Enhancing microelectronics education with large-scale student projects

Using the example of the University of Southampton Small Satellite

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***Abstract*—This paper discusses the benefits of using large-scale projects, involving many groups of students with different backgrounds, in the education of undergraduate microelectronics engineering students. The benefits of involving students in large, industry-like projects are first briefly reviewed. The organisation of undergraduate programmes is presented, and it is described how students can be involved in such large projects, while maintaining compatibility with undergraduate programmes. The generic discussion is illustrated with an example of the University of Southampton Small Satellite (UoS^3) project, which has been running for two academic years and involved a number of students to date. It is discussed how the work on a project can be split between different student groups so that they can be assessed on it. Definition of interfaces between different groups, as well as how they are managed in the UoS^3 project, are described. The difficulties that large, student-run projects are likely to face are mentioned and recommendations about the structuring of degree programmes to amend them to large projects, are made. Lastly, conclusions about the applicability and benefits of small satellite projects to undergraduate education in electronics are drawn.**

Keywords—undergraduate education; programme; small satellites; cubesat; University of Southampton Small Satellite

I. Introduction

The benefit of engaging in a multidisciplinary project that can span multiple years lies in its similarity to the reality of today's industrial and scientific work. In an ever more complex world, projects become larger in scale and require the expertise of multiple disciplines. This environment brings about new challenges such as the importance of communication between the contributing teams, having an understanding of the dependencies of one's own subproject to other subprojects (system engineering), and working towards common interfaces. Implementing such a project in the curriculum of university students prepares them uniquely for these challenges and fosters their ability to make efficient contributions in today's work environment.

Building a small satellite falls into the category of a large, multidisciplinary project. The cubesat standard was released in 1999 and specifies design requirements for a class of very small satellites - the Pico satellite group of cubesats [1] that is distinguished by its $10x10x10cm^3$ general dimensions. The appeal of using the cubesat standard stems from the reduced cost of building and launching a cubesat through standardisation of overall dimensions, and interfaces to the satellite launch vehicle. Reduced cost and the small, hence manageable, size of cubesats has enabled universities and amateur groups to engage in building their own satellites. Cubesats have, since, proven themselves as a valuable educational tool.

Complex projects, such as building a satellite, can usually be subdivided into subprojects which can be addressed by student groups as part of their curriculum. In fact, other projects that share these characteristics can be treated in a similar fashion and this paper discusses how any complex and multidisciplinary project can beneficially be embedded in a university environment.

The University of Southampton Small Satellite project, or UoS^3 in short, is used to provide concrete implementation examples of the general recommendations for managing a student-oriented, complex project in a university environment. The paper also provides lessons learnt and recommendations for how universities can be more accommodating of such projects, as well as key aspects that project leaders should be aware of. Student feedback received to date indicates that students who participated in UoS3 valued the challenge and recognized its benefits for their future employments.

II. Large Programmes in University Environment

Engaging students in large, industry-like projects prepares them to assume their professional roles quicker after they leave the university. However, the university environment is different to industry, which complicates embedding work on large projects in the student curriculum. In order to better understand how this can be done, the

Figure 1 – Key dates of the academic year 2015/16 at the University of Southampton.

structure of a university undergraduate degree will be first described on an example of the University of Southampton. Then, the nature of a generic large-scale project will be presented, together with a way of how students can be involved in it as part of their courses.

A. The university environment

The most fundamental difference between the university and industry environment is the cycle of the academic year, which limits every project that a group of students might undertake. The key dates of an example academic year at the University of Southampton are shown in Figure 1. Throughout the academic year, most of the students will be involved in exams, which they have an incentive to do well in. This means that the students will tend to devote more time to exam preparation than any other undertaking they might be involved in. The academic year is also punctuated by holiday periods, making collaboration difficult. What is more, the university courses nominally last four to five years, meaning that every year a different cohort of students is present at the university.

