Photonic systems integration for postgraduate students in the Centre for Doctoral Training in Applied Photonics

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ABSTRACT

Photonics is a broad research area that underpins many different areas of science and engineering. The future of the United Kingdom (UK) photonics industry depends on training the next generation of photonic engineers and scientists to lead research and innovation across a wide range of industrial applications. In 2018, the UK government invested £446 million through the Engineering and Physical Sciences Research Council (EPSRC) in 75 Centres for Doctoral Training (CDT), of which one is focused on industry inspired Photonics, Imaging, Sensing and Analysis (CDT in Applied Photonics). A key element of these CDTs is the increase in formal taught components to enhance technical interdisciplinary knowledge and broaden the postgraduate research student's skills and knowledge base.

This paper presents the development, implementation and evaluation of a new taught course for the CDT in Applied Photonics to broaden the skills of photonics researchers to integrate analogue and programmable digital electronics in to photonic systems. The course builds fundamental theoretical knowledge in digital and analogue electronics and provides practical laboratories using accessible programmable digital hardware. It also provides the opportunity to apply this knowledge through a practical group project developing an integrated photonic system, culminating in an assessed practical presentation and demonstration of the working systems. The course uses National Instrument's myRIO, designed to allow access to industry-grade embedded system technology combining LabVIEW's graphical programming environment with a processor, reconfigurable field programmable gate array (FPGA) and convenient hardware interfaces. This facilitates access to the technology for postgraduate students from a range of undergraduate backgrounds, yet also provides a pathway to develop similar technology used in industrial photonic research.

Keywords: postgraduate training, photonics, systems engineering, Centre for Doctoral Training, myRIO

1 INTRODUCTION

Photonics is an enabling technology underpinning modern industries such as telecommunications, advanced manufacturing, healthcare, energy and quantum technologies. Unlike other technologies, such as electronics, photonics is harder to define precisely but encompasses devices and processes that either generate, detect, guide or manipulate light. As such, photonics impacts a vast array of different industries, products and devices and this diversity is a key strength of the global photonics industry. In 2022, it is estimated that approximately 3% (US$2.5 trillion) of the global economy can be attributed to photonics-enabled businesses and services [1]. The photonics industry has maintained solid growth (4-6%) and employs more than 1.2 million people globally. Asia dominates the global market followed by North America and then Europe. In the United Kingdom (UK), the photonics industry contributes £14.5 billion to the annual economy, employing ~77,000 people and is the 5th most productive manufacturing industry in the UK [2,3]. It is predicted that photonics will play a leading role in the growth of the UK economy and as an enabling technology will be instrumental in advanced manufacturing, digital connectivity, future healthcare, quantum technologies and achieving net zero; thus, the UK photonics industry is expected to grow to £50 billion adding an additional 150,000 jobs by 2035 [3]. In order to achieve this growth, the industry requires skilled workers with knowledge of photonics at all levels, from technicians, engineers,

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Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023,
edited by David J. Hagan, Mike McKee, Proc. of SPIE Vol. 12723, 127231O

scientists and future research leaders. UK universities must ensure photonics is included in science and engineering degrees at both undergraduate and postgraduate level. In the UK, universities are the primary drivers of photonics research where fundamental research and curiosity has led to many innovations in photonics. While advancing the fundamental research it is also important that universities work closely with industry to reduce the time from research discoveries to the application, engineering and commercial development of new technologies. In the UK, Scotland has a strong track record of achieving this. This originates from a regional cluster of historic universities, such as the Universities of St Andrews, Glasgow, Aberdeen and Edinburgh founded in 1413, 1451, 1495 and 1583 respectively [4,5,6,7], and to support the industrial revolution technical colleges were formed, such as Anderson's Institute, founded in 1796, which is now the University of Strathclyde [8] and Edinburgh School of Arts, founded in 1821, which is now Heriot-Watt University [9]. These universities have provided a strong foundation of physics and engineering from which modern industrial optics and photonics companies have emerged. One of the first being Barr & Stroud Ltd, formed in the late 19th century; they were an optical engineering firm based in Glasgow producing optical range finders and submarine periscope range finders for the UK Royal Navy [10]. In 1977 Barr & Stroud were purchased by the Pilkington group and in 2001 became part of Thales UK who continue to develop lasers and photonic systems in Glasgow. The Universities of St Andrews, Glasgow, Edinburgh, Strathclyde and Heriot-Watt have created many spin-out companies in photonics, such as: Edinburgh Instruments, Microlase Optical Systems (now Coherent Scotland), Cascade Technologies (now Emerson), PowerPhotonic, Helia Photonics, Chromacity, PhotoSynergy, Vector Photonics and PureLiFi to name a few. In 2015-2018, these universities created an innovative bridging partnership with Stanford University, CA, USA and local industries to help sustain and develop entrepreneurial activity in photonics [11]. Additionally, the University of Strathclyde hosts the UK's first Fraunhofer Research Centre – Fraunhofer Centre for Applied Photonics, supporting the transition of research to industry [12].

