, whereas the other end of the enclosure is fused to a magnetic coupling joint containing the rotor. The top of the enclosure allows wire entry via M10 penetrators, making a waterproof, high-pressure seal to pass Ethernet cable into the enclosure. The bottom of the enclosure is fitted with a M10 plugged vent, allowing trapped pressure to escape from an enclosure after it is closed. This is also used for testing the watertight seal on the enclosure with a vacuum plug attachment that connects to a hand vacuum pump and inserts into the enclosure vent. Segments are joined together using a magnetic-coupling joint allowing a servo in each joint to rotate an external rotor that in turn will rotate an internal rotor to move the next joint connected to the fork. Four guides with holes are built in on the outside to allow the attachment of fins, control surfaces, ballast, or other accessories as required. Internally, components are mounted on a 3D printed mounting plate. The servo fits into a 3D printed frame moving on linear rails, working as a tilting drawer to provide the required tension for the timing belt by adjusting the sliding servo on the rails and locking it in place with two screws.

- **Head:** is a modified segment with the same 10cm diameter cylindrical enclosure but with an extra front end that looks like a cockpit, allowing the attachment of clear acrylic dome end cap. The dome shape allows for extra room within the enclosure for additional two or more cameras or sensors! It has a wider field of view than that of a flat end cap. It is optically clear and won't warp or distort footage. The demo is fit into the head using a flange that has a double O-ring seal. The dome has been extensively pressure tested and is rated to 500m water depth . Like the other segments the head enclosure is fit with a pressure releasing vent and two penetrators. It is also provided with an additional M10 penetrator at the head nose, allowing a waterproof, high-pressure seal to pass a 4-8mm tether into the head should be required. To mount the acoustic modem and rangefinder on the head without being obstructively visible, the head has an external hollow at the bottom, in which both devices are placed. Internally, like in the segment, components are mounted on a 3D printed mounting plate and the servo is fit into a tensionable 3D printed frame.
- **Tail**: which is a caudal fin directly connected to a magnetic joint enabling active control of the fin motion, maneuverability and thrust generation of the overall body. A proper fin design can compensate for any flaws of the fish body for device stability and maneuverability.

A key innovation of the RoboFish body is the Magnetic Joint**:** this provides a mechanical non-contact bond between two rotors. The bond continues through any fluids and solids that do not interrupt the magnetic field. The design process is focused on maximising the magnetic coupling force while remaining within the dimensions of the overall swimmer and keeping the weight as low as possible. To this end, a design oriented model has been established to approximate the maximum transmittable torque of different numbers, types and arrangements of magnets. With the aim to reduce the cost of the prototype, only off-the-shelf block type magnets were considered. Fig. 8 in the appendix shows the magnetic joint internal parts. The created joint design promises sufficient coupling force between a freely rotating inner shaft and servo driven outer shaft. Both components are physically separated by the watertight enclosure, safely protecting the electronics components and leaving only the inner shaft exposed to water. The current version of the joint is run by a digital servo motor. The torque between servo and outer shaft is transmitted via a HTD M5 profile timing belt.