All this affects student involvement in large programmes in several ways. Firstly, the skill and knowledge base that the programme can make use of will vary from year to year. Secondly, duration of no task should exceed the period between exams and holidays, unless it can be put on hold. Lastly, ensuring continuity of knowledge about the programme between consecutive academic years becomes problematic and should not rely entirely on the undergraduate students.

A university programme consists primarily of lecture modules, which are typically assessed based on exams and relatively small pieces of coursework, such as essays. It is rare for students to undertake large projects and be assessed on them. One such occasion is a group design project (GDP). A GDP is an activity where a number of students from the same discipline would typically design, manufacture and test a piece of hardware [2] [3] and this is implemented in the mechanical engineering MEng programme at the University of Southampton (UoS). Besides a GDP, a MEng programme includes an individual project (IP), where a student performs an individual research, design, and/or manufacturing activity. At the UoS, the IP takes place in the third and the GDP in the fourth, final year of the MEng programme.

Apart from assessed project work, two more opportunities to engage undergraduate students in large projects exist; Students can volunteer to work on the project in their spare time, for example through involvement in student societies, or, students can be employed as interns if appropriate funding exists. However, in both of these cases, the student involvement is still limited by the structure of the academic year.

Given that students can only be expected to spend a limited portion of their time on a large project, one way to increase project productivity is to employ more students. However, the size of every university is limited and it is not up to the institution to decide how many students and with what backgrounds will be present in every student cohort – this is dependent on student applications.

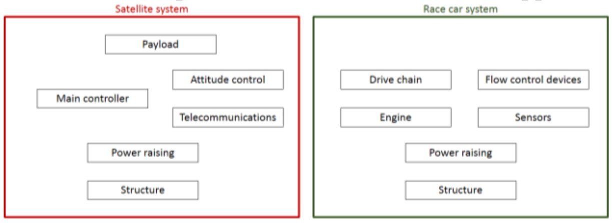

Figure 2 – Block diagrams of two example systems, a satellite and a race car. Every subsystem can be further decomposed into smaller elements, and made stand-alone if its interfaces to other subsystems are defined.

B. Nature of large projects

A "large project", in the scope of this paper, is an activity involving a number of people from multiple backgrounds working together over a time period longer than one academic year to design and build a final product. Here, the final product is a system, which can be decomposed into smaller subsystems that deliver one or more of its top-level functions. Block diagrams of two examples systems, a satellite and a race car, are shown in Figure 2. Example subsystems are a structure that houses the components of any physical system. Additionally, a race car requires an engine and a drive chain in order to propel itself, and a satellite requires a dedicated system to control its attitude (orientation in three dimensions). Both systems require a power raising and management system, which will deliver electricity to all the actuators and sensors on board. It should be clear that even such vastly different systems can be decomposed into smaller functional elements, or subsystems.

Every subsystem could be further decomposed into its own subsystems. For example, a drive chain in a car will consist of gearboxes, wheels, clutches etc., each of which can be an arbitrarily complicated piece of hardware and software. Similarly, the power raising system on a satellite will typically consist of solar panels, which generate electricity whilst the satellite is in sunlight, a battery that powers the spacecraft whilst flying through Earth's shadow (i.e. in eclipse), and power conditioning elements.

C. Embedding work on large projects in student curriculum

Bearing in mind the limited time that students can spend on a project as part of their degree programme, it would be unreasonable to task a single group of students with design, manufacture and testing of a large, complex system because this would exceed their work load capacity. However, the observation that any, arbitrarily large and complex system can be decomposed into smaller subsystems, can be leveraged here to involve the students in a large project.

It is up to the project managers and supervisors to decompose the system at hand, say a satellite, into subsystems that can be designed and built by students in the time they have available. Different subsystems can be built by students as their IPs or GDPs, for example. If it is impossible to find subsystems that can be finished in one project, a number of consecutive internships, IPs and GDPs can be used to work on the same subsystem. For example, design, manufacture, and testing could be conducted by different groups of students. However, this is not recommended in order to ensure continuity of knowledge about the subsystem.