In Scotland, the photonics industry has identified a shortage of skills as a barrier to growth. To alleviate this, Scotland's research-intensive universities have worked collaboratively and with industry partners to train the next generation of photonics researchers to support growth in the Scottish and UK photonics industry. "Demand for higher level qualifications is growing strongly, and today's PhD students are often tomorrow's research leaders, entrepreneurs and industrial researchers. [13]" This paper will briefly outline the landscape of postgraduate research training in the UK, focusing on Centres for Doctoral Training (CDT). The Centre for Doctoral Training in Applied Photonics will be described in more detail investigating its structure, operating model and industrial partnerships. With this background the paper will focus on the development and implementation of a new taught course for the CDT in Applied Photonics. The delivery of this practical course during the period of disruption and UK lockdowns due to COVID-19 will also be discussed and how the challenges of remote learning and on campus access limitations were overcome.

2 BACKGROUND

2.1 UK Research Training

The UK government is key to funding research and fostering innovation to support and grow the UK economy. In 2018, a new non-departmental public body was launched: UK Research and Innovation (UKRI) [14]. This body is sponsored by the UK government's Department for Science, Innovation and Technology. The UKRI brings together seven disciplinary research councils, see Table 1, Research England and Innovate UK and in 2021/22 had a budget of £7.9 billion [15]. This budget is split to fund many different research activities such as: research grants; skills and training; infrastructure; international partnerships; and national research institutes and catapults.

The skills and training budget of £880 million supports the training of around 30,000 postgraduate students including Doctor of Philosophy (PhD) and Engineering Doctorate (EngD) students. The EngD research degree was first introduced in 1992 to recognize PhD-level research undertaken in close partnership with an industrial sponsor where students also undertook taught technical and business courses [16]. The research can be much more applied and at a higher technology readiness level compared to PhD research. Both degrees must demonstrate the generation of new knowledge but an EngD can demonstrate a contribution to knowledge through engineering advancements.

Table 1. UK Research Councils and Budgets, 2021-2022.

Research Council	**Budget 2021-22 (£ million)**
Arts & Humanities Research Council	£61
Biotechnology and Biological Sciences Research Council	£306
Economic and Social Research Council	£114
Engineering and Physical Sciences Research Council	£617
Natural Environment Research Council	£289
Medical Research Council	£563
Science & Technology Facilities Council	£485

Photonics research and training primarily comes under the remit of the Engineering and Physical Sciences Research Council (EPSRC), the largest of the research councils. The EPSRC supports research training through 3 funding mechanisms: Doctoral Training Partnerships, DTP (~45%); Centres for Doctoral Training, CDTs (~45%) and Industrial Cooperative Awards in Science & Technology, iCASE (~10%). Doctoral Training Partnerships are block grants allocated to universities to provide flexible PhD support. Centres for Doctoral Training are focused towards a specific research area where there is strategic need to train students in a cohort-based fashion, typical 8-12 students per annum. Finally, Industrial CASE awards are provided to industry who co-fund EPSRC research grants and are highly focused on meeting the needs of industry. The company chooses the project and which university to partner with. PhD and EngD studentships funded through CDTs or iCASE awards are 4 years in duration, whereas PhDs funded through DTPs can be between 3-4 years duration. This paper will focus on the training of cohorts of students within CDTs, specifically using the CDT in Applied Photonics as case study and example.

