Building a bioreactor: truly multidisciplinary bioengineering teaching

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***Abstract*—This Innovative Practice Work-In-Progress paper presents an ambitious project for an entire cohort of undergraduate bioengineering students to build miniature electronically controlled photo-bioreactors from a custom designed kit of parts. The students must work with a culture of the alga *Dunaliella salina CCAP 19/30* to determine optimum growth conditions, and then measure the output products after growing the alga in their own photo-bioreactor.**

This project bridges the gap between the fundamental science and engineering taught in traditional modules, skills development and experiential lab practicals, and fully independent engineering design-and-build projects. Bioengineers require a vast array of practical skills, from chemical handling and biological analysis to electronics and coding. In the first years of an undergraduate bioengineering degree, students are exposed to basic knowledge and practical techniques in an array of disciplines. However, when attempting to integrate their skills into an independent project later in their degree programme, students can struggle to make links between the wide-ranging topics, and to use their practical skills appropriately.

Multidisciplinary and interdisciplinary working capabilities are regarded as key skills for engineering students to acquire, and this is particularly true in bioengineering. Within this single practical module, electronics, programming, internet of things (IoT), chemistry and biological product growth measurement are all linked together in realistic context. Particular focus is made on constructive developmental alignment from the content of prior modules in both electronics and biotechnology, while providing clear signposts to techniques that will be useful for future project work.

This wide-ranging practical course requires a truly multidisciplinary teaching team, and the advantages and disadvantages of having a dedicated academic department to teach practical skills across disciplines are described. In addition, the challenges in constructing a practical module suitable for an entire cohort to participate simultaneously are discussed.

***Index Terms*—multidisciplinary engineering education, bioengineering, bioreactor, project-based learning, algae**

I. Introduction

Bioengineering is a vast subject covering a wide range of topics [1], and is possibly the most multidisciplinary engineering stream available to be studied by undergraduates. To produce successful multidisciplinary engineers, bioengineering courses comprise a range of modules from across the engineering spectrum; common bioengineering course requirements include instrumentation, physiology and mechanics [2], which in turn require basic skills in electronics, programming, biology and chemistry.

Practical laboratory competencies are a core requirement for the modules that make up bioengineering programmes. However, the skills learned in the first two years of laboratory exercises are generally basic, in order to build "scaffolding" of capability for future experimental work [1], [2]. Although this initial skills development may be thorough, students may not be directly able to implement their skills in unfamiliar situations [3], likely due to a lack of developmental progression through a curated laboratory programme. There is a reasonable body of published work on constructivism within individual laboratory activities [4], yet there is little work on the creation of a laboratory programme specifically to bridge gaps between basic skills and independent design.

Open-ended practical design projects with little or no guidance from teaching staff are seen as a gold standard in engineering teaching programmes [5], yet the use of guided challenges and problems has been shown to be far more effective for knowledge retention [6]. A range of methods to provide scaffolding to support problem based learning (PBL) in engineering was shown in [7], although most prior work on scaffolding for PBL considers individual teaching sessions, rather than whole modules in the context of programmes, as in [8], [9]. Work on gap-bridging practical exercises in a chemical engineering programme was shown to be effective for third year chemical engineering students [10], although the teaching in [10] was focused on experimentation skills rather than preparing students for design-build-test cycles.

Within the undergraduate bioengineering programme at the University of Sheffield, students take first year modules in Electronics, Modelling and Control, Mathematics, Biomaterials and the Biology, Chemistry and Physics of Living Systems. Although this provides a broad yet thorough grounding in fundamental science, the knowledge gained in these modules is rarely applied effectively in free-form projects in later years. This is most evident in a third year group project module, which requires the students to independently work in teams to design and build bioincubators, incorporating key skills from all prior modules in an independent practical exercise. Many students required one-to-one support to successfully complete their third year projects, and were not able to work with as much independence as staff desired and expected.

The bioreactor project module described in this paper was therefore constructed for two purposes: firstly to unite the

broad range of bioengineering key skills within a single project; and secondly to bridge the gap between fundamental engineering practice and a freeform design exercise, by creating a closely guided yet inspirational project.

This project was scheduled to run throughout February-May 2020, and has been heavily disrupted by the suspension of face-to-face teaching due to the Coronavirus pandemic. Although the teaching of this project was revised, including student feedback and assessment, this paper still presents contributions in project design, programme alignment and implementation at scale.