Successful design of the subsystems requires the interfaces of the subsystem at hand to be defined. These interfaces are, for example, the physical envelope of the printed circuit boards (PCBs), location and type of connections to other subsystems, top-level functionality, and data bus to use.

The process of decomposing the system into subsystems and formulating the work breakdown structure (WBS), consisting of work packages that describe the tasks required to complete the overall system, and their schedule, should be performed by the project leaders. Project leaders are in the best position to conceive the scope of the project in its entirety and, thus, judge its divisibility and schedule. Project leaders should ideally be involved in the programme since its inception until the final delivery, because they will possess unique knowledge about the entire system. Having access to this knowledgebase throughout the entire programme is of key importance when subsystems are added, removed or redesigned.

III. UoS³ Project Description

The idea to build a cubesat at the University of Southampton became concrete in early 2014 and the project's progress is documented in [4]. In this section, the project is described in more detail. Cubesats are small satellites that adhere to a common design standard which enables the setup of affordable satellite projects. Today, cubesats are well established in the commercial space sector [5] and begin to play a larger role in space exploration [6].

A. *The UoS³ Mission*

The objectives of the UoS³ are threefold:

1. The first satellite designed and manufactured at the University of Southampton with the effect of bolstering the University's reputation in astronautical research and student education. An on-board camera for picture acquisition from orbit will help to utilize UoS³ for publicity purposes.

2. Delivery of experimental orbit decay data to support space object re-entry predictions for application in space debris research (for additional information see [7]).

3. Educational tool for students from various backgrounds to provide them with the opportunity of working on a complex project and to apply their skills in a practical way.

A low altitude operational orbit is necessary to perform the objectives outlined above. Furthermore, a low Earth orbit ensures that the satellite will not remain in orbit for longer than 25 years after the end of its mission, which is recommended to limit the number of debris on-orbit. In fact, in the baseline mission scenario, which foresees a deployment from the International Space Station, the orbital lifetime of the UoS³ would range between 6-18 months. After this period, the UoS³ will re-enter and burn up in Earth's atmosphere.

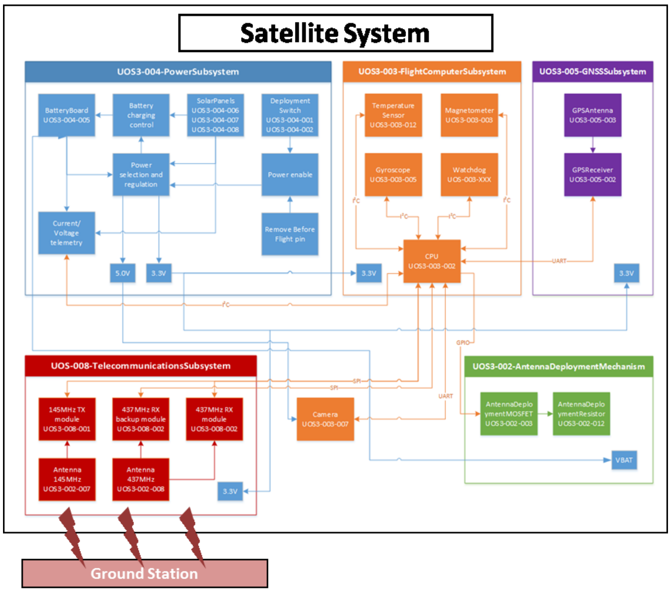

Figure 3 - Simple UoS3 system block diagram including satellite system and ground station.

B. *The UoS³ system architecture*

Error! Reference source not found. visualises the system architecture of UoS³. The satellite system consists of several subsystems that are connected via power and data interfaces. Furthermore, all subsystems are connected mechanically via the structure and need to share the same mechanical interfaces for that reason. A ground station is used to create a radio link with the telecommunication subsystem of the satellite, in order to receive data from and send commands to the satellite. The ground station forms an essential part of the satellite system, and is, thus, deemed one of the subsystems of UoS³.

Dividing the overall system into subsystems allows allocation of subsystem projects to individual student teams.