2.2 Centre for Doctoral Training in Applied Photonics

In 2018, EPSRC launched a call for proposals for CDTs aligning to EPSRCs 30 priority areas selected through consultation with researchers and users. Examples of priority areas include: Enabling Intelligence; Next-Generation Medical Imaging; Quantum Technologies; and New Science and Technology for Sensing, Imaging and Analysis. Commencing on 1st October 2019, the Universities of Heriot-Watt (lead – Prof. Derryck Reid), Strathclyde, St Andrews, Glasgow, Edinburgh and Dundee collaborated as part of the of the EPSRC Centre for Doctoral Training in Industry-Inspired Photonic Imaging, Sensing and Analysis, (EPSRC Grant Number: EP/S022821/1). This award was the fifth consecutively won award from competitive funding calls for postgraduate training, making the CDT the longest running Centre training postgraduate students in photonics. The Engineering Doctorate Centre: Photonics Engineering was first established in 2001 by Prof. Duncan Hand and Prof. Julian D.C. Jones and brought together strong and complementary photonics research across three universities: Heriot-Watt, St Andrews and Strathclyde to meet the needs of industry and established an Engineering Doctorate degree in photonics (EPSRC Grant Number: GR/R99744/01). The Centre has grown and evolved to the current day CDT in Industry-Inspired Photonic Imaging, Sensing and Analysis – generally referred to as the CDT in Applied Photonics. This CDT aims to train postgraduate researchers in the concepts and methodologies of photonic sensing, imaging and analysis who undertake specialized doctoral research collaboratively with industry. Additionally, the aim of the CDT is to produce future industry research leaders by complementing the development of technically excellent researchers with entrepreneurship, business, communications and productivity skills. The CDT in Applied Photonics is co-funded by EPSRC (£5.1 million), industry (£2.5 million) and university partners (£0.9 million) to train 55 doctoral students over the period of October 2019-March 2028. The CDT will train 5 cohorts of students with ~11 students per intake in years 2019-2023. The four-year CDT research training model is shown graphically in Figure 1 and comprises of 9 months of taught technical courses (120 credits) shown in yellow, followed by a 39-month research phase, shown in orange, with additional taught courses in business (60 credits – purple) and non-credit bearing professional skills workshops (pink & blue). The taught technical courses are delivered in two academic semesters. The first semester, September to December, consists predominantly of photonics courses and is delivered at St Andrews University. Typically, most students stay in university halls of residence for this semester and this helps create a strong bond within the cohort. The second semester, January to May, is made up of core and optional classes provided by the Universities of Heriot-Watt, Edinburgh, Glasgow and Strathclyde. For the research phase, in addition to the original EngD degree, the current CDT recognizes industry's interest in more fundamental research and includes an industry sponsored PhD degree. Typically, EngD research is conducted at the site of the industry partner whereas PhD research is conducted within one of the university partners. All CDT doctoral students are jointly supervised by an academic supervisor and an industry supervisor. To successfully complete the programme, all students must gain 180 taught credits by passing all taught courses (minimum pass mark 50%) and successfully pass a viva voce examination of their EngD or PhD thesis. To ensure students achieve this, there is a formal progression monitoring system of quarterly review meetings between academic and industry partners and an annual appraisal of the student by an independent academic i.e. who is not part of the supervisory team.

