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The Maturing Discipline of Robotics*

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The nature of the robotics discipline is changing. In turn the traditional engineering-based degree programmes that have promoted robotics as an application of engineering principles need to be supplemented with robot-centred degree programmes that reflect the diverse character of robotics, the diverse interests of students, and the diverse multi-disciplinary contributions to the robotics discipline. In this paper the nature of the change that robotics has undergone in recent years is described. An outline of the subject material of robotics, comprising robotics science and robotics engineering, is discussed. The teaching of robotics degree programmes in the past has been hampered by the expense required to install and maintain a robotics teaching laboratory. Availability of online robot systems and numerous robot kits has changed this situation to some extent. However, the paper concludes that there is still a need for good educational toolkits for teaching robotics at a first degree level.

Keywords: robotics education; robotics body of knowledge; undergraduate robotics programmes; interdisciplinary robotics programmes; robotics toolkits; robotics science and engineering

INTRODUCTION

OVER THE PERIOD of the last forty years, since the mid-1960s, the field of robotics has undergone a dramatic transformation. The subject material of robotics over this period has broadened from a narrow focus on manipulator systems for repetitive industry-based operations to include biologically inspired and humanoid robot systems. Robotics technology, systems, architectures and intelligence has similarly undergone a dramatic transformation. The field of robotics has been enriched with new materials, mechanical and electronic systems, computational and algorithmic techniques, and behavioural and cognitive insights from the biological and social sciences [1]. The subject of robotics is no longer solely the province of the engineering disciplines or the engineering departments.

This transformation has been most significant over recent years and is readily apparent from even the most cursory examination of contributions and contributors to the major international conferences on robotics and by the growing number of conferences and workshops in robotics. It is not apparent, however, from even the most cursory search for first degree programmes in robotics or by the amount of robotics material covered in existing engineering degree programmes. Why is this so?

There are a number of answers to this question. The first is perhaps the most important. The traditional educational approach to robotics, of treating it as another application of engineering principles rather than as topic worthy of study on its own account, has prevented the creation of more imaginative robotics programmes. The traditional programme incorporates foundation material in mathematics, mechanics and control engineering as underpinning studies for later practice in designing, building and programming engineering systems. The best such programmes, from the perspective of their robotics content, generally include introductory material on robotics, leaving the more substantial treatment of robotics to advanced master's level programmes. The requirement for mathematics, mechanics and control incorporated in these programmes and the late introduction to materials in robotics is not appealing to many of the students who might today take an interest in robotics.

The second answer is that while the subject material of robotics is reasonably well understood in robotics research, robotics education does not have a well established and recognized corpus of knowledge that it can pin its banner to. This reflects to a large extent the continuing viewpoint that robotics is largely an application of engineering principles and practice. If the wider diversity that is now characteristic of the robotics field is to be reflected in first degree programmes in robotics, robotics education needs to claim its body of knowledge. This is largely the purpose of this paper.

The third answer is that robotics is to a large extent a practical subject. Whether it is a mechanical engineering student building a robot system, a computer science student developing an implementation of an algorithm for robot mapping, or a cognitive science student exploring human-robot interaction, the experimental realisation needs be practical for a proper appreciation of robotics.

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Educators have recognised the importance of practice in robotics but have in the past shied away from programmes in robotics when confronted with the cost of providing the resources required to support this practice. This situation is now changing with the availability of a wide range of small, medium and large robot kits and systems at reasonable prices. These have in fact motivated educators to exploit robotics as a basis for individual projects and team building activities at a number of levels and in a range of disciplines [2–4]. The prospects for creating innovative degree programmes in robotics are now better than ever. However, there is still a shortfall in the range of robot kits and systems available and the integration of these toolkits with robotics education has still to be forged. These can only be addressed successfully under the guidance of a robotics body of knowledge.

Robotics must break ground beyond its traditional engineering heritage if it is to respond to these challenges. The robotics community must in particular identify the body of knowledge that defines robotics. It must as well build on the current enthusiasm for robotics to create more imaginative first degree programmes that reflect the current breadth and depth of the subject. This paper addresses both these issues and provides a characterisation of a robotics degree as an integrating systems-based discipline. It distinguishes robotics engineering from robotics science and provides a perspective on the subject material of robotics.

