OCEAN ENGINEERING MINOR: Use of ROVs for the Teaching of Ocean Engineering

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SUMMARY

Over the past two years, an Ocean Engineering Minor has been offered at University College London for undergraduate students. The first module of this programme is offered to second-year students and represents an introduction to ocean engineering. This article describes in detail the preparation of the coursework component of this module, which consists in a design and build project of simple ROVs. The aim of the coursework is to help students apply their knowledge of naval architecture to a practical problem and learn about the difficulties and inaccuracies associated with practical work in the process. A detailed description of the project is provided, with an accurate cost break-down so that other institutions may include a similar component in their teaching portfolios. Improvements on the current set-up based on students' feedback are also described.

NOMENCLATURE

DoF	Degrees of Freedom
IEP	Integrated Engineering Programme
OEM	Ocean Engineering Minor
OEF	Ocean Engineering Fundamentals
ROV	Remotely Operated Vehicle
UCL	University College London
UUV	Unoccupied Underwater Vehicle

1. INTRODUCTION

For a second-year module in ocean engineering at University College London (UCL), a coursework has been developed, which relies on the build of simple remotely operated vehicles (ROVs) for the teaching of naval architecture to students. Inspiration for this project has been taken from the SeaPerch[1] program by the MIT Sea Grant College Program [1], which is an outreach programme for high-school students. At UCL, the project time is reduced, a greater number of components is used and greater emphasis is placed on the hydrostatic, dynamic and structural analysis of the designs so as to reflect the university-level complexity of the project. The following sections will describe the ROV design and build project, assess its performance and success based on students' feedback and lessons learnt over two years of teaching and finally conclude with some suggestions for other institutions on how to implement a similar module in their portfolio of courses in naval architecture and marine engineering.

2. OCEAN ENGINEERING FUNDAMENTALS COURSEWORK

2.1 BACKGROUND TO THE OCEAN ENGINEERING MINOR

Over the past two years, Integrated Engineering Programme (IEP) Minors have been introduced at UCL. "To give students a distinctive edge after graduation and capitalising on UCL's strengths in various research areas, all students study an IEP Minor option as part of their degree"[2]. With a view to training students for the marine industry and to foster additional interest in the Master of Science degrees in naval architecture and marine engineering, the Maritime Engineering group has been offering the Ocean Engineering Minor (OEM) as a result.

This programme comprises of one module for second-year students and two modules in the third year in the fields of naval architecture, marine and coastal engineering. These courses may also be taken by non-engineering students. The second-year module, Ocean Engineering Fundamentals (OEF), is an introduction to naval architecture and marine engineering.

2.2 BACKGROUND TO OCEAN ENGINEERING FUNDAMENTALS

As part of the OEF module, students are expected to have an introduction to:

- the subjects within naval architecture, namely stability, structures, resistance, seakeeping and manoeuvring;
- the subjects within marine engineering, namely propulsion and auxiliary systems designs;
- the ship design spiral [2];
- the difficulties and inaccuracies associated with practical, experimental work [3];
- team work.

The module is subdivided into a teaching and tutorial component, during which students are taught the theory of ocean engineering, and a laboratory component, where they can apply their knowledge to the design and build of a small ROV in pairs. The module is assessed through an exam and an individual technical report, both of which

[1] https://seaperch.org/index

[2] http://www.engineering.ucl.ac.uk/integrated-engineering/minors/

contribute 50% towards the students' final grade. Whereas the exam tests their theoretical knowledge, the technical report assesses students' report writing skills, their ability to work in groups and their design capabilities.

2.3 COURSEWORK DESCRIPTION

After an introduction to the coursework and laboratory, the design, build and test stage lasts 6 weeks, with two hour-long slots per week of face-to-face tuition. Students have access to a workshop and a small wave basin during this time. In the final week of the project (week 7), a competition is held (with a duration of 4 hours) where the ROV designs are judged according to the following criteria:

- Lightest overall vehicle;
- Least ballast (and flotation aid) mass;
- Fastest ROV in a straight line;
- Fastest qualification time in a task consisting in the ROV lifting a ring underwater from a frame and placing it in a different frame.

These criteria are deemed to be representative of actual unoccupied underwater vehicles (UUVs) designs [4-5], with the requirements for low mass and ballast mass reflecting lower construction costs and energy requirements and the fastest designs corresponding to greatest emphasis being placed on performance.

