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Robotics education: a review of graduate profiles and research pathways

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ABSTRACT: Robotics is a rapidly emerging field of engineering, and many of the Australian universities that offer a Bachelor of Engineering now offer majors in robotics/mechatronics. This article explores and analyses some implications for robotics education, with a focus on graduate attributes and research pathways. The preliminary results of this review suggest that courses in robotics tend to include introductory material from a relatively large number of sub-disciplines, and robotics courses do not ordinarily permit the selection of sub-majors from other inter-related disciplines. This analysis finds that the current structures can in some cases prevent students from traversing pathways towards postgraduate research in their own particular areas of special interest. It is concluded that courses might place greater emphasis on the graduate attributes that are essential to be able to work effectively in cross-discipline teams. It is also concluded that it may be beneficial to undertake further research, which compares the approaches to robotics education taken within Australian universities with the approaches of overseas counterparts.

INTRODUCTION

Robotics is a rapidly expanding field of engineering. If current trends continue, it is estimated that the robotics field will in 2020 employ the same number of people as were employed in the IT sector in 2005 [1]. Such estimates highlight the likely benefits of greater levels of robotics-related research, education and workforce training. Australian universities have a strong track record in robotics research and development, and considerable depth and breadth can be seen among mechatronics/robotics options for undergraduate and postgraduate students.

There exits some debate about the meaning of the word *robot* – the modern sense of the word has been in circulation for nearly a century, and is derived from the Czech word for slavery [2]. Automated production-line machines including robotic arms have been responsible for great improvements in manufacturing productivity since the 1960s [3]. However, many roboticists would not consider the vast majority of these manufacturing machines to be true robots – instead the majority of manufacturing machines may be viewed simply as tools, albeit some with state-machine programming.

An autonomous robot is ordinarily made up of hardware, such as mechanical and electronic components, and software, which amongst other things enables re-programmable functionality including sensing and control. Notwithstanding, commentators tend to agree that it can be difficult to draw a line between robots and certain other machines – for example, microcontrollers, sensors, embedded operating systems and programs are used in many modern electronic devices such as power drills and automated kitchen appliances, yet these devices are not usually thought of as robots. The term *robot* is currently typically associated with sensing mobile devices that are designed to perform actions that are repetitive, dirty or inherently dangerous – well known examples of current robots perform tasks such as vacuum cleaning, bomb-disposal and toxic-waste management.

ROBOTICS COURSES IN AUSTRALIA

A review of Australian university engineering courses indicates that many universities are now offering a Bachelor of Engineering with a major in mechatronics. In some cases, the academics who deliver the courses are members of research groups such as the Australian Research Council Centre of Excellence for Autonomous Systems – some of these are identified in Table 1.

Robotics is also offered by non-university vocational education and training providers such as Technical and Further Education (TAFE) – an example is the Advanced Diploma of Engineering Technology – Robotics and Mechatronics.

Table 1: Engineering courses majoring in mechatronics at Australian universities (non-exhaustive list).

University	Courses/Activities
Australian National University	Bachelor of Engineering (Mechatronic Systems, Australian National University Robotic Systems Group)
Curtin University of Technology	Bachelor of Engineering (Mechatronic Engineering)
Deakin University	Bachelor of Engineering (Mechatronics and Robotics)
Queensland University of Technology	Bachelor of Engineering (Infomechatronics)
University of Melbourne	Bachelor of Engineering (Mechatronics)
Monash University	Bachelor of Engineering (Mechatronics), Robotics, Automation and Manufacturing Research Group
Swinburne University of Technology	Bachelor of Engineering (Robotics and Mechatronics)
Royal Melbourne Institute of Technology	Bachelor of Engineering (Advanced Manufacturing and Mechatronics)
University of New South Wales	Bachelor of Engineering (Mechatronic Engineering), ARC Centre of Excellence for Autonomous Systems
University of Newcastle	Bachelor of Engineering (Mechatronics)
University of Queensland	Bachelor of Engineering (Mechatronics)
University of South Australia	Bachelor of Engineering, Electrical and Mechatronic
University of Sydney	Bachelor of Engineering (Mechatronic), Aerospace, Mechanical and Mechatronic Engineering, ARC Centre of Excellence for Autonomous Systems, Australian Centre for Field Robotics
University of Technology Sydney	Bachelor of Engineering - Mechanical and Mechatronic, Centre for Intelligent Mechatronic Systems, ARC Centre of Excellence for Autonomous Systems
University of Western Australia	Bachelor of Engineering (Mechatronics)
University of Wollongong	Bachelor of Engineering (Mechatronic Engineering)

ESTIMATING FUTURE DEMANDS OF ROBOTICS GRADUATES

Robotics is an inherently inter-disciplinary field, covering many aspects of mechanical, electronic and computer systems engineering. To estimate the likely future demands of a robotics graduate, it may be helpful to first gain at least a rudimentary understanding of trends within the field. Table 2 briefly sets out one approach for estimating future demands, by considering some actions that the current generation of robots can and cannot do autonomously.