THE ROBOTICS DEGREE

Robotics is now both a largely integrative discipline and an expansive subject. This section focuses on the first of these. Robotics is an integrative subject since the embodied robotic mechanism, typically comprising sensors, actuators, and computational platforms and processes on a single physical chassis, is a system.

A modern-day robot, as a system, comprises elements at a number of different levels:

1. The materials and mechanical systems, including motors and gears, which define the main physical core of the system.
2. The control and measurement systems that enable the robot system to operate under conditions of stability.
3. The electronic systems that embed lower level intelligence and integrate sensors, actuators, and controls, with higher-level computational systems.
4. The computational systems, typically centred on a real-time operating system, which offer the medium for high-level programming, multi-threaded and concurrent processes, sensor integration and fusion.

These four levels define the practical robot system that is in turn the embodiment of:

a) The robot architecture and intelligence that encode the task the robot system is to perform. The robot architecture defines the way in which components of the system are integrated and the robot intelligence defines the contents of these components. The realisation of a practical robot system must take account of the task the robot is to perform, the environment in which the task is to be performed, and techniques, drawn from robot architectures and intelligence, collectively robotics science, that are used to structure and populate the design and implementation of the system (Fig. 1).
b) The inspiration and innovation provided by Artificial intelligence (AI), cognitive science, and indeed the physical, biological and behavioural sciences. AI was the first to systematically explore the integration of sensors, controls and high-level reasoning on a mobile robot system (i.e. Shakey [5]) and was, following mechanical engineering, the second home for robotics. Cognitive science is particularly influential in the area of human-robot

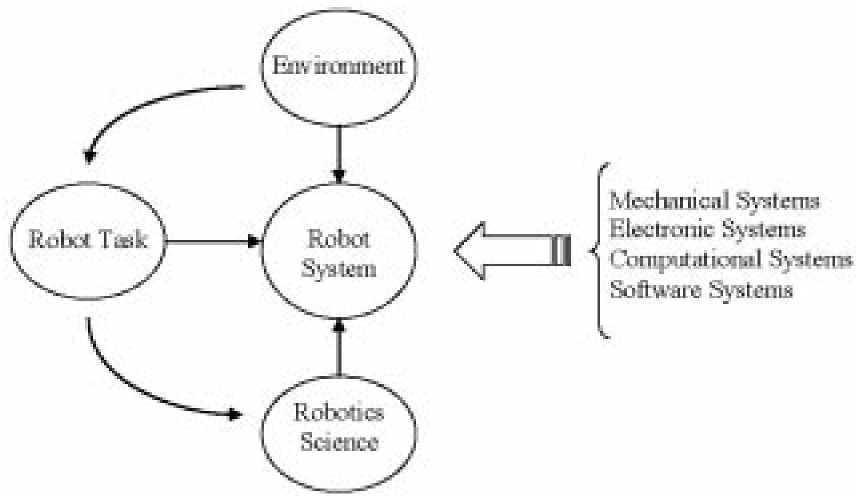

Fig. 1. The many influences on the design of a robot system.

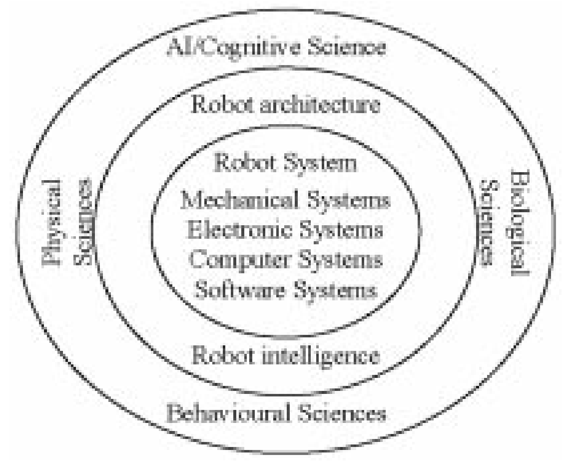

Fig. 2. The modern-day influences on the discipline of robotics.

interaction and will become more so in the area of humanoid robots. The biological and behavioural sciences have a strong influence through neural network models and biologically inspired robot systems. One can also add the physical sciences as the inspiration for nano-robotics, for example. These inputs exert influences across the entire robot system.