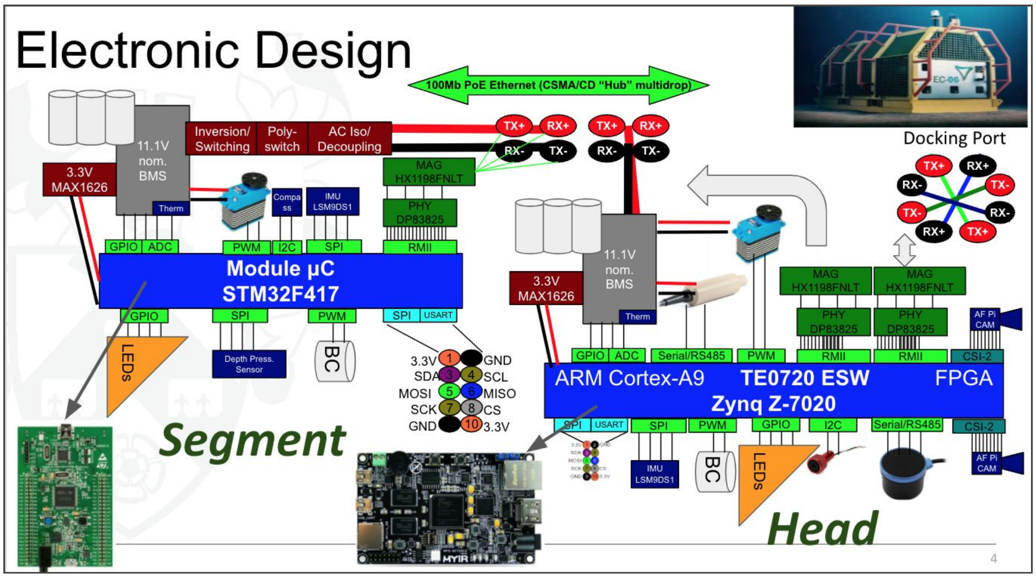
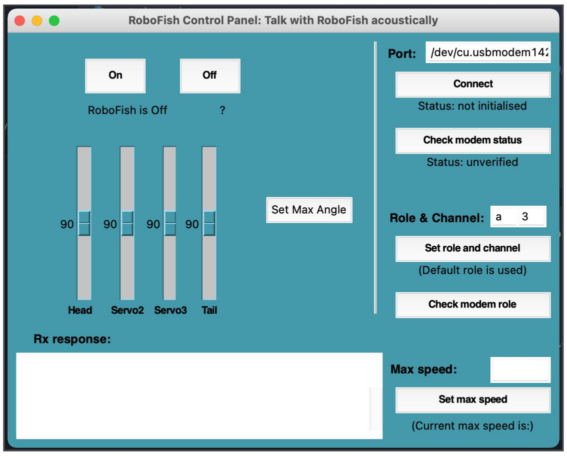


Fig. 4 Electronic Design

4.2. Electronic Design

A simplified design schematic of the RoboFish electronic systems is shown in Fig. 4. RoboFish uses modular software and hardware architecture. Each segment is self-contained and includes self-managed battery power, internal and external sensor data, and actuator control using a low-cost microcontroller. Communications and power transfer between segments are performed through a customised 100Mbit Ethernet bus, and it can charge autonomously underwater by docking with a source such as EC-OG's Subsea Power Hub. The head segment contains a powerful Xilinx Zynq SoC that serves as a master control node, communications router, and FPGA-accelerated vision platform with an acoustic rangefinder for position detection. While Wi-Fi communication is only available on the surface, RoboFish can also communicate at low rates underwater by an acoustic modem. It currently uses vision for close-range navigation and inspection of structures, with the ability to build complete visual models of the structure by using 3D reconstruction methods.

Hydrodynamic characteristics modelling: to achieve self-sustainability with the capability to dock for recharging and communication as needed, hydrodynamic investigations have been conducted into the optimal multibody kinematics, and the application of Fluid Structure Interaction (FSI) simulations to this robot. From simulations, a prototype PID controller has proven accurate in controlling the motion of RoboFish in a Computational Fluid Dynamics (CFD) simulation framework. Based on these models, several swimming gaits have been designed with very high agility for an efficient inspection and autonomous docking.



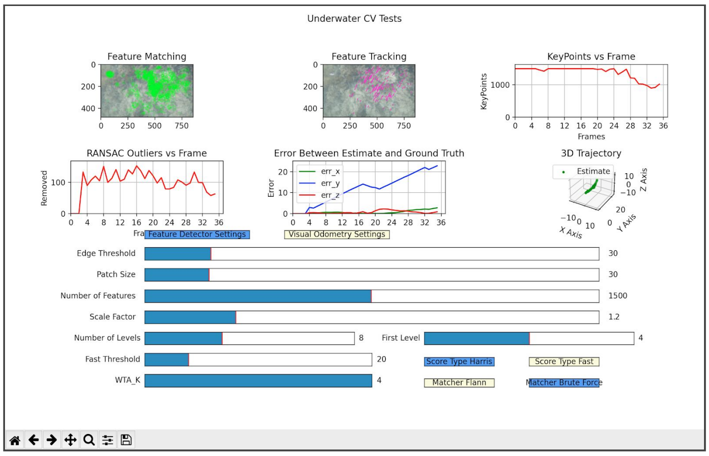


Fig. 5 (a) GUI for Acoustic Communication   Fig. 5 (b) GUI for Underwater Computer Vision