II. Project Design

The overall goal of the project is for small groups of 5-6 students to each construct a miniature photo-bioreactor, prepare measurements to determine the optimum salinity of media for maximum algal growth, and then leave their bioreactor operating to grow as much algae as possible over a two week period. The alga *Dunaliella salina CCAP 19/30* was chosen for growth due to its tolerance of high salinity and non-sterile environments. The bioreactor is constructed from a custom designed kit of parts, including an ESP32 microcontroller (chosen for WiFi connectivity and Arduino IDE compatibility), a motor system for mixing, LEDs for illumination, and a pH probe, as shown in Fig. 1.

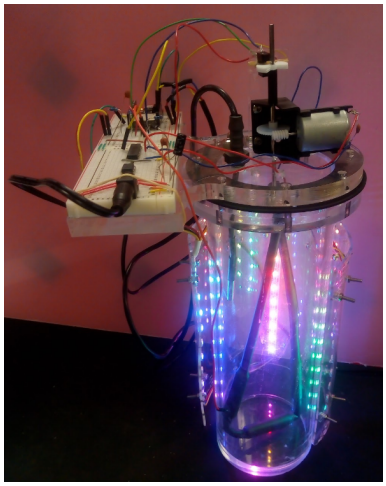

Fig. 1. A complete photo-bioreactor constructed during the guided project

The project consists of 6 individual sessions of 2 hours each, with a post-/pre-lab task to be performed in between each session to link together all activities. The sessions are timetabled two weeks apart during a single semester.

During each session, each group must split into 2 subgroups so that both an electronics and biological task can be performed. Each student should alternate between electronics and biological tasks throughout the project; this is enforced when checking student attendance at each session. Table I shows the schedule of sessions for the whole project.

The project is designed to directly implement skills learned in the basic modules of year 1 in a guided fashion, such that students can confidently design and implement their own subsystems in a large project.

TABLE I
Project Schedule

Session	Electronics and Coding Tasks	Biological and Chemical Tasks
1	Basic hardware setup, power supplies and WiFi connectivity, lighting subsystem	Create standard curve for OD at 410 nm of glycerol concentrations
2	Motor drive and rotation speed measurement subsystem	Quantify glycerol produced by *D. salina* using OD measurement and standard curve
3	Reactor temperature measurement and heating subsystem	Quantify chlorophyll present in algal samples and relate this to glycerol
4	Reactor pH measurement subsystem	Explore hygiene and cross-contamination when working with sterile containers
5	Combine and test all subsystems together	Prepare growth medium and algal sample to be left in bioreactor for a 2 week operating period
6	None	Use glycerol and chlorophyll measurements to quantify the amount of algae produced over the operating period

For example, the use of transistors as switches for inductive loads is theoretically described in a year 1 electronics module; a guided task in this project to construct a motor drive circuit controlled by a microcontroller should give the students knowledge and confidence to work independently with pumps or solenoid valves in future. This constructive scaffolding structure at a programme level underpins the design of both the electronics and biological tasks in every session.

A. Electronics tasks

The bioreactor design is modular, comprising a number of subsystems which are independently interfacing with the ESP32 microcontroller, as shown in Fig. 2. Each session is self contained, and structured for students to construct and test a single subsystem within the time available.

The initial session reminds students how to work with breadboards for system prototyping (which has been taught in prior labs) by initially crafting basic LED circuits. The session then uses RGB LED strips with individual control chips per LED (WS8212), and the Internet of Things connectivity protocol MQTT to send data from a web browser to the devices to control the LED brightness. The relevance of the activity to the bioreactor is highlighted by creating photosynthetically active radiation - colour mixing the RGB spectrum to match sunlight to encourage algal growth, and designing on/off timing ratios to match natural daylight cycles.

Session 2 introduces the motor drive subsystem, using a brushed DC motor driven via a Darlington transistor chip. This allows students to become familiar with the need for transistors and external power supplies to control high current loads from a microcontroller, and reminds them to use flyback diodes for current paths when driving inductive loads. An independent

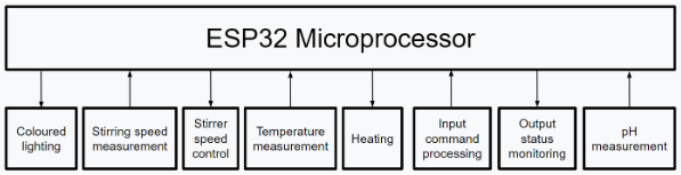

Fig. 2. The subsystems of the bioreactor system and information flow to/from the controller

rotation speed measurement system is also implemented using a photointerrupter and a custom designed plastic blade attached to the motor shaft. This hardware setup also allows relatively complex software concepts to be demonstrated: PID control of the motor rotation rate, and interrupts for measuring the frequency of photointerrupter pulses. The importance of mixing for nutrient distribution through the growth medium and insolation is emphasised.