The multiple levels described above, and their interactions, capture the important requirements and ingredients of an undergraduate degree programme in robotics, namely the robot system as an engineered artefact, robotics science as the conceptual organisation of the robotic system, and the influences that innovate and inspire robotics science and systems (Fig. 2). If to these components are added the mathematical techniques (pure and applied, discrete and continuous) that underpin theory and concepts in engineering and computing, one can envision a science and engineering programme in robotics comprising the following themes:

- Underpinning methods and practice in **mathematics**, **computing** and **control**.
- **Control Engineering theory and practice:** Feedback control systems, nonlinear control, optimal control and estimation, Kalman filtering, simulation and modelling, etc.
- **Electronic Systems theory and practice:** Systems and circuit theory, analog and digital electronics, programmable devices, microcontrollers, embedded systems, sensor and actuator devices, interfacing, etc.
- **Computer Systems theory and practice:** Microprocessors, instruction sets, operating systems, real-time systems, networking, distributed systems, man-machine interfaces, algorithms, software engineering, and programming, etc.
- **Robotic systems and practice:** Robot architectures, robot design and modelling, manipulator robotics, telerobotics, mobile robots, behavioural-based systems, deliberative systems, multi-robot systems, swarm robotics, mobility systems, modular robotics, applications, application domains, etc.
- **Artificial Intelligence techniques and practice:** Representation and reasoning, heuristic search, planning under uncertainty, fuzzy reasoning and control, uncertain reasoning, decision making, etc.
- **Cognitive Science (and other):** Cognition, perception and planning, problem-solving, thinking, knowledge representation, spatial awareness, hand-eye coordination, cognitive architectures, neural and brain science, biological systems and organisms, etc.

In the traditional engineering course a robot system is just one example of an engineering solution. Such a programme emphasises underlying principles, tools and techniques that can be applied across a range of engineering solutions. A robotics programme must turn this on its head. It must start with the artefact and both explore and expound the principles, tools and techniques that can afford the creation of that artefact.

An individual robotics degree programme can emphasise one or more of the above themes depending on the local strengths of the institution offering the programme. However, three broad categories of degree can be identified. The first focuses on designing and building the robot artefact from a materials and mechanical baseline. Such a degree will typically comprise the first three themes above. One might call this the robotic engineering strand. It would involve a strong element of control and measurement theory.

The second focuses on the programming of robotics systems and the prior availability of a robot artefact suitably rich in sensors and controls for the exploration of simple behaviours and complex robot architectures and intelligence. Such a degree programme would focus on the middle themes above. One might call this the computational robotics programme.

The third focuses on the interaction of the robot system with humans at a cognitive level. Such a degree would emphasise the lower three themes above. One might call this the cognitive robotics degree programme. It would incorporate strong elements of cognitive architecture, representation and reasoning, and human-robot interaction.

In the above description the term 'robotics science' has been used to focus on those concepts that are peculiar to robotics. These cover the broad notions of robot architecture and robotic intelligence. Where in these degree programme possibilities lies robotics science? Indeed, is there scope for an undergraduate degree programme in robotics science?

If one takes a view that robotics science is concerned with remapping the biological organism into man-made robotic forms, and there is no reason why not to, then a science of robotics both envelops and reaches beyond the robotics programmes described above. It is essentially the robotics programme described above but with a strong multidisciplinary emphasis and a broader remit for robotics that includes recreating biological systems (man and the organisms around him) in man-made materials and mechanisms. This broader multidisciplinary character would be exemplified by the incorporation of themes on biological systems and organisms, artificial intelligence, and cognitive science.