5. Acoustic Communication & Computer Vision

The RoboFish-specific powerful Xilinx Zynq SoC, shown in Fig. 11 in the Appendix, is designed to serve as a minicomputer on board to work as communications router, FPGA-accelerated vision platform and convert various range of DC voltages to the modems, rangefinder and camera. A half-duplex 64bps acoustic modem, called M64, is used to provide low-rate communications at medium range for remote control, telemetry, and inter-vehicle coordination. An interactive Python GUI, shown in Fig. 5 (a), was developed to run the RoboFish manually from a distance with serial communications over an acoustic channel. The modem has a configurable data link that can be used to implement other MAC protocols. Another Python GUI shows results from running a computer vision algorithm that uses ORB feature descriptors to perform visual odometry on any fixed objects in the field of vision as as shown in Fig. 5 (b). The ORB-SLAM algorithm has also been implemented to perform visual object reconstruction from a monocular camera, and testing on recorded datasets shows that visual odometry and SLAM work with less than 10% positional error in the short term but error increases if feature tracking is lost. The Xilinx Zynq SoC includes an FPGA which will be used for acceleration of the tracking algorithms for faster and more efficient visual tracking and recognition in future work.

6. RoboFish on a Field Trial

RoboFish underwent its first test outdoors in December 2020. The test went well and answered a number of questions. Robofish undertook some basic tasks in this test, but the test was not a very long test that examines all the Robofish features. This test is considered as the foundation of more task-specific tests to come. RoboFish accomplished all we set out to do in the test. The objectives of the test can be summarised as following:

- Testing water-tightness
- Testing the functionality of magnetic-coupling joints
- Testing propulsion

Fig. 6 the tested Robofish prototype with a head, tail and one segment

A smaller Robofish prototype was put together for the test. This is composed of a head, tail and one segment. Fig. 6 shows the tested prototype. The test was conducted in the University of York Campus West lake. The depths were around 1-2m. Temperature of around 8°C, 10 mph wind speed, visibility underwater was poor.

The prototype was put together and tested shortly on the shoreline (the lake's edge platform) just before it was let go into water. In one testing scenario, RoboFish was dropped slowly into the water from the platform using two ropes. To test swimming on the surface, two side plastic buoys prevented it from sinking or turning upside down and it maintained positive buoyancy and good balance with the right position. With it being directed toward the centre of the lake, the Go button was pressed and RoboFish swam as expected. It was tethered to be brought back to home point in the case of failure or battery recharge. In another testing scenario, RoboFish was released and operated underwater.

Fig. 7 (a) Robofish swimming on the surface

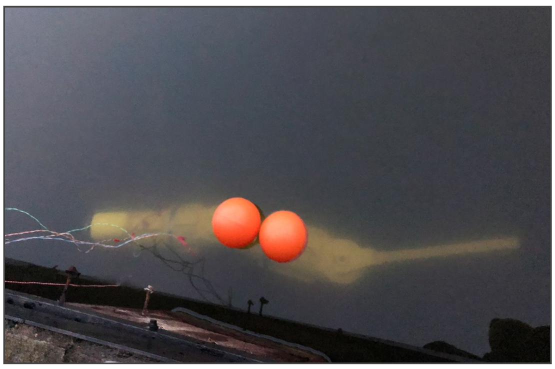


Fig. 7 (b) Robofish submerged in lake

This was the first outdoor test for RobofIsh. The shallow lake seems to be an ideal place to carry out more tests to examine the functionality of control, electronic and acoustic systems. As for computer vision, the location needs to be investigated further. Given that it is the first real outdoor trial, the performance of RoboFish is as good as it was expected. Improvements on its buoyancy, thrust and swimming gait can be achieved via further hydrodynamic analysis. This could involve making the head undulate less and the tail oscillate more. Adding more segments will also improve the swimming gait.

7. Future work

Future versions of a smaller size RoboFish, with particular focus on the modularity of the body design and easy connect/disconnect magnetic joints, will provide a flexible and dynamic platform for numerical data validation and experimental investigation in hydrodynamic laboratory testing. This will be highlighted in future projects as this work cannot be done under COVID-19 restrictions. Anticipated investigations include the analysis of the flow field influenced by different fin and body geometries and kinematic locomotion parameters, smart soft materials for passively deformed body parts as well as analysis of different actively controlled body kinematics using linear and nonlinear control. This will provide further insight to disseminate the hydrodynamic performance under different flow conditions to prepare for application within complex chaotic and harsh ocean environments. In practical sense, this will especially support the targeted underwater docking, which requires accuracy and reliability of the swimming motion.