Table 2: Estimating future demands of graduates by considering the capabilities of autonomous robots.

Autonomous robots are currently able to:	Autonomous robots are NOT currently able to:
Perform repetitive physical tasks with consistent quality, speed and accuracy. Operate in dangerous/hostile environments. Navigate, drive, walk, swim, float, fly, listen, watch, smell, manipulate (touch), wait.	Learn new tasks independently – however, optimisation techniques may be applied to improve the performance of discrete tasks. Operate reliably in unstructured or unforeseen circumstances. Interpret the intentions of humans by way of gestures, body language, etc.

An analysis along the above lines suggests that much of the future work in robotics may be in areas of autonomous learning, improving the ability to operate in unstructured or unforeseen circumstances, and to safely operate in environments that are also populated by humans.

It is proposed that service-robotics in 2010 has similarities to the information technology sector in the mid 1980s. Robotics is no longer the preserve of elite well-funded research laboratories. However, personal robots are yet to reach the price-bracket of the mass-consumer hobbyist.

In computing, a rapid increase in the size of the sector came about when hardware and software reached a certain standard and price-point, such that a large number of people could purchase and use personal computers. To illustrate, Table 3 provides a brief comparison of specialisations and operators in the IT and robotics fields.

It is predicted that robots will assist in a vast range of tasks including fire-fighting, search and rescue, removing significant danger, underground mining, dealing with hazardous materials, military reconnaissance and surveillance, major construction, care for disabled or older people, surgery driving, domestic chores, education and entertainment.

Table 3: Comparison of IT and Robotics across different specialisations.

Specialisation	IT	Robotics
Infrastructure	Internet/network access, online-storage, power, e.g. Cisco, AT&T, IBM, Google	Emerging
Component Hardware and Peripherals	Processor, RAM, motherboard, PSU, graphics, monitor, printer, battery, etc, e.g. Intel, AMD, Kingston, Crucial, Gigabyte, Asus, Epson, Canon	Emerging, microcontrollers, small-board computers, sensors, actuators, power, e.g. Atmel, Intel, Microchip, SICK, Honeywell, Maxon, Bosch, Riegl
System Builders	Integration, design, marketing, distribution, e.g. DELL, Apple, Sony, Toshiba	Emerging, possibly Sony, iRobot, Honda
Operating Systems and Middleware	Application-machine interface (industry-standard), e.g. Microsoft, Apple, Sun, Linux-variants (open-source)	Emerging, emphasis on real time and middleware, e.g. QNX, Linux, Microsoft, ICE, JAUS
Applications and Service	e.g. Microsoft, Adobe, Google, IBM, many others	Emerging, possibly domain specific involving physical interaction, e.g. agriculture, mining, construction, health-care, defence

The manufacturing sector in Australia, while small by international standards, already uses a wide-range of automated machine-tools and industrial robots to increase productivity. Great potential for growth in the service robotics industry comes from the ongoing improvements in capability, and reduction in cost of sensors, actuators, batteries and processors. Programming remains the most challenging problem in robotics research today [4]. Industries experiencing a shortage of skilled workers (such as mining and elderly-health-care) are areas already identified as prime targets for robotic automation [5]. Whilst it may be true that robots may replace the jobs of semi-skilled workers, the same was said for the IT industry which has since created millions of additional jobs in previously unforeseen disciplines (e.g. web-design).

ROBOTICS GRADUATE PROFILES – THE IMPORTANCE OF CROSS DISCIPLINARY SKILLS

A graduate of robotics may find themselves in the following roles:

- Automation engineer;
- Mechatronics engineer;
- Robotics engineer/designer;
- Control systems engineer/designer;
- Other specialist engineer;
- Engineering management;
- Other field.