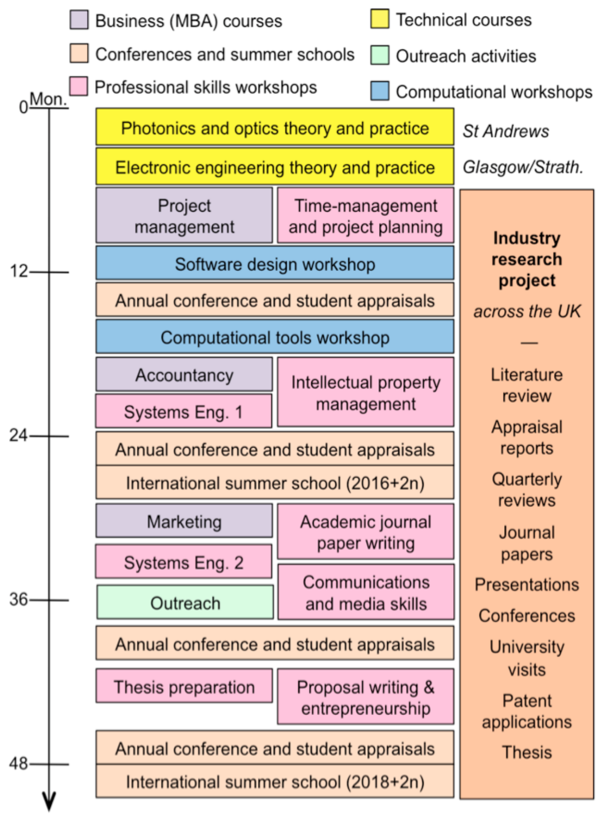


Figure 1. Diagram of 4-year postgraduate training programme for the CDT in Applied Photonics.

3 COURSE DEVELOPMENT

3.1 Objectives

In comparison to standard PhD studentships in the UK, CDTs have a greater emphasis on providing more formal taught training and building cohorts of researchers. The CDT in Applied Photonic was designed to not only equip students with a strong understanding of the core areas of photonics but also to broaden their skills. As part of the CDT re-bid process, there was an increased focus on the breadth of formal training and a strong desire to increase our training provision in the area of integrative technologies. As our doctoral students are predominantly based in industry developing the next generation of photonic systems, success typically requires integration of software, electronics, instrumentation and control systems. To help equip future cohorts of students, a new purpose-built 20-credit taught course, EE979 Systems Engineering Project, was developed in the Department of Electronic and Electrical Engineering at the University of Strathclyde. The aim of the course was to provide fundamental knowledge of analogue electronics and programmable digital hardware with the opportunity to apply this knowledge to integrate hardware and software for photonics orientated applications. The primary learning outcomes (LO) were:

- LO 1: Acquire and apply analytical skills to design and analyse analogue circuits.
- LO 2: Understand underlying concepts of amplifier circuits and the principles of feedback to control gain and stabilise circuit operation.
- LO 3: Use digital hardware comprising of programmable hardware (FPGA) and processor, critically analyse specifications, design software and hardware to interface with digital and analogue circuits.
- LO 4: Critically evaluate an engineering problem and to break down the problem to define a project plan in order to design, build and implement an engineering solution within a group environment and recognise the roles of project management, monitoring and reporting.

Photonics is an enabling technology and as a result, the CDT partners with companies from many different industries such as laser manufacturers, healthcare, optical communications and defence. The scope of research projects available within the CDT is also broad and varies year on year depending on the needs of industry. Projects might research novel laser sources, optical metrology systems, laser-based sensing and instrumentation or the application of machine learning to imaging systems. Therefore, the CDT attracts students from a range of science and engineering disciplines. Our students include physicists, electronic and electrical engineers, computer scientists, mechanical engineers, chemists and optometrists. Therefore, it was crucial that the design of the Systems Engineering Project course made it accessible to students from a variety of backgrounds and did not assume prior knowledge of electronics or software. We wanted to ensure students could implement solutions to photonics challenges and explore industry relevant technologies but were also conscious of the steep learning curve required to access technologies such as FPGAs.

3.2 Course Design

The Systems Engineering Project course is structured to deliver the formal taught aspect through lectures, tutorials and teaching laboratories before the students undertake an open-ended group project. As a 20-credit course, this is equivalent to 200 hours of student effort and is broken down as lectures (20 hrs), tutorials (5 hrs), laboratories (15 hrs), assignments (40 hrs) and private study (120 hrs). The course is assessed through three components: class test (30%), individual laboratory report (15%) and group project (55%).

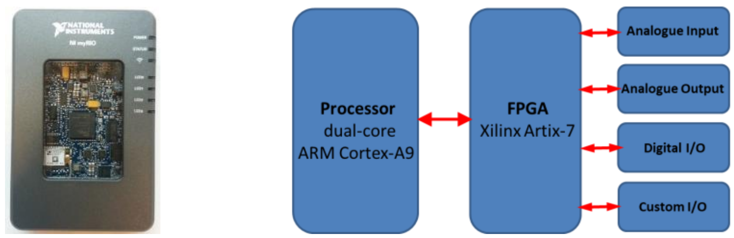
The analogue electronics content of the course introduces fundamental circuit theories and develops practical circuit analysis techniques for DC and AC circuits. Amplifier theory, equivalent circuit models and the application of negative feedback to design practical circuits using operational amplifiers is covered. Lectures also cover bipolar transistor operation and transistor amplifier biasing. Finally, a case study based on 2-D tomographic imaging of CO_2 concentration and temperature due to combustion processes in an aero-engine exhaust plume using tunable diode laser spectroscopy. This highlights optical design, optical power budgets, electronics for photodetection and data acquisition requirements.