These then are a range of possible robotics degrees, starting from what might in fact be called a core robotics engineering degree, through a number of specific variants, to a broader robotics science degree programme. How would these degree programmes map onto traditional degree programmes?

The robotics engineering programme is very much the traditional engineering programme, but with an emphasis on the robotics artefact and a broader appreciation of varieties of robot systems. Students wishing to focus on designing and engineering robot systems would be wise, in the absence of a robotics engineering programme, to follow the traditional engineering programme.

A variant of this robotics engineering programme is one that emphasises electronic systems, particularly embedded systems. Here the materials and mechanical systems of a robot are of less importance compared to the way in which sensors and controls are integrated to form a hardware-oriented realisation of robotic intelligence. Students wishing to specialise in this area would be advised to take a degree that incorporates robotics within an embedded and electronic systems programme.

Students wishing to focus on the computational aspects of robotics, under something resembling a computational robotics programme, would be advised to find a computer science or computer engineering programme that emphasises programming methods, algorithmic techniques and software engineering principles for robots. A computer science programme that incorporates strong elements of geometric algorithms and artificial intelligence is a good option.

Students wishing to explore the cognitive side of robotics would be wise to pursue a programme that incorporates elements of computer science, artificial intelligence and cognitive science. These might be available through a range of departments, but are typically based in the engineering or computer science departments.

The broader robotics science programme described above, however, does not currently map well onto an existing degree programme. Hence, there is little scope currently for a potential student to pursue a substantial and coherent body of knowledge and practice in robotics as a first degree. They must look to combining a first degree in one of the forms above with a master's level programme having significant robotics content.

There is a major obstacle that can be raised to the creation of a first degree programme in robotics: Where are the career opportunities? Although there is currently great interest in robotics, and there is a market for robot systems to support research and teaching, there is as yet a relatively small robotics industry. However, that should not deflect from the creation of a robotics degree programme. The purpose of education is to help the individual discover, explore and develop their abilities. The good engineering degree programmes do so and turn out graduates who can rise to many challenges. Robotics degrees can and must aspire to the same.

PROGRAMMES, ENTRY POINTS AND TOOLKITS

The programmes described in the previous section assume an underpinning knowledge of mathematics. Mathematics is essential for an engineering-centred robotics programme. For the science of robotics it is essential as well to have a strong mathematics background. However, it can be argued that there can be softer routes into robotics. The central idea is that much can be achieved with an intuitive understanding of mathematics and relevant components of the required mathematics can be introduced as needed. This approach affords a more constructivist, a more artefact centred, and a more problem-oriented robotics programme. In short, the traditional pattern to engineering programmes, of presenting underlying principles and subsequently introducing an applications orientation, can be turned on its head: the artefact, or application, can motivate the pursuit of the underlying principles. The mathematics material can be consolidated and expanded into a coherent body of principles at a later stage.

Figure 3 shows a chart that aims to capture both the breadth and depth of robotics. From left to right are the key system aspects of robotics, namely mechanics and materials, control and measurement, electronic systems, computer science, AI and cognitive science. From top to bottom is the depth of coverage, from mathematics itself and its use in capturing the underlying theory of the domain, through advanced methods and tools for designing and programming robotics systems, to lighter-weight module-based construction of robot systems.

For mechanical engineering, for example, emphasis at the lighter (synthesis/modules) end is given to a motor and its controller as a modular building block of a robot system; its causal affect (i.e. motion) is more important that its theoretical underpinnings. The LEGO MINDSTORMS kit exemplifies this level well for relatively simple robot systems. At the intermediate level emphasis is placed on the nature of the motor as an electromechanical system and the control systems required to operate it. At a deeper level we are interested in the theoretical foundations, both mathematical and physical, of motors and