Given the above roles, the graduate-profile of a robotics graduate will likely include some or all of the following skills/attributes:

1. Identify purpose and duties of robot.
2. Determine how the robot will interact with its surroundings.
3. Determine what sensors, actuators and level of mobility the robot will need.
4. Design, procure/manufacture and integrate mechanical and electronic components, including aspects such as safety, reliability, and end-of-life waste-management.
5. Develop or apply algorithms for carrying out the robot’s various tasks. These will include traditional robotics tasks such as object-recognition, path-planning, fault-diagnosis, and communication, but will also require algorithms specific to the robot’s activities.
6. Testing, documentation.

The design and development of an autonomous robot is ordinarily a large and complex systems-engineering undertaking and usually requires a considerable amount of teamwork involving specialists from different sub-disciplines [6]. This being the case, it is proposed that the attributes desired of a robotics graduate would include team-working/social skills, in particular, the ability to communicate and negotiate. In addition, it is proposed that these skills would be complemented by skills in reading and writing and the ability to solve complex problems through innovation and lateral-thinking.

Robotics is inherently a cross disciplinary field of research. For example, the disciplines within robotics include software engineering, mechanical engineering, mechatronics, electronics and control. Students who enter the robotics field at a postgraduate level often have a background in mechatronics, which itself is a synergistic combination of mechanical-engineering, electronic-engineering and computer-science; although other entry paths include physics, mathematics and aeronautics.

One of the key challenges for cross disciplinary fields arises from the different *languages* of each discipline. Due to the different disciplinary *languages*, translating information and methods from one discipline to another can present difficulties. Thus, it is proposed that greater cross disciplinary understanding might be achieved by providing options within educational programmes that enable improved cross disciplinary engagement [7]. This is not to say that graduates should be experts in all areas – instead, the courses could prepare students to work in teams with experts from other specialisations

Although cross disciplinary activity is encouraged in principle by government/institution initiatives [8-10]; not only can it be difficult to identify potential successful collaborations without an external perspective, competition for funding and pressure to fit within identifiable fields can be limiting [10][11]. Some university robotics programmes acknowledge the importance of cross discipline attributes, and have been developed with an explicitly documented high-level aim to develop these attributes. Examples include the Robotics Engineering undergraduate programme at Worcester Polytechnic Institute [12], and the work performed by the Multidisciplinary Project Action Group (MPAG) at the Southern Illinois University in the USA [13].

ROBOTICS EDUCATION/RESEARCH PATHWAYS

Consider a school leaver who wants to pursue a career in bio-inspired robotic research. The school leaver may have a particular interest in the gaits of hexapods, climbing robots or insect-like flying machines. A question arises as to what would be a good *pathway* to a PhD in this area. The student might consider a double degree that combines biology and engineering. However, a double degree may not permit the student to enrol in the relevant electives and sub-majors that will provide sufficient knowledge and expertise during their undergraduate studies. A similar problem is found for such emerging fields as *human-robot interaction* and *human-machine interfaces*, combining mechatronics with psychology and medical-science respectively. These examples of inter-disciplinary research have integrated specific branches of disparate fields to form new areas of study. Yet there seems to be no clear pathway for an undergraduate student to adequately prepare themselves to contribute to many of the emerging specialisations within the robotics research community.

One of the challenges for robotics students arises from the breadth of their courses. It can be difficult for robotics students to attain a significant degree of depth in certain specialised areas of interest, and this can make it harder for some robotics students to continue through to postgraduate research. For example, many mechatronics courses do not have sufficient room for students to opt to follow the paths associated with alternative sub-majors. Robotics students are typically doing more *introductory* subjects, and less *chains* of subjects. This is a concern because those *chains* are often where more-sophisticated critical thinking and probabilistic reasoning is developed [14].

A complicating consideration is the *syllabus cram* that is inherent in engineering, in part due to the vast depth and breadth of knowledge in the field. A well-known strategy for developing engineering competence is problem-based learning (PBL) [15]. PBL has a number of advantages over traditional lecture or even lab-based learning, in that it promotes intrinsic learning attributes within the students, develops communication skills, fosters teamwork, and provides opportunities to seek novel solutions to problems outside the original remit. Whilst some research has shown that PBL has only limited potential to improve grades in engineering and the sciences compared to the humanities [15][16]; perhaps due to the fact that problem-solving is itself such an inherent part of engineering to begin with, it seems that it may be very well-suited for developing certain robotics graduate attributes.