The temperature measurement subsystem is constructed in session 3, where a basic resistive water heater is constructed, again using the Darlington transistor chip to provide control of the power delivered. However, due to the bioreactor power supplies being constrained to just 5 V, the water heating elements would take over 6 hours to heat 500 ml of water to the target temperature of 25 °C. To maximise students' learning opportunity in the laboratory, they are also set an interactive simulation task in MATLAB to complete while the water heats. This simulation task guides students to characterise the step response of the water temperature upon application of electrical power to the heating elements, and includes both theoretical and empirical modelling techniques. The students are also provided with pre-selected research papers describing bioreactors growing strains of *D. salina*, to choose and justify their own optimal operating temperature.

In session 4, the students construct the pH measurement subsystem, using a pH electrode and basic op-amp circuits, connected to an analogue to digital converter on the microcontroller. In their first year electronics course the students study basic op-amp theory including inverting and non-inverting configurations, meaning elements of this design (e.g. gain calculation and resistor choice) can be left for them to complete independently. The session concludes with calibration of the response of the pH probe using known buffer solutions.

The electronics tasks in session 5 are simply for students to complete any outstanding work from the prior sessions, and to ensure that all optimal system variables from prior experiments are inserted into the code for the operational run. There are no electronics tasks scheduled for the final session.

For each session, a number of partly written Arduino code scripts are provided, although several tasks are left to the students to complete. These tasks are selected as representative of basic coding skills that the students will need to master for success in their own future independent projects, including:

- Installation and use of libraries;
- Use of interrupts (timer and external); and
- Interfacing using serial and IoT connections.

B. Biological and chemical tasks

Over the 6 project sessions, a series of independent developmental tasks are set for students to practice their skills in basic biological sample handling and measurement tasks.

Session 1 required the students to make up a set of dilutions of glycerol, and then use a spectrophotometer to create a standard curve relating absorbance at 410 nm to the concentration of glycerol in the solution. Glycerol is produced by *D. salina*, so this standard curve can be used later to quantify the activity of the algae cultured in the bioreactor. The students are also required to perform basic data analysis on the fitting of the measured data to the curve, such as R^2 values.

The students are then provided with samples of *D. salina* grown in six different salinity concentrations during session 2. They must measure the absorbance of the samples at 410 nm and use their standard curves to infer the glycerol present in each sample. This is in direct preparation for measuring the glycerol outputs after the bioreactor operational run.

In session 3, the chlorophyll content of the algal culture is measured, again using spectrophotometry, at 645 and 663 nm. These measurements are repeated for cultures in different salinity media, and the chlorophyll concentration can be related back to the glycerol produced using prior results.

Session 4 is a standalone session looking at good hygiene practice. Students are instructed to prepare dilutions of solutions of a colourless liquid, and transfer them to well plates. A UV light is then used to illuminate the fluid and show the contamination of surfaces, equipment and people that has occurred. Although *D. salina* is highly tolerant of non-sterile conditions, other cultures that students may use in future projects or employment may require more careful handling.

The setup of the bioreactor for the two week continuous run of operation is the only activity planned for session 5. Given that there are 15 groups participating in the module, different groups can be allocated different salinity media to use in the final run, so that a complete dataset is acquired across the whole cohort.

The final session is used to measure the outputs of the bioreactor after the two week operational run. Students should use the same techniques from sessions 2 and 3 to quantify both the glycerol and chlorophyll present, which in turn requires their standard curve measurements from session 1.

III. Teaching Material

The material for all parts of the project was provided as Google Docs files, which enabled collaborative working when writing them. Since all students work on the electronics tasks using laptops, this also enabled rapid direct editing, including efficient changes during the teaching sessions where required.