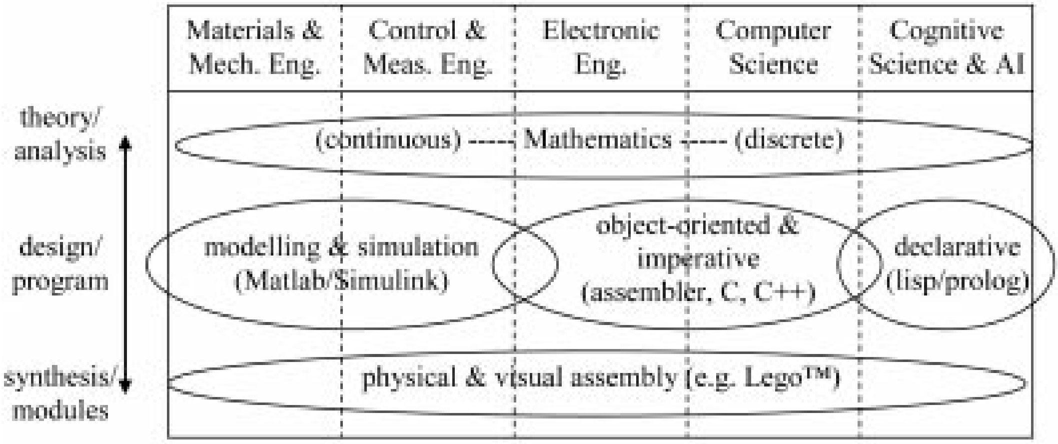

Fig. 3. The breadth and depth of robotics.

controllers. This deeper understanding is where the traditional engineering programme is rooted.

For electronic systems the depth ranges from plug and play integration using modules employing serial interfaces, through system-level integration at the bus level, to board-level integration of IC modules. The first requires visual programming skills, the second textual and device-level programming skills combined with board-level understanding, and the third requires board-level electronic design skills. This third, deeper level requires mathematical understanding of both electronic and communication technologies.

For computer science the depth ranges from iconic-based construction and programming environments, exemplified again by the LEGO MINDSTORMS visual programming interface, through high-level programming languages with a good appreciation of algorithms and data structures, to a theoretical understanding of algorithmic techniques and efficiency. The latter is grounded predominantly in discrete mathematics, but linear algebra, which is important for many areas of robotics, is also important for computational geometry.

We can also draw out cross-cutting themes. The first, at the deeper level, is the theoretical underpinnings of the different subject areas, grounded in continuous and discrete mathematics: continuous mathematics towards the engineering end of the chart and discrete towards the computational end. The second, at the intermediate level, is the modelling and integration of systems, generally programming methods or models, that range from modelling tools at the engineering end of the chart through various forms of low and high-level programming languages and environments towards the computational end. Finally, at the lighter level is the visual, physical and modular robot construction exemplified by such toolkits as LEGO MINDSTORMS.

The chart in Fig. 3 can be used also to convey some of the historical background to modern-day robotics and hence to provide an appreciation of the breadth and depth of the robotics discipline itself over and above the topics listed. The robotic engineering of the 60s and 70s, for example, had its focal point in the top left-hand corner, where emphasis was placed on a sound theoretical understanding of mechanical and control engineering principles. Artificial intelligence also offered a home to robotics during this period. The classic exemplar of the well-rounded mobile robot system, Shakey, was motivated by AI research [5].

With the emergence of the minimalist robot paradigm in the mid-1980s the presence of software, or more accurately the use of an internal representation, was vigorously discouraged [6]. Robotics engineering had much more in common with electronic engineering than with either mechanical engineering or artificial intelligence during the period immediately following this. The change in emphasis, however, did not lead to the emergence of a separate and coherent programme in robotics, or to robotics moving its home towards electronic engineering.

In the mid- to late-90s robotics gained a great deal of popularity with the launch of LEGO MINDSTROMS, which was motivated to a large extent by pedagogical goals and facilitated by advances in microtechnology that afforded the creation of *intelligent blocks*. Through these developments robotics has also been brought to a wider audience through the guise of *robots in education* programmes where robot kits support group-based activities aimed at instilling team-based skills in students [7, 8].