An emerging trend in robotics is the development of ability through participation in competitions. This has seen increased interest in science and engineering subjects at high school level [17][18], through to the generation of novel science led by research-centre participation in such events as the DARPA Urban Grand Challenge [19]. Similar projects have now been implemented in Europe and Australia. This approach, while popular with students, does have several drawbacks. There can be some tension between the objective to win and the objective to facilitate a learning environment for team members. In addition, it can be difficult to adequately convey the ethical and safety considerations required within a competitive engineering environment. Competitions in engineering also have a tendency to appeal more to men than women, and are therefore, unlikely to help change this already male dominated discipline. Finally, competitions based on set goals (such as the DARPA Grand Challenge) may prevent valuable (but non-point-scoring) ideas and methods from being considered and developed.

Recent years have also seen the emergence of remotely accessible laboratories. Given the high costs of state of the art sensors and certain other pieces of robotic equipment, several institutions have implemented remote laboratories to enable students to access/control/program robots from a remote location. For example, a system used at the University of Craiova enables skills in localisation algorithms [20]. Students at Fern Universität, Hagen, use a remotely accessible

Pioneer 3 AT mobile robot with a laser scanner [21]. The University of Technology Sydney has been using remotely accessible laboratories in non-robotics engineering subjects since 2001 [22], and is currently extending the system to be used in two robotics subjects, Mechatronics 2 and Advanced Robotics [23]. Using remotely accessible robots, students develop localisation algorithms off-line, and then test and validate the algorithms on the robot from a remote location. The remotely accessible laboratories are intended to enable students of robotics to spend less time troubleshooting problems that are caused by faulty actuators, sensors or software, and more time on the development of specialist robotics skills and abilities.

High-school and vocational-college level courses in robotics have also seen increasing enrolments. These courses typically include fundamentals in electrical and mechanical engineering, and in some cases, significant coverage in relevant areas of computing and mathematics. It is thought that such courses can be effective in developing skills suitable not only as a groundwork for more advanced courses, but also as a qualification suitable for future careers in robotics maintenance, and robotics support-industries [24]. Bachelor-level robotics courses may provide a suitable grounding for the bulk of the future robotics workforce [25], but it is proposed that graduate level courses at masters or doctorate level may, in some cases, be necessary to provide a sufficient degree of specialisation suitable for research and development work. This multi-tier system, which could also include the facility for continuous professional development courses and minor-level undergraduate courses, might also act as a conduit for the general population to obtain a subsidiary knowledge in robotics, in much the same way that an IT qualification has been useful in past years, and could facilitate cross-disciplinary collaboration between roboticists and non-engineers.

CONCLUSIONS

This analysis finds that many of the Australian universities that offer a Bachelor of Engineering now offer a major in robotics/mechatronics. In addition, courses in robotics are now offered in several vocational institutions and high schools. Curriculum developers must, to some extent, understand trends in the field and attempt to predict the demands of robotics graduates. It is proposed that much of the growth in robotics will be in areas related to the development of additional robot functionality such as the ability to operate in unstructured environments, uncontrolled lighting, learn new tasks independently, and to operate safely in spaces that are shared with humans. Graduate profiles are likely to include skills related to requirements analysis, design and integration of electrical and mechanical components, software development, systems integration, testing and documentation.

Robots generally involve many complex interacting components and many lines of code, and robots are ordinarily developed by sizeable teams where different members have different domain-specific specialisations. The preliminary results of this review suggest courses in robotics tend to include introductory material from a relatively large number of sub-disciplines, and robotics courses do not ordinarily permit the selection of sub-majors from other inter-related disciplines. This can make it difficult for students to traverse certain research pathways that are aligned with their interests – for example, it could be difficult for a student who is interested in pursuing a PhD in hexapod-gaits to include a sub-major in biomechanics. If more robotics students are to traverse a pathway towards postgraduate research in their own particular special area of interest, it is proposed that the field would benefit from courses that offer greater flexibility with respect to enrolment in related sub-majors. Rather than try to produce robotics graduates who are skilled in each and every sub-discipline, it is proposed that courses might attempt to ensure that graduates are able to work effectively in cross-discipline teams.

Further educational research in this area is recommended. Fruitful avenues for further research could include an effort to determine the extent to which the inability to enrol in sub-majors may be preventing students from traversing their preferred pathway to postgraduate research. In addition, it may be useful to systematically measure and analyse the relative effectiveness of attempts to enable engineering students to work effectively in cross-discipline teams, perhaps comparing the approaches taken in Australia with those of overseas institutions.

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