Care is taken within the teaching material to not simply repeat concepts and ideas that students should already know, but to signpost to the specific modules where the prior concepts were taught. Exercises are also set within the lab script, requiring the students to critically consider their practical work. These links are clearly highlighted in different

coloured boxes, directly linking to prior knowledge and clarity in expected observations, as shown in 3.

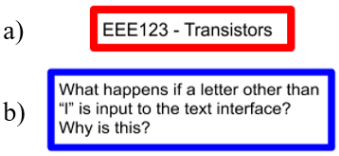

Fig. 3. a) an example signpost back to learning from a first year module, highlighted clearly in red; b) observations required to be noted by the students in their lab books, highlighted clearly in blue

Students are also supplied with printed copies of instructions for the biological tasks for ease of use, and all students are provided with blank lab books for their own notes. The students need to share values within their groups (e.g. chemical results will need to be communicated to the electronics team after each session) for use in the post-lab assessments.

IV. Assessment

This project sits within a 10 credit (5 ECTS, notionally 100 hours) module entitled "Advanced Bioengineering Topics". Within this module, 50% of the credits are awarded for participation in this group practical project, while the other 50% of the credits are awarded for a flipped learning course in statistics for bioengineers (beyond the scope of this paper).

There are two modes of assessment for the project:

- 5x Pre- and post- lab exercises (5% of the module each)
- Group poster design (1 exercise worth 25%)

Before the first practical session, all students must complete a pre-lab exercise based on the risk assessments for the task and pre-reading of the practical instructions, to ensure that the students approach the work safely. This exercise does not bear module credit, but is a mandatory prerequisite for taking part in the practical activities.

In between each session, an online test is set which covers detailed topics from the laboratory exercises. The test is to be taken individually, but it includes elements of both the electronics and biological tasks. This necessitates the students sharing their results and learning within their teams, encouraging communities of learning to form between sessions.

The final group poster design requires the students to summarise their bioreactor construction, critique some relevant literature, and analyse their results. Use of collaborative tools for all group members to work on the poster simultaneously are encouraged (e.g. Google Slides); although the poster will not be physically printed and presented, designing a visually appealing yet informational display is a key transferable skill.

V. Producing Multidisciplinary Project Teaching at Scale

The strength of this project is its multidisciplinarity, and the only way to successfully construct a teaching activity of this nature is with expert staff. The structure of the department of Multidisciplinary Engineering Education, comprising a team of specialist practical engineering teachers with a range of specialisms, has been key to designing this activity. Bringing staff with electronics, biological, chemical, design and manufacturing skills into one team allows rapid prototyping and ideation, so that creative and ambitious projects across disciplines can flourish [11].

To ensure that the activities retain a multidisciplinary group feeling, a large flat space is essential for teaching. All students in each group should feel part of all activities (regardless of which tasks they are performing in that session), so groups performed the biological and electronics tasks facing each other, enabling interaction between all team members and sharing of insight from previous steps in the practical activities. This enables social interaction and a shared learning experience, an effective method of practical teaching [12].

For efficient delivery of the project to the full cohort, thorough preparation is key. It is crucial to carefully prepare kits of parts required for each session, for both the electronics and biological tasks. Testing of the software environments is also essential to avoid wasting precious lab time on student queries not directly related to the project. In both cases, economies of scale can be exploited; a talented multidisciplinary team of technicians can prepare computers, equipment and consumables well in advance of the teaching sessions.

By the end of the project, 20 functionally identical bioreactors will be constructed, which will allow for interesting research hypotheses to be tested during times when this teaching project is not running. For example, although the mixing of *D. salina* is of critical importance for optimum growth, its fragility makes it susceptible to damage from shear stress. Using multiple bioreactors to simultaneously test several stirring variables (rate, blade size etc) can efficiently explore a wide parameter space.

VI. Conclusion

Guided practical projects are ideal teaching methods for the middle years of undergraduate engineering degrees, to provide scaffolding between basic laboratory skills from fundamental modules and independent engineering design projects, and to give students confidence in applying their knowledge.

By building a bioreactor from a kit of parts using electronics and coding skills, and performing a structured series of biological and chemical experiments, a guided project has been designed to precisely fill the practical skills gap in the bioengineering programme, with clear signposting to prior knowledge and future applications.

Student feedback and assessment data on this project are not presently available, due to the suspension of face-to-face teaching caused by the Coronavirus pandemic. Anecdotal discussions with student participants have been overwhelmingly positive, and we look forward to presenting deeper analysis of student progress and perceptions in future.

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