3. ROV DESIGN

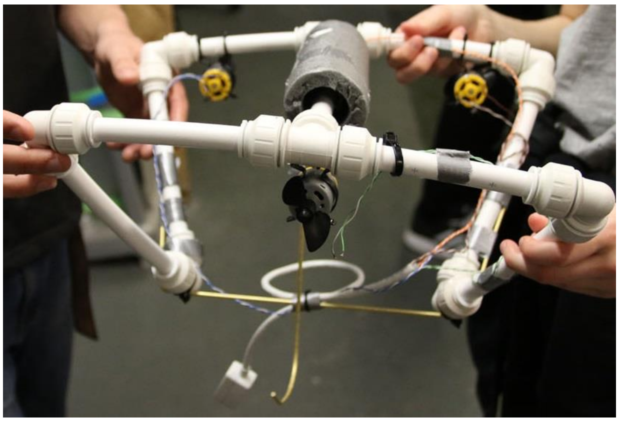
When creating the ROV design and build project, teaching staff have been careful to select the components for the ROV designs so as to:

- ensure students would be able to physically build the ROVs in the expected time frame assuming very little practical experience;
- ensure the ROVs can be built using the existing UCL facilities and equipment;
- minimise health and safety risks to students during construction and testing;
- maximise the range of different design options to foster students' innovation;
- maximise the time spent by the students on the mechanical design;
- minimise the time spent by the students on the electronics and controller design, since these topics go beyond the scope of the module;
- minimise the overall cost per ROV.

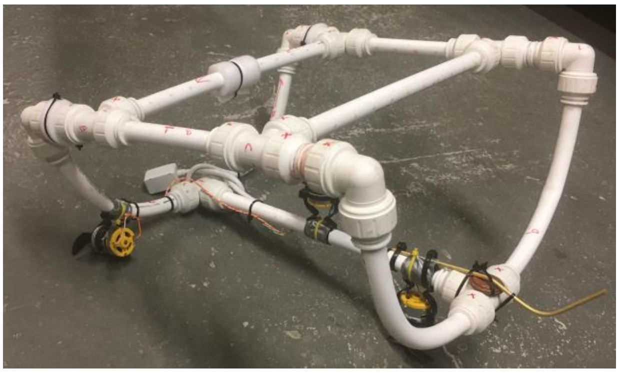
As a result, the following changes have been with respect to the original Seaperch design [1]:

- the controller is now provided to the students so that they can focus entirely on the ROV development;
- the motors are not sealed in protective casing, since corrosion has not found to be a problem for the selected motors for short-term projects in the water of the UCL wave tank;
- the motors are connected to the controller through a network (Ethernet CAT6) cable for simpler wiring;
- four rather than three thrusters are used so as to improve the manoeuvrability of the ROVs;
- students must use the components they are given, which are described in Sec. III-C.

The resulting variation of successful ROV designs is summarised in Figure 1, which shows four examples from students from the 2017/18 cohort.



(a)



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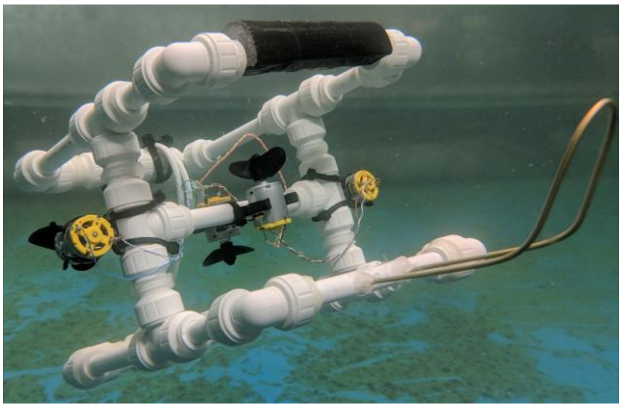

(c)

Figure 1: Example students' ROV designs.

3.1 ORIGINAL THRUSTERS DESIGN

A simple design for the thrusters is selected, with a model-boat propeller connected to a DC motor. As can be seen in Figure 2, the four pairs of a CAT6 cable are connected each to one motor. The female head enables a simple connection to the long male-male CAT6 cable, which is used to carry the power set by the controller. The motors can be operated in either direction.