The CDT requests feedback from all students on all taught modules. This is presented at the CDT Programme Committee meetings (January and June) and is fed back via each University's CDT Co-ordinator to the academic staff delivering the taught programmes. Therefore, a continuous improvement model is implemented.

3.3 Taught Laboratories

The teaching laboratories focus on the boundary of hardware and software. The laboratories have adopted National Instruments latest student orientated product myRIO [17]. This is an embedded hardware device comprising of a Xilinx Zynq-7010 all-programmable system on a chip with additional electronics and communications, such as built-in 3-axis accelerometers, USB and WiFi interfaces, display LEDs and a wide range of possible input and output configurations, see

Figure 2. Overall this hardware provides a processor capable of running a real-time operating system and a field programmable gate array (FPGA) which can all be programmed using LabVIEW – a graphical programming software. This hardware and software combination, known as LabVIEW reconfigurable input/output (RIO) architecture is also used in a range of National Instruments products that are targeted to industry. Therefore, the programming skills and techniques learnt are directly relevant to systems that may be in use in the students' sponsoring companies. Another benefit of using this system is that the students can easily access the power and flexibility of implementing signal processing in hardware using the FPGA through high-level programming functions. This allows the students to focus on the overall functionality rather than developing advanced programming skills.



(a) (b)

Figure 2. (a) Photograph of myRIO device and (b) simplified schematic of myRIO architecture.

Students complete online training provided by National Instruments, LabVIEW Core 1 [18], as an introduction to the graphical programming language LabVIEW. The graphical nature of LabVIEW programming allows students with little, or no, prior programming experience to build applications to control the myRIO and to also provide a graphical user interface. The students are taught key programming concepts such as loops (for & while loops), sequential & parallel programming and LabVIEW structures such as case and sequence structures. Students are also introduced to different architectures to build their code, such as state machine architecture. Students put this in to practice through taught laboratories investigating aspects of the myRIO such as how to access and use the built-in accelerometers, LEDs and user switch. Students investigate in more detail the electronics interface between digital hardware and external circuits by building simple external LED circuits and studying the behavior of current sinking or sourcing configurations and controlling LEDs through pulse width modulation. Simple FPGA code is developed to highlight the potential speed benefits of performing processes in digital hardware such as pulse width modulation compared to software. To give purpose and relevance to the taught laboratories, the students also work on a mini-project to develop a simple temperature controller to cool a Peltier element. Students investigate bipolar transistor behaviour and the application of negative feedback using operational amplifiers to achieve a linear voltage controlled current source to drive the Peltier element. Students develop their own proportional and integral feedback control and investigate tuning the proportional and integral gains to achieve optimum temperature stabilisation. Figure 3 shows a system diagram of what the students must build in hardware and software in the myRIO.