There have also been other inspirations to robotics whose impact has been in broadening both the subject material of robotics and encouraging further interest in robotics. Two are of note. The first is human-like robots. These systems have surfaced very recently in the form of small and large human-like walking robot systems. Their development reflects continuing research efforts but also progress in underlying technologies—motors, drives, electronic systems—that has enabled their practical realisation. Humanoid robots exemplify the advanced state of current robotics technology [1].

The second is biologically inspired robot systems. The emergence of these systems can be traced in recent times to the minimalist robotics programme in the late 1980s. The miniaturisation of technology, however, has also impacted on the realisation of robotic systems that mimic biological organisms. Indeed, many of the biologically inspired robot systems are built in natural science laboratories [9].

When these two cases are taken together one can see that a more exploratory, a more organic, and a more science-oriented approach to robotics has emerged that emphasises the *robotic organism*. This does not displace, but stands alongside the more traditional task-driven approach of industrial robotics. When these two complementary approaches to robotics, the scientific and the industrial, are put together the robotics footprint across the natural and physical sciences, and engineering, is large—robotics is pervasive.

The breadth and depth of the disciplines underpinning robotics, illustrated in Fig. 3, and the current pervasiveness of robotics as outlined above, both argue for a richer set of entry routes into robotics science and engineering. Specifically one can envisage a more lightweight route wherein, in particular, the mathematically intensive material is approached in a more intuitive manner or scheduled to later in the programme. This more lightweight route will introduce robotic engineering using visual and component-oriented programming models based on practical robot toolkits and robot simulation tools. These can be complemented with more theoretical studies in AI, cognitive science, the behavioural and biological sciences, and indeed the physical sciences.

Central to the development of a good robotics education programme is the availability of practical robot toolkits. While there have been a growing variety of toolkits available for exploring robotics at an introductory level, and a growing number and variety of mobile robot systems to support research, there is still a limited range of robot kits or systems available for teaching a first degree programme in robotics. Educational systems at this level not only need to be affordable but also must integrate into the educational programme, and while there are a great variety of custom solutions that do integrate well with robotics education in local programmes, few are generally available [3, 4, 10].

This state of affairs is exemplified in the area of robot manipulators. Inexpensive robot manipulators readily available from online robot stores are inadequate since the control and sensor readouts they offer are either too limited or non-existent. Manipulator systems at the high end of the scale, on the other hand, are too expensive and bulky relative to the cost of integrating them into educational programmes accessible to large numbers of students. There is a need for more functional manipulator systems that can be swapped across desktop and mobile robot platforms and satisfy the requirements of undergraduate programmes in robotics.

A subject-centred viewpoint is also valuable when reviewing toolkits for robotics education. Computer science degree programmes are a good example. Robot systems typically have some component of software and indeed in sophisticated robot systems a significant software component. Computer science programmes can offer modules that emphasise the programming and algorithmic techniques required for robotics. However, it would be a significant financial burden to a computer science department to fund a sizeable fleet of mobile robot systems to support teaching to a large body of students. When the expense is weighed against the current cost of software and computer equipment for teaching it would be untenable. Online robot systems offer one solution to this accessibility problem [11]. Robot simulation software is a useful teaching resource in these settings, but cannot replace the experience of working with a real robot system. New solutions are required.

A second supporting case will be broached more briefly. A large element of biologically inspired robotics can be found in non-traditional laboratories; neuroscience laboratories for example [9]. What background in robotics engineering, and the biological sciences is required for contributing to the development of such systems? What sorts of toolkits should be provided to support the coverage of topics in robots within these programmes, and indeed what sorts of topics should be covered? These are open questions for robotics education.

ROBOTICS SCIENCE AND ENGINEERING

Although robotics has not found a home of its own it does possess, nevertheless, a well established body of knowledge. However, that body of knowledge has not yet been rigorously encoded. This section, therefore, aims to draft a broad picture of the robotics subject. The starting point is robotics science and engineering.

Robotics science asks the question, what comprises a robotics system? Robotics engineering asks a quite different question: given a task, how does one design and build a robot to perform that task? It is out of the first of these questions that robotics has lately taken on the opportunity to engage in the more expansive enterprise that includes the exploration and replication of biological systems in silicon. The second of these questions has led in the past to industrial robotics, but more recently has been broadened to encompass a larger range of non-industrial applications including applications for the military, in terrestrial search and rescue, and for space exploration.