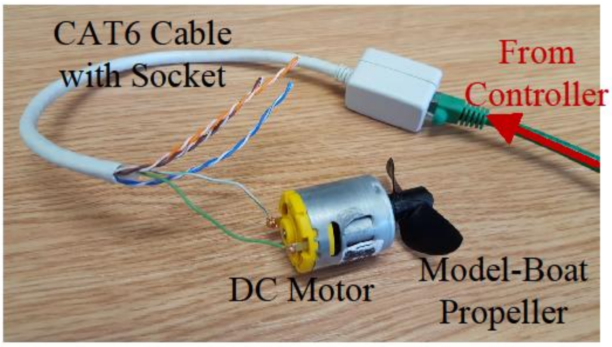

Figure 2: Original ROV thrusters design.

Originally, the propellers were bought from a specialist supplier of model boat propellers. Nevertheless, this has been now changed after students' feedback, as described in Section 4.2.

3.2 ORIGINAL CONTROLLER DESIGN

To reduce the time spent by students on the electronics, a simple analogue controller was designed to be used by all groups in turns, which is shown in Figure 3. The controller comprises of four variable resistance resistors to modulate the power to each motor and four switches to change the motors' thrust direction. Power is provided through a DC power source, whose voltage and current can be controlled. In fact, the voltage is set, while the current is controlled by the dials of the controller connected to the resistors.

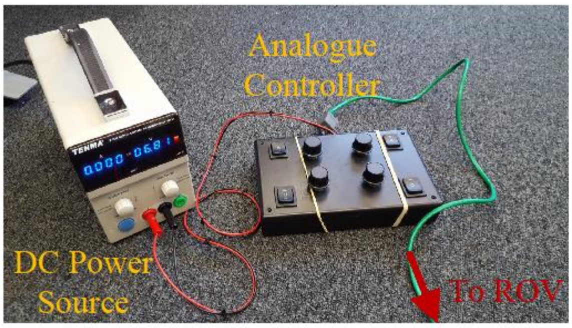

Figure 3: Analogue controller.

3.3 ROV BUILD COMPONENTS

UCL provides the build materials for the ROVs, which the students must use. A list of all items, their dimensions and quantity per ROV can be found in Table 1, while Figure 4 shows the appearance of the components. As can be seen from Table 1, the cost per ROV is approximately £60. This includes a cost for the propellers, which has now become redundant due to their new 3D-printed design. Since a project is shared by two students, the total cost of the coursework is affordable. Note that the costs in Table 1 refer to the catalogue prices of UCL's suppliers without the application of additional discounts specific to UCL. For other institutions, these prices may differ, although the change is expected to be small. Similarly, the individual components may be changed to better reflect a different reality, as the original Seaperch design has been slightly modified to better accommodate UCL's needs.

Figure 4: ROV components. The legend for the numbers can be found in Table 1.

Table 1: ROV build components inclusive of dimensions, quantity and cost per ROV.

No.	Item	Dimensions	Quantity per ROV	Price per ROV (£)
1	Pipe	D=15 mm, t=3 mm, L=3 m	1	4.39
2	Elbow joints	D=15 mm	10	11.33
3	Tee joints	D=15 mm	4	3.78
4	Pipe insulation	D=28 mm, t=13 mm, L=1 m	1	0.89
5	Brass rod (for the hook)	D=0.318 mm, L=0.5 m	2	2.79
6	Small cable ties	L=4 in	15	0.24
7	Large cable ties	L=12 in	8	0.57
8	Motors	DC, 7.2 V, 19.68 W, shaft diameter=2.3 mm	4	17.92
9	Motor clamps	D=27 mm	4	1.95
10	Propeller	2 blades	4	6.08
11	CAT6 cable	1 m, RJ45 socket	1	7.78
Total				57.71

3.4 ROV BUILD TOOLS AND FACILITIES

The design and build phases of the project were performed on work tables in the engineering and fluids laboratories of UCL. To abide by high health and safety standards, students were given an induction on using the tools and materials provided and worked under direct supervision throughout the project. The following tools have been shared by students to build he ROVs:

- pipe cutter,

- glue gun,
- scissors,
- pliers,
- drill (optional, required to speed up the flooding of the ROV chassis if desired),
- soldering iron (optional).