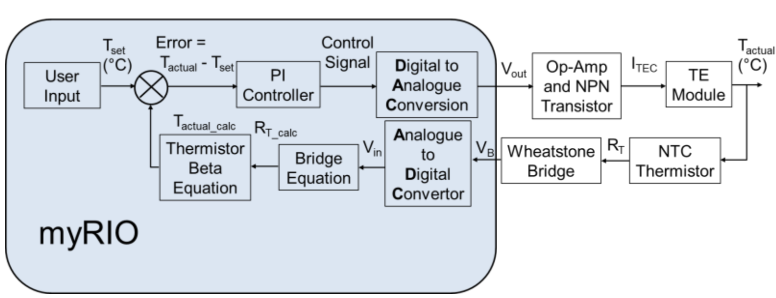


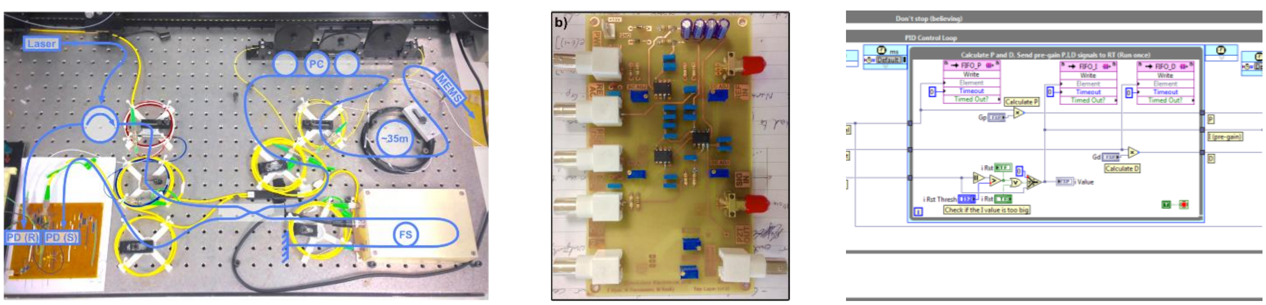
Figure 3. System diagram of mini-project Peltier temperature controller.

Students submit a short, 2-page, individual laboratory report in the style of a journal paper, i.e. using a journal template, detailing their achievements in the mini-project. This assessment aims to help students develop their technical writing skills and awareness of preparing their work for publication.

3.4 Group Project

The final integration of software, programmable digital hardware and analogue electronics is brought together in the systems engineering group project. Students typically work in groups of three or four to tackle an open-ended project that requires integration of electronics and photonics. Each group is assigned an academic mentor who proposed the project but it is made clear that the mentor is not the project leader and is not there to solve technical problems. The mentor provides a top-level aim and some key objectives. The group undertake some initial research, develop the project objectives in more details and meet with the mentor to refine these. Each group initially submits a Preliminary Design Specification detailing relevant background and context to the project, the agreed objectives utilising the SMART concept (specific, measurable, achievable, relevant, time-bound), a project management plan and Gantt chart, a technical risk analysis and a safety risk assessment of the project. The group project culminates in a practical demonstration of the working system, along with an oral presentation and formal technical report. This is an excellent opportunity for students to develop their programming and electronic skills further, in addition to developing valuable problem solving and trouble-shooting skills.

Group project topics have included: quadrature phase-locking of an optical fibre Mach-Zehnder interferometer; laser frequency stabilization using an FPGA – locking a laser to a confocal Fabry-Pérot cavity; smart single pixel imaging – integration of two-axis MEMS scanning micromirrors; free space optical communications with a moving target; and interrogation of an electrically isolated MEMS device for photoacoustic spectroscopy. An example of the optical system, corresponding electronics and LabVIEW code for the photoacoustic project are shown in Figure 4.



(a) (b) (c)

Figure 4. (a) Photograph of optical fibre Michelson interferometer with MEMS mirror, (b) photograph of electronic circuit for photodetectors and (c) snapshot of LabVIEW FPGA code [19].

4 COURSE DELIVERY DURING COVID-19

The course contains a significant proportion of practical work including taught myRIO laboratories and the group project. On the 23rd March 2020, the UK government issued a stay-at-home order and the country entered the first lockdown. As a result, all access to the university was terminated and this primarily impacted completion of practical work for the group project. For this cohort the activity pivoted to concentrate more on a proposed design solution rather than construction of a practical system. For the following academic year, 2020/21 the course was timetabled to run in the second semester, January to May 2021. Scotland entered a second lockdown on 4th January 2021; therefore, the whole course had to be delivered remotely. To achieve this, all traditional lecture material was reviewed and short, 10 to 15 minutes duration, prerecorded videos were prepared. All video material was hosted on the University of Strathclyde's virtual learning environment; closed captions and a full transcript were provided for each video to meet accessibility requirements.