8. Conclusion

Despite the chaos caused by COVID-19, RoboFish was built successfully to the point at which it was able to complete a lake trial. A substantial amount of knowledge was gained in the RoboFish project regarding the technologies required for a robotic fish that can loiter with a camera around complex structures autonomously or remotely controlled via an acoustic link. This will all be published in two new journal papers that are nearly complete in addition to the three already published conference papers. An industrial impact case study for EPSRC with the Supergen ORE Hub is underway now, and will include follow-up research and additional impact generated. The use of modular electronics and actuator control algorithms, the networking architecture, the 3D printing approach, and most of all the magnetic joint design are novel contributions to the state of the art that will enable new opportunities and future research projects. This represents an opportunity for more publications and additional research arising from the development of RoboFish and increases the likelihood of further funds. The strong RoboFish consortium that has formed around this project will continue to innovate and raise more funding that will allow development and deployment of new robots and vehicles for inspection and intervention.

9. Project Publications

1. M. Wright, W. Gorma, M. Post, et al. ”Multi-actuated AUV body for wind- farm inspection: lessons from the bio-inspired RoboFish field trials” 2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV)(50043). IEEE, (2020).

2. M. Wright, W. Gorma, M. Post, et al. ”CFD-FSI analysis on motion con- trol of bio-inspired underwater AUV system utilizing PID control” 2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV)(50043). IEEE, (2020).
3. Luo, Y., Xiao, Q., et al., (2020) Effect of variable stiffness of tuna-like fish body and fin on swimming performance, *Bioinspiration and Biomimetics,* https://doi.org/10.1088/1748-3190/abb3b6S
4. Luo, Y., Xiao, Q. , Zhu Q., (2020) Pulsed-jet propulsion of a squid-inspired swimmer at high Reynolds number, *Physics of Fluid* 32, 111901; https://doi.org/10.1063/5.0027992
5. W. Gorma, M. Post, et al. ”Development of Modular Bioinspired Autonomous Underwater Vehicle for Close Subsea Asset Inspection”, to be submitted to the Special Issue “Advances in Aerial, Space, and Underwater Robotics” of the journal Applied Sciences, (2021)
6. (Selected Extended) W. Gorma, M. Post, et al. ”Multi-actuated AUV Body for Wind Farm Inspection: Lessons from the Bio-inspired RoboFish Field Trials”, to be submitted to the Special Issue on Innovation in Computing, Engineering Science & Technology organized by Advances in Science, Technology and Engineering Systems Journal (ASTESJ), (2021)

10. Appendix: More Figures for Report

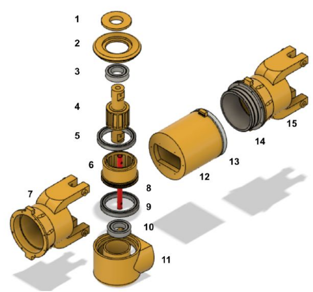


Fig. 4: All parts compromising one tested RoboFish segment: 1- Inner joint housing lid; 2- Outer joint housing lid; 3 & 10- Zirconia full ceramic bearing; 4- Driven shaft; 5 & 9- Stainless steel bearing; 6- Driving shaft; 7 & 15- Electronic housing; 8- Reinforcement Aluminum bar; 11- Joint housing; 12- Servo housing; 13- Female Stainless steel ring; 14- Male Stainless steel ring

Fig. 8 RoboFish Magnetic Joint

Fig. 9 Robofish Components

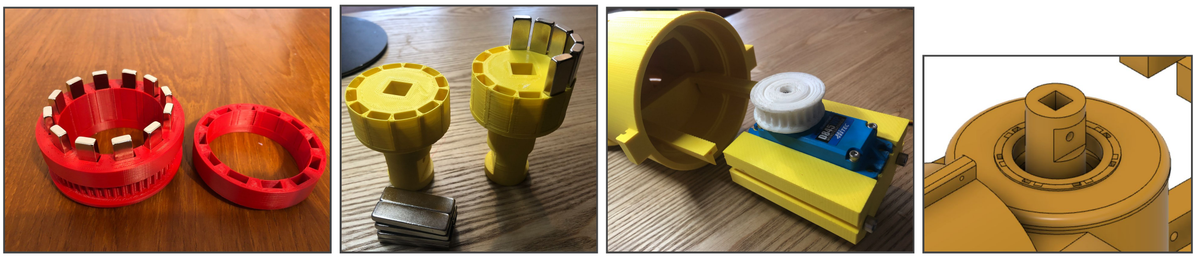


Fig. 9 from left to right, the outer shaft; inner shaft; moving part of servo mounting; joint lids