C. *Work Breakdown Structure Definition*

The work breakdown structure describes the project schedule and its individual work packages and tasks. To facilitate project scheduling, a Gantt chart was drafted. This methodology also helps to identify dependencies between work packages which, in turn, helps to identify the "critical path". In other words, it shows which tasks need to necessarily be finished to enable work on a subsequent task. The individual work packages were populated with specific tasks while keeping in mind the time and workload limitations of student involvement formats (such as GDPs or IPs).

D. *Managing the ongoing project*

When new students start to work on their tasks, the first priority is to ensure that they understand the overall system and how their task applies to it, thus, allowing them to understand the implications of their design choices. For UoS[3], this meant having introductory meetings at the start of each subproject and sharing contact information to potential interface partners. Ideally, these initial meetings include all potential interface partners and aim to initiate communication between the interface stakeholders and to share expert advice on interface requirements.

While the project is running, it is paramount that all members have access to the same information and share information. For this purpose, a Microsoft SharePoint server was setup on which all contact information and project documentation is stored. All project members were given access to this database allowing them to research interface requirements and design choice consequences on their own, thus, easing project leader workload.

Meetings, held throughout student activity duration, facilitated progress revision and project schedule compliance.

How this worked in practice can be shown by example of the power subsystem module.

IV. Example of Power Subsystem

A GDP team from the Department of Electronics and Computer Science (ECS) was tasked to design and prototype the power subsystem for the satellite following initial work from an intern. For this exercise, the UoS[3] programme leaders played the part of the "customer". The initial specification for the system was communicated to the group. An important first part of this project, which was only partly anticipated, was the need to negotiate and define the specifications with the customer. The group were given access to the SharePoint site, meaning that they could view and create specification documents. Owing to the short duration of the GDP (just over three months, and spanning a 3-week vacation) the team had to "hit the ground running", negotiating and defining specifications as the design progressed. Pressing external factors proved very important, and influential to the project: the long lead times on the photovoltaic (PV) modules and batteries meant that early design decisions had to be made and those components ordered, but with the aim of being as flexible as possible.

A notable example was the requirement for co-design of the power subsystem and the photovoltaic modules. Examples of the decisions that had to be made included the connection of the cells (i.e. series or parallel); in order to maximise the flexibility of the design, it was decided that each PV cell should be independently connected. Additionally, early discussions had suggested that due to lack of space on one panel (which also housed the camera), a single PV cell would be accommodated. This had major implications for the early design of the power conditioning circuit, which had been put together with the assumption that there would be two cells on each panel. The design of the panel was revised so that two smaller cells could be included. Similarly, it was decided that after early evaluation of the power conversion circuitry, that a temperature sensor would not be required on the photovoltaic modules as a true maximum power-point tracking integrated circuit (IC) was available. However, this decision caused later problems for the group, when it was discovered that the chosen device was incapable of directly charging the lithium chemistry cells chosen. This forced the use of an additional dedicated lithium battery charger IC, but interfacing issues between this and the maximum power-point tracking (MPP) IC meant that voltage collapse between them became a real issue. Had a temperature sensor been integrated into the panels, it would have given the team greater flexibility to choose alternatives to the MPP IC (based on temperature rather than continuous perturb-and-observe). This illustrates an issue with running such a complex project with a short timescale. In some ways, this is more demanding than typical industry projects, which may have the luxury of being able to run over a longer period and to accommodate the required lead times.

The team produced a test PCB, which incorporated all of the newly-designed modules (e.g. over-current protection, under-voltage protection, current measurement, voltage conversion). This allowed early functional verification, and allowed some problems to be ironed out early in the project. Following this, the team entered a PCB foot printing phase, where they worked with the approximate required area of each module, ensuring that the final designed board would be able to deliver the functionality required with the module designs developed, given its constrained dimensions. This flagged up the fact that the initial plan to use six separate MPP ICs would not be feasible, so an alternative topology was designed where only two were required. Again this illustrates how the early selection of a certain topology constrained the later design stages. Following foot printing, the final PCB was laid out. Even as late as this stage, there was an element of negotiation with the customers, as the mechanical design of the overall satellite was refined.