3.5 TESTING EQUIPMENT AND FACILITIES

During the design projects, students were provided with a cylindrical tank, a measuring jug, a scale and a string so that they could measure the buoyancy, mass and the approximate position of the centre of gravity of their designs. They would measure the displaced volume by filling the cylindrical tank by half and marking the waterline. Then, they would immerse the ROV in the tank and mark the new waterline. At this point it is possible to calculate the volume displaced by the ROV based on the difference in water depth and the cross-sectional area of the cylindrical tank. The students could approximate the position of the centre of gravity by hanging the ROV and shifting the position of the string until the ROV is balanced in space.

These experimental estimates are important to ensure the achievement of a design that is neutrally buoyant and has sufficient stability. In addition to the experimental estimates, students also produce weight and buoyancy tables based on the mass and displaced volume of the individual components to obtain a more accurate estimate of the position of the centres of gravity and buoyancy, as standard practice in naval architecture [6]. The design is then updated in a spiral until a suitable design is achieved to meet the operational requirements [2].

The trial runs and final competition are run in the UCL wave and towing tank, as shown in Figure 5. The main advantage of this tank for this task is its glass walls, which allow students to view the ROVs in action (despite refraction effects). Normal pools are also suitable for this project, though.

Figure 5: UCL wave tank during the ROV competition day.

4. FEEDBACK AND LESSONS LEARNT

Some of the students' ROV designs can be seen in Figure 1. The original objective to foster innovation has been met, with students coming up with ideas to achieve triangular and even circular shapes (achieved by bending pipes with hot water) in addition to standard cuboids. Furthermore, all students have learnt the importance of structural, static and dynamic considerations in the design of marine structures as well as the iterative nature of design. This was reflected by the overall high quality of the reports they produced.

Additionally, students have learnt to appreciate the inaccuracies associated with experimental measurements and the difficulties involved in practical design. A typical example is the drop of 6-digit precision in their calculations of the positions of the centres of gravity and buoyancy to more sensible values. Furthermore, students have come to appreciate the practical implications of the subjects covered during the theoretical component of the OEF module. For instance, one group designed a ROV with a chassis symmetrical about the *x-y* and *x-z* planes. At the start, they placed the motors on the top of the structure. As soon as they put the ROV in the water for testing, it capsized thus teaching the students a perfect lesson in hydrostatic stability.

The winning team, whose design can be seen in Figure 1a, has been the best one in applying the topics of hydrostatics, dynamics and structures in their design. In addition to being the lightest, their ROV has been the only one to successfully complete the complex task of moving the ring with a mass attached to it underwater from one frame to another. This was achieved through a perfectly neutrally buoyant design and the placing of the hook base vertically in line with the centre of gravity and buoyancy of the design, thus causing minimal pitching moments as a result of the lifting of the ring.

The ROV that won the prize for quickest in a straight line can be seen in Figure 1b. This result was possible mainly due to the good directional stability associated with this design as well as due to the team's choice to make the structure watertight, which reduced the need for additional flotation aid and its associated high drag.

4.1 STUDENTS' FEEDBACK

Overall, the OEF module received very positive feedback, with a mean score of 4.71 out of 5 and a standard deviation of 0.47 out of a 79% response rate. The small class size had an impact on this score (only 14 students enrolled on the module). However, most students identified the ROV design and build coursework as the best feature of the module and described it as enjoyable, interesting, challenging and engaging.

Nevertheless, after the tank tests and competition day, some points were highlighted as problems that needed rectifying:

- the motors were found to stop working when used underwater for long periods of time;
- the model-boat propellers did not fit well to the motors; as a result, they would sometimes detach from the thrusters;
- the analogue controller showed unexpected behaviour after strong, long use due to wear and tear;
- students had difficulties controlling the ROVs from the sides of the tank.

The engineering solutions to these problems, which have required a major redesign of these components, will be described in the following sections.

4.2 IMPROVED THRUSTERS DESIGN

As a result of students' feedback the possible failure of the DC motors when operating underwater without protective casing was investigated. The motors were run from a voltage of 5 V to a voltage of 12.5 V in steps of 0.5 V for 5 min for each motor. This time corresponds to the maximum time expected from a typical run in the tank. The tests were repeated 4 times for 4 different motors.