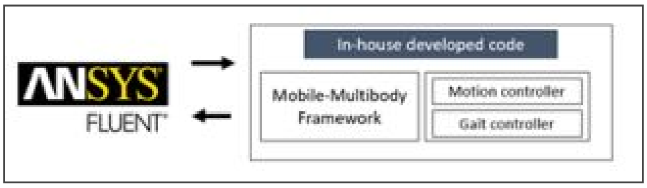


Fig. 10 Simulation environment

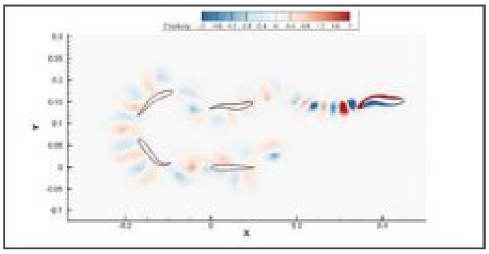


Fig. 11 Vorticity contour of U-turn manoeuvre of a multi-body swimmer

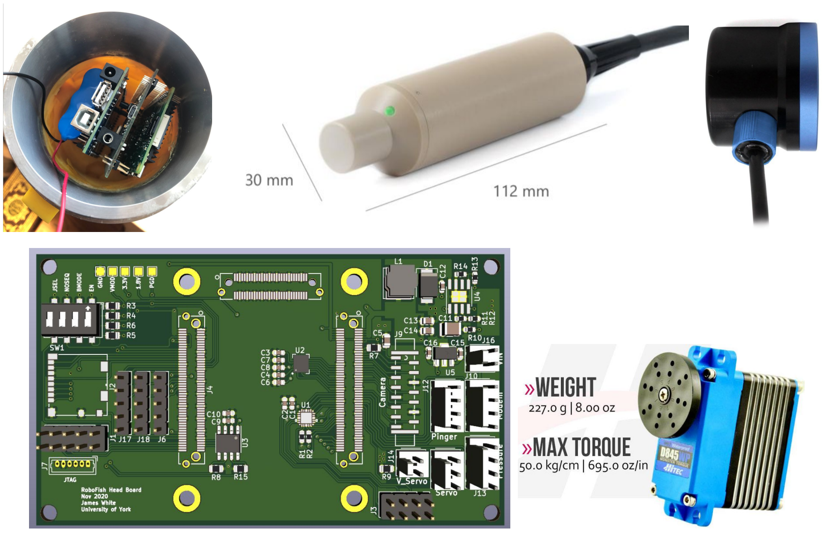


Fig. 11 Acoustic modem; rangefinder; servomotor; and the head SoC

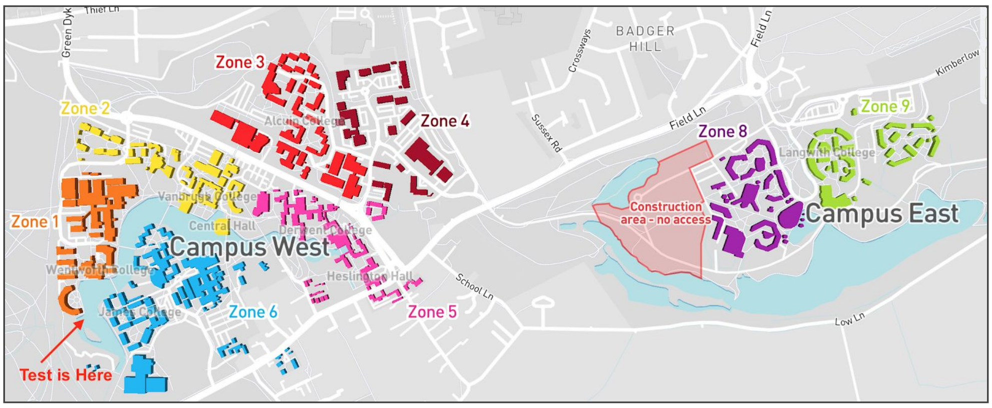


Fig. 12 Test location at University of York