The final board was produced, assembled, and performed as intended, apart from a couple of minor issues which were fixed externally to the board. The successful execution of this project was largely due to excellent motivation of the group, as well as them taking the initiative to define their own interface/specification documents where details were lacking. Communications with the customer were also highly important, and their responsive nature ensured that this was not a cause of slippage in the project. The highly time-constrained nature of the task meant that the GDP team had to make critical design decisions earlier than would have been ideal, but nonetheless a fully-featured and thoroughly-tested power supply PCB was produced.

V. Recommendations

Before UoS[3], no precedence information on how to set up a student focused, multidisciplinary project within the University of Southampton existed. Inevitably, the project encountered numerous challenges because the educational environment was not designed with such a large project in mind. Recommendations as how to increase amenability for UoS^3-type projects within the University and what project leaders need to be aware of are presented below.

A. For institutions

At the UoS, the organisation of project modules has been amenable to the demands of large student-led projects that encompass multiple sub-projects, across multiple disciplines and across multiple years, as demonstrated by the success of the UoS^3 project. In particular, the UoS^3 project has leveraged GDP and other student project modules, such as IPs or internships. However, the UoS^3 project has highlighted a number of opportunities for making the organisation of these modules even more amenable to large student-led projects.

- *Ensure that modules are sufficiently large*. More specifically, modules should allow a sufficient number of person-hours to be devoted to each project work package. This avoids the requirement to decompose the overall project into a large number of very small, and inefficient sub-projects. Ideally, modules should comprise group working between four to six students and should carry around 22.5 European Credit Transfer and Accumulation System (ECTS) points, which corresponds to 450 hours of effort from each student. IPs carrying around 22.5 ECTS points can also be useful for some particular sub-projects that are relatively-small and self-contained.
- *Run project modules throughout the year*. This allows each sub-project to begin soon after the completion of the previous sub-project, maintaining momentum and continuity for the overall project. While GDPs span both semesters in the Faculty of Engineering and Environment (FEE), they run only during Semester I in ECS. This has broken the continuity of the electronics development for the UoS^3 project during Semester II. Undergraduate programmes do not typically run over the summer and MSc Summer Projects are typically IPs. If summer group project are required, then this can be arranged as group internships for undergraduate students, if a supporting budget exists. Unifying the project module duration across faculties would furthermore facilitate interdisciplinary GDPs as outlined below.
- *Position project modules towards the end of degree programmes*. In this way, all of the skills, experience, knowledge and understanding that the students develop during their degree programmes can be leveraged towards the overall project. Note, however, that if project modules are positioned at the very end of degree programmes, then the students will typically leave the university before follow-on projects have started, damaging continuity. This is a problem for MSc Summer Projects and GDPs that span both semesters of the final year.
- *Offer multidisciplinary group project modules*. This enables the composition of the group to be tailored to the specific requirements of the sub-project. ECS GDPs enable collaboration between Electrical Engineers, Electronic Engineers and Computer Scientists. Meanwhile, FEE GDPs enable collaboration between Mechanical Engineers and Aerospace Engineers, for example. However, the UoS does not offer a GDP module that spans both ECS and FEE. Other inter GDP collaborations that have been fruitful for the UoS^3 have been with the Physics faculty for feasibility analysis and the Winchester School of Arts for publicity and non-technical documentation.
- *Align assessment with delivering for the overall project*. In order to maximise the value of the students' work towards the overall project, the assessment scheme must incentivise the documentation and packaging of all source and designs for all deliverables. The assessment should reward students that have maximised value for the customer of their project, namely the organisers of the overall project.