Robotics science, which emphasises the nature of the robotics system, and robotics engineering, the task of putting the robot system together, delimit the subject material of robotics. At core the two share a common enterprise, namely the integration of a wide range of components into a system. The first aims to discover which components to use while the second merely attempts to use them. Both are concerned with robot architectures and intelligence. Robot architecture is the way in which the components are put together while robot intelligence is the way in which these components express the behaviour that is ultimately to be displayed by the robot system in its operational, or living, environment.

The detailed subject material of robotics is captured by the following questions:

1. What is a robot system?
2. What use are robot systems?
3. What are the components of a robot system?
4. How does one build a robot system?

What is a robot system?

The first of these questions is perhaps the most important for the current generation of roboticists. The traditional introduction by way of a classification of industrial manipulator systems is far too narrow. Nor will a description of a mobile robot system suffice. The following all need to be conveyed:

- A robot system is a sensorimotor system integrating sensing and action, via low-level reactions and behaviours and high-level deliberation. Some understanding of robot intelligence and architectures should be conveyed.
- Robot control system implementations exist at a number of scales. These range from small scale systems incorporating analogue or digital electronic circuits linking sensing to action, through systems incorporating microcontrollers, up to systems incorporating a real-time operating system, a wide range of interface devices and instruments and a significant software footprint. Examples include stick insect robots, small mobile robot systems and large science rovers, respectively.
- Robots come in a variety of shapes and sizes, including small two-wheeled mobile robots, larger science rovers, robot manipulators, indoor robots, all-terrain robots, reconfigurable robots, nano-robots, flying robots, underwater robots, humanoid robots, robot insects, and so forth. One of the aims should be to demonstrate the diversity of modern-day robots.
- Robot systems may comprise more than one robot and more than just robots. A robot system may be a single self-contained robot, a set of two or more cooperating robots, a team or even a swarm of similar (homogeneous) or different (heterogeneous) robots [1, 12, 13]. A robot system may be part of a larger application system, for example a manipulator systems operating within an industrial work cell to which are fed parts and from which are removed subassemblies, or a telerobotic system which interacts with one or more human beings [14, 15]. Indeed, a robot system may be an embodied entity within some environment or embedded within the actual environment.

In short, robotics today is many things and can be found in many domains. It is essential that educators convey this breadth to the student.

What use are robot systems?

The traditional response to this question would be to cite industrial spray painting applications, pick and place operations in assembly plants, and to a lesser extent operations in hazardous environments, most notably nuclear power station cleanup, as exemplars of the utility of robot systems. These applications are still important and have been extended considerably with the application of desktop manipulators in the pharmaceuticals industry. It is lamentable, however, that robotics systems have still not found major markets outside its traditional fields. One of the most successful recent applications, of course, is space exploration, even though only three successful robotic rovers—Sojourner, Spirit and Opportunity—can be named. Despite this, experience is growing in the use of robotics systems in an expanding area of applications as technology advances enable robots to find a better fit with the target application environment. Medical robotics is one example where miniaturisation of robotic systems—manipulators—and higher quality feedback is offering finer dexterity [16]. Many target applications are still in the experimental stages. These include rehabilitation robotics, medical robotics, search and rescue, surveillance, space and underwater, military and naval applications. Entertainment is a particularly important avenue for the exploitation of robot systems and technology. Good examples are museum robots and the Robocup competition [17, 18]. And, of course, an excellent and important application of robotics principles and techniques that is also offering insights into robotics science is biologically inspired robotics [9].

In summary, there is now a diverse range of application opportunities for robotics systems and increasing penetration of robotics into some of these application domains. An introduction to robotics needs to outline this diversity and to offer students more detailed insight through at least one and preferably through a number of case studies.

What are the components of a robot system?