From these tests, no failures were observed for a motor voltage $\leq$10 V. A failure rate of 10% was observed at the highest voltage of 12.5 V within the 5-min duration. Therefore, the conclusion is that students must have exceeded the 7.2 V rating of the motor during the competition day to try to increase the performance of their ROV. This has resulted in the arcing of the coil and the brushes, thus causing heat wear and subsequent burn-out [7]. Hence, the solution for next year is to keep using the same motors without protective casing, but ensuring students do not change the settings of the DC power source. A voltage of 7 V will be set. Furthermore, the additional mass will be removed from the ring so as to simplify the task and reduce the thrust required in the move of the ring.

The existing model boat propellers presented two problems: firstly, they kept on falling off due to the poor fit onto the motor shafts; secondly, they are particularly difficult to source from a UCL purchasing perspective. Thus, they have been replaced with 3D-printed propellers specifically designed to fit tightly onto the motor shafts. 3D-printing means that the blades had to be created thicker than the minimum tolerance of the printer. The large dimension of the propellers will enable the motors to achieve the same levels of torque and thrust at lower revolutions. The new thruster unit can be seen in Figure 6, which can be compared with Figure 2. Furthermore, hot glue will be replaced with epoxy to ensure a stronger bonding.

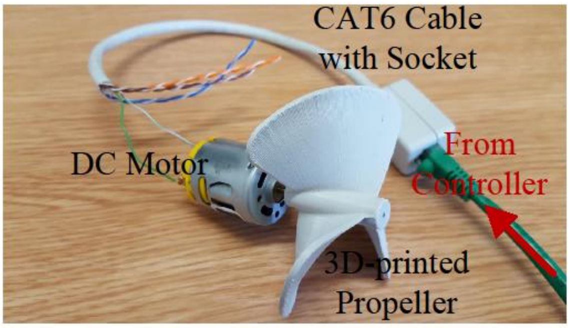

Figure 6: Improved thrusters design.

4.3 IMPROVED CONTROLLER DESIGN

Based on students' feedback, the analogue controller has been replaced with a digital controller. This approach offers many benefits over the original system:

- improved ease of use, with students being able to use a joystick instead of four dials and four switches;
- simple integration with a camera that can be fixed to the ROV, which improves the students' awareness of the ROV position and orientation;
- increased robustness to wear and tear;
- increased flexibility for future changes and upgrades;
- improved teaching objectives, with students being introduced to some control theory.

The proposed digital controller design can be seen in Figure 7. As in the analogue controller, the motors are still powered by an adjustable DC power source. Nevertheless, the power flow is now controlled by a motor shield, which is connected to a micro-controller. The micro-controller is programmed from a laptop computer. Users can use a joystick to control with the ROV (not shown in Figure 7), with the graphical user interface (GUI) of the program showing on the laptop the orientation and position of the ROV through a camera video stream, the requested motion and the corresponding thrusters input in real time (Figure 10).

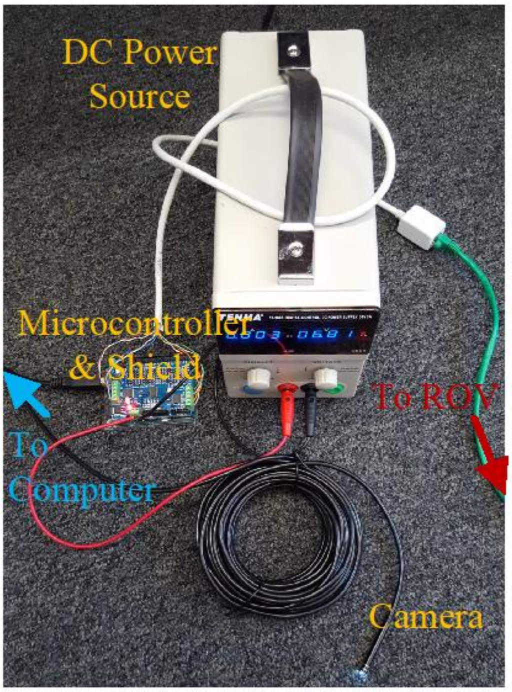

Figure 7: Digital controller.

4.3(a) Controller Software Design

Figure 8 shows the diagram of the digital controller. Using the video stream as feedback on the position and orientation of the ROV, the students control the input to the motors by specifying changes in the six degrees of freedom (DoF) through the joystick.