B. Project Leader Recommendations

Initiating, leading and managing the UoS^3 project has been a learning experience not only for the involved students, but for the project leaders as well. Below are some recommendations that will help increase effectiveness of leadership:

Even though the overall project may be decomposed into sub-projects, this does not remove the need for communication and common design standards between subsystems. Early and specific definition of those interfaces and resources that are necessarily used by many sub-projects will enhance the efficiency of the sub-project teams and will speed up overall system development. A specific example for the UoS^3 is the PC-104 pin assignment for the system bus which needs to be accessed by all electronic subsystems. A pin assignment document did not exist at the start of the project and needed to be derived as the project moved along taking away time of core development work.

The challenge in defining common interfaces is trading off provision of a clear interface definition at an early time, and making a well-informed design choice. Taking up the example of the pin assignment: The knowledge of pin number and location evolved as the overall system matured. Allocating the wrong pins for a specific function early will hurt project efficiency later as those pins need to be reassigned to accommodate evolving needs. A good compromise is to generate definition documents early under the common understanding that it is a document in development (a "living" document). Proposed design choices may be distinguished from fixed design choices by adding the note (To be confirmed – TBC).

From the very beginning of the UoS^3 project, the project leaders maintained a detailed Computer Aided Design (CAD) model of the cubesat and this living document has proven itself invaluable throughout the development process. It helped define available volumes for subsystems, interfaces, facilitated the generation of technical drawings and production of 3D printed components. It is highly recommended to maintain such a file for similar projects.

Another trade-off is time spent on progressing module development and documentation. Documentation is necessary to facilitate later subsystem operations and to transfer knowledge to the next team. However, documentation requirements can be excessive and can take too much time away from actual project work. Within the realm of the UoS^3 a conscious effort was made to keep requirements on documentation simple and, instead, rely on self-responsible report work by the subproject teams. Similarly to documentation, testing of hardware and functionality is an area with significant trade off potential. Testing is required to ensure proper functionality and quality of the product and should be done extensively and thoroughly. However, testing takes time away from project progression and can damage the hardware. A mindful approach to the subject of testing facilitates a successful, customized approach to the specific subsystem at hand.

The meeting schedule was found to be suboptimal in the beginning of UoS^3. To ensure good communication between the different module teams, a big meeting with all involved parties was scheduled every two weeks. However, different teams operated on different schedules resulting in varying work progression speed. The growing progression discrepancy resulted in dissonance in available and requested information from the teams. One group needed more detailed information faster than the other team could provide. Consequently, it was realized that a big bi-weekly meeting schedule did not serve a good purpose and was abandoned in favour of direct email communication. A better approach is to have an initial big meeting, another one after 2 months and further meetings upon request. It was observed that students would initiate physical meetings whenever this was deemed a more efficient approach than email correspondence to solve problems.

A similar approach was adopted for meetings of subproject teams and project leadership. After initial weekly meetings, it became apparent that this schedule was not effective. A more efficient approach was found by setting up 2-3 weekly meetings at the beginning of the subproject work and subsequent meetings upon request. This approach encourages self-responsible work of student teams and conveyed to them the feeling of design authority within their subsystem after proper introduction to the mission and overall system. The approach requires project leaders to trust in the skills of the student team and resulted in better team motivation.

VI. Conclusions

This paper presents how large, student-focused projects can be implemented in a university environment. The appeal of implementing these kinds of projects lies in their similarity to large scale projects in industry or academia and it allows involved students to appreciate this environment and learn how to apply themselves in it. Challenges are the separation of tasks such that they are suitable for a diverse range of students and formats of student engagement such as group projects or individual projects. The interconnected and multidisciplinary nature of these projects demands special attention on efficient communication between groups so that common interface requirements can be met. The authors expand on the generic discussion about these types of projects by providing specific examples from the ongoing and, thus far, successful University of Southampton Small Satellite (UoS^3) project. The UoS^3 project is described from a managerial point of view as well as its goals for student education, university publicity and its scientific contribution to space object re-entry prediction. Furthermore, recommendations and lessons learnt are provided and these are applicable to similar projects that share the characteristics of student focus, interdisciplinarity and being embedded in a diverse environment.

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