Two options were considered for the taught laboratories. One option was to eliminate the hardware component and focus purely on LabVIEW software programming. The second option, and the chosen option, was to deliver the labs remotely. To do this kits of electronics components, prototyping boards, Peltier cooling systems with heatsinks and thermistors, and myRIOs were shipped to all students all over the UK and also to one student who was still resident in Italy due to the lockdown. Additional instructional material was prepared and hosted on the virtual learning environment and online laboratory support sessions were facilitated using Zoom, where students could use their cameras to show the circuits they were building or share their screen to show the LabVIEW software they were writing. It took a little time to get the right level of support and online sessions to make this run smoothly. The temperature controller mini-project was also delivered in the same way; however, it was not possible to send external power supplies for the Peltier circuit to the students. To overcome this, all students were provided with a modified USB cable to plug into a phone charger to provide ~1 A of current at 5 V. This was sufficient to power the Peltier circuit and allowed students to design and build a simple temperature controller in their own homes.

To deliver the group project remotely, the overall scope was simplified and students were paired remotely. Group projects topics included: myRIO optical theremin, myRIO photoplethysmogram, myRIO DVD spectrometer and myRIO non-contact door lock using hand gestures. As in previous years, students worked in pairs to research and design the system with guidance from a mentor. However, two sets of identical components were purchased for each project and sent to the pair of students. Therefore, each student in a project pair was able to build and test the design and they were able to work collaboratively but remotely. As in previous years, each group presented and demonstrated their project but in an online session rather than in person.

Finally, the traditional class test was replaced with an online quiz. The quiz consisted of calculation-based questions and some short answer questions and delivered on the University of Strathclyde's virtual learning environment which uses Moodle. To help ensure robust assessment, some questions were drawn from a question bank and calculation-based questions utilised datasets from which the question would pick different values for each student. For more complex calculation-based questions, they were broken down into stages rather than just submitting a final answer. All answers were submitted in the online quiz which would mark the submission. Short descriptive answer questions were marked manually. Additionally, students were required to submit a scanned document of any working. This allowed us to double check the student's work and potentially to award partial marks if necessary. Overall, this was well received by students and has been retained for subsequent years.

5 CONCLUSIONS

In conclusion, the landscape for postgraduate research training in the UK has been introduced. The model to deliver photonics research training in partnership with industry in the Centre for Doctoral Training in Applied Photonics has been detailed. The design of a new taught course to broaden student's knowledge and skills to help integrate photonics with analogue and digital electronic systems has been described. Student feedback has been positive and has highlighted the group work part of the course. Areas where students have highlighted potential change has been to disseminate group project topics earlier in the semester and start the background research and design part of the group project earlier. In the taught laboratories, students work in pairs sharing a myRIO and building analogue electronic circuits; however, feedback in 2022 has suggested each student should have a myRIO. This has not been raised previously but will be considered.

The design and implementation of the course has allowed students from a range of different backgrounds to meet the learning outcomes. Students are equipped with fundamental circuit theories to understand analogue electronic circuits including operational amplifiers and transistors. The decision to use LabVIEW and the myRIO has made hardware and software integration accessible to students with no prior programming experience. The temperature controller mini-project in the taught laboratories and the larger group project have also been successful to assess the students' abilities to critically evaluate a problem, design and build a solution integrating photonics, electronics and software running on the myRIO. The mini-project laboratory report, written in the style of a short journal paper, prepares students for publishing their own research. Working in groups also helps students build a network of peers and cohort integration that helps support students through their EngD or PhD journey. This is further reinforced when students regroup for professional skills courses and the CDT annual conferences throughout their 4 years.

The COVID-19 pandemic led to multiple lockdowns in the UK impacting the delivery of this practical course. We successfully adapted and delivered the full course remotely by sending students myRIOs and packs of electronics to allow them to do the laboratories at home. The group project scopes were reduced and students successfully worked collaboratively and remotely.

Students completing the course have commented on the usefulness of the taught course. "The main objective of my EngD project was to investigate ways in which to make ultrafast lasers more compact, cheaper and less complex. The systems engineering project (using LabVIEW and myRIO) undertaken at the start of my EngD was a great help in familiarising myself with LabVIEW, and as such allowed me to hit the ground running when I started my research at Fraunhofer. [20]"

ACKNOWLEDGMENTS

We would like to thank National Instruments for their valuable support using myRIOs.

This work was funded by the Engineering and Physical Sciences Research Council [grant number EP/S022821/1].

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