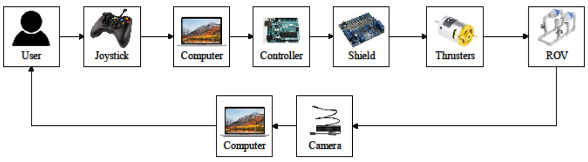

Figure 8: Diagram of the digital controller input to the motors.

The computation of the motors input is shown in Figure 9. The desired change in DoF is expressed by

$$\delta\mathbf{x} = [x \;\; y \;\; z \;\; \varphi \;\; \theta \;\; \psi]^T, \qquad (1)$$

where x indicates surge, y sway, z heave, φ roll, θ pitch and ψ yaw in the *body-fixed frame* [8]. Note that the body-fixed frame is selected due to the viewpoint the students have of the environment surrounding the ROV from the camera, which is fixed to the ROV itself. The two movement sticks on the joystick are programmed to control surge and sway and pitch and yaw, respectively. Heave is controlled through the two analogue triggers (one for upwards; the other one for downwards). Roll is set to zero throughout this work, i.e. it is assumed it cannot be controlled, as the ROVs are expected to be hydrostatically stable (pitch may be important to pick up the ring, though).

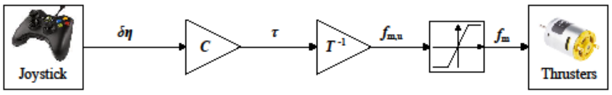

Figure 9: Diagram of the digital controller input to the motors.

As can be seen in Fig. 9, the desired change in DoF is mapped to a desired thrust vector in the body-fixed frame as

$$\boldsymbol{\tau} = \boldsymbol{C}\cdot\delta\boldsymbol{x}, \qquad (2)$$

where $\boldsymbol{C}$ = diag([1 1 1 0 0.25 0.25]) is a diagonal matrix of coefficients. Note that this matrix is designed to give more importance to translations than rotations. The number 1 represents the highest motor setting that can be achieved by the controller due to the selected MATLAB interface, i.e. 100% motor power.

The desired thrust vector in the 6 DoF is then transformed into a vector of the inputs for each motor through multiplication by the thrust allocation matrix $\boldsymbol{T}$ [8]:

$$\boldsymbol{f}_{\mathrm{m,u}} = \boldsymbol{T}^{-1}\boldsymbol{\tau}\,. \qquad (3)$$

The thrust allocation matrix is obtained from the coordinates of the motors, $\boldsymbol{p}_i$, where i = 1,2,3,4 indicates the motors index, and the overall centre of gravity of the vehicle in 3D (in m), $\boldsymbol{x}_{\mathrm{g}}$, and the unit vectors of the motor orientation, $\boldsymbol{o}_i$, that the students must specify before running the tests. For each motor i, it is possible to calculate the following variables:

$$\boldsymbol{f}_{x,i} = \boldsymbol{o}_i \odot [1\;0\;0]^T, \qquad (4a)$$
$$\boldsymbol{f}_{y,i} = \boldsymbol{o}_i \odot [0\;1\;0]^T, \qquad (4b)$$
$$\boldsymbol{f}_{z,i} = \boldsymbol{o}_i \odot [0\;0\;1]^T, \qquad (4c)$$

where $\odot$ indicates element-wise multiplication which are assembled in the row vectors $\boldsymbol{f}_x$, $\boldsymbol{f}_y$ and $\boldsymbol{f}_z$ of size (1×4) (for 4 motors). If the motors position vectors are assembled into the matrix $\boldsymbol{P}$ of size (3×4), the thrust allocation matrix can be assembled as follows:

$$\boldsymbol{T} = \left|\begin{array}{c} \boldsymbol{f}_x \\ \boldsymbol{f}_y \\ \boldsymbol{f}_z \\ \boldsymbol{f}_z\odot\boldsymbol{P}(2,:)-\boldsymbol{f}_y\odot\boldsymbol{P}(3,:) \\ \boldsymbol{f}_x\odot\boldsymbol{P}(3,:)-\boldsymbol{f}_z\odot\boldsymbol{P}(1,:) \\ \boldsymbol{f}_y\odot\boldsymbol{P}(1,:)-\boldsymbol{f}_x\odot\boldsymbol{P}(2,:) \end{array}\right| \qquad (5)$$

where (j; :) indicates all columns of the j^{th} row. In general, an ROV with four actuators cannot be expected to control 5 DoF, since it is under-actuated [8]. Nevertheless, in practice the selected controller, due to its simplicity and reliance on user input, has been found to be well behaved. Hence, to prevent to numerical instability the inverse of the thrust allocation matrix has been replaced with its pseudo-inverse. Finally, the vector of the inputs to each motor, $\boldsymbol{f}_{m,u}$ is clipped to values within ±1, as shown by the saturation block in Figure 9.

It is clear that the selected controller does represent a state-of-the-art controller for ROVs [8], with students still needing to learn the sensitivity of the joystick for their specific design. Nevertheless, this approach enables them improved control capability over the original analogue controller. Additionally, students learn about the concept of the thrust allocation matrix in ROV control.

4.3(b) Application Implementation

The controller software is implemented in MATLAB App Designer using the support packages for Arduino Hardware and Webcams. The application (app) is then packaged into an executable that can be run from any web browser. Note that the selected packages work only with the selected hardware, i.e. an Arduino Uno mini-controller (or a clone) and an Adafruit Arduino motor shield version 2 (or a clone). Figure 10 shows the main page of the app GUI page. As clearly identified in the figure, the user specifies the motors position and orientation on the top left side of the figure in addition to the position of the centre of gravity. The position coordinates are expected to be in m, while the orientation is expressed in unit directional vectors. The top-left figure shows the real-time requested forces and moments on the ROV in 6 DoF as arrows. The actual values can be read from the top line. Conversely, the top-right figure shows the real-time control input into each motor as arrows, with the actual values being visible on the top line. Control can be stopped and restarted by moving the left switch or pressing the B and A buttons of the joystick, respectively. The camera video stream is shown in the bottom figure and can be started or stopped with a switch. Both the MATLAB code and the package app are freely available from Github.

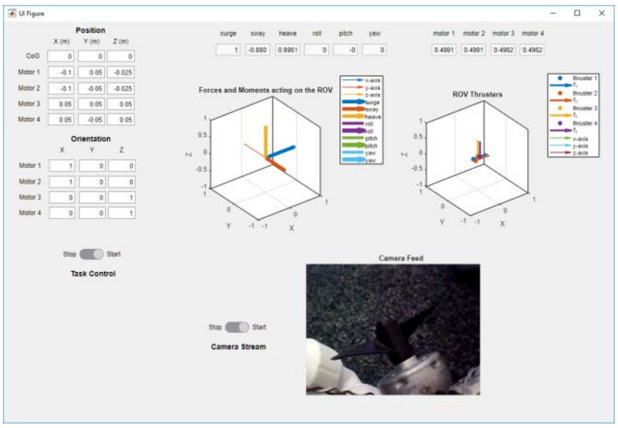

Figure 10: GUI design of the digital controller application.

4.4(c) Controller Components

Similarly to Section 3.3, a list of the components used in the new digital controller can be seen in Table 2. In addition to these components, a laptop is required to run the developed program. The cost of the components is reflective of the price on the UCL suppliers' website without accounting for UCL-specific discounts. Hence, much lower prices are expected for the electronics components if sourced from other vendors. Additionally, most of these items are likely to be found in any engineering laboratory. These costs are one-off, with a single controller being required for the whole module.

Table 2: Components of the digital controller inclusive of description, quantity and cost.

No.	Item	Description	Quantity per ROV	Price (£)
1	DC power source	Adjustable, 1 output, 0-30 V, 0-3 A	1	52.30
2	Microcontroller	Arduino Uno	1	18.39
3	Motor shield	Adafruit v2	1	23.68
4	Joystick	Prous Xbox 360	1	15.99
5	Camera	USB, IP67, 10 m long	1	15.17
6	CAT6 cable (female)	1 m long, RJ45 socket	1	7.78
7	DC cables	Banana plug 3 mm	2	1.52
8	CAT6 cable (male-male)	30 m long, RJ45 plug	1	13.78
Total				148.61

5. CONCLUSIONS

Building on the SeaPerch programme by MIT, the design and build of simple, affordable ROVs has been transformed into a coursework appropriate for the teaching of an introductory module in ocean engineering at university level. Engineering challenges associated with the design of the propulsion and control systems of the ROVs have been faced and solved by designing a digital controller and water testing the motors. The resulting programme is simple for other institutions to adapt to their needs and environment for the teaching of ocean engineering.

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