The third and fourth questions are intimately linked, and hence it is first important to understand this link before addressing the specific questions. In fact, delimiting the nature of this linkage is an important goal of robotics science. The notion of a task is central to this linkage. A task translates into a goal that is to be achieved and a sequence of operations that need to be performed to achieve the goal. The task needs to be performed within the environment in which the robot will be embodied. The robot, in turn, needs to display both an understanding of the task and an ability to cope with the environment. These are captured in the intelligence of the robot.

The intelligence of the robots includes awareness of its environment and the ability to reason about the environment in order to respond appropriately in a variety of situations or to plan future actions. This intelligence needs, in turn, to be reflected in a physically embodied robot system. This includes mapping knowledge, skills and behaviour onto representations in hardware and software so that these can be expressed via interaction (sensing on the one hand and mobility and manipulation on the other) with the environment.

From these considerations one can appreciate the link between robotics science and robotics engineering on the one hand and between robotic intelligence and robotics architectures on the other. Specifically:

- Robotics science aims to discover the components of robotics intelligence, both the overt behavioural components and their internal representations.
- Robotics engineering aims to determine how to represent these components in hardware and software. It is concerned with the practical realisation of robot systems that display useful and appropriate behaviour.

Both robotics science and engineering are concerned with robotics intelligence and architecture, but with a very different emphasis:

- Robotics intelligence is reflected not only in the way the robot behaves but also how its behaviour combines from moment to moment, now and in the future, and in its interaction with the environment.
- Robotics architecture is concerned with the way in which the internal components onto which this behaviour is reflected integrate with each other within the computational and physical body of the robot.

The components, then, of a robot system comprise elements of both intelligence and architecture. For intelligence read:

- *The relationship between situation and action in the context of a task and/or environment.* What are the relevant situations the robot needs to be concerned with? How is one situation distinguished from another? What are the possible actions and how are actions selected for each situation? Work in the area of action selection mechanisms based on behaviour-based architectures is a relevant here, but should be studied within a task context [12, 19].
- *The robot's awareness of its environment and its task.* Specifically, to what extent does a robot need an internal representation of its task and environment, and to what extent is that representation procedural or declarative? These can be translated into the familiar robotics concepts of mapping and localisation. For environment read spatial maps and spatial localisation within those maps and for task read state models, states and state transitions. For declarative representations one can also add the ability to reason about the task or environment and the ability to plan in either.
- *The robot's ability to sense, and indeed perceive, its environment.* Sensing can range from simple feature detection, perhaps embodied directly in the sensor, to more elaborated models that incorporate sensor data analysis, sensor fusion, feature and object models and their representation, sensing strategies, sensor placement for active interrogation of the environment, and ultimately the creation of a symbolic representation that can be reasoned over.
- *The robot's ability to act within its environment.* Essentially this means, at one level, mobility and manipulation, and at a lower level the actuators, drives and controls that facilitate mobility and manipulation. Relatively recent research in manipulators has focused on modular reconfigurable systems. Mobility systems for robots, however, have shown a significant diversity over recent times. Coverage of mobility systems should include not only wheeled systems (indoor and all-terrain), but also legged mobility (two, four and more; insects and humanoids), snake-like mobility, swimming robots, airborne mobility systems (helicopters, dirigibles, winged), systems that bore into the ground, jumping robots, and so forth. There is a lot of lively activity ongoing in this area and a fruitful topic for experimental robotics.

For architecture read:

- *The integration of the above components into a robot model.* Architecture is concerned both with splitting a robot system into components and with integrating those same components to form a system. The key question it asks is what are the components of a robot system, and how are these components linked together. It is best studied through cases, which should include the classic architectures of Shakey [5] and the Stanford Cart [21], multi-level representational architecture (e.g. [21]), behaviour based architectures and the more recent hybrid architectures that combine deliberation with behaviour-based reaction [1, 12]. It should track the development of the subsumption architecture through to more recent work on formal approaches to action selection [12, 19, 22]. It should cover not only single robot architecture, whether monolithic, modular or agent-based, but also multi-robot architecture, from small teams of cooperating robots to robot swarms [13]. It should cover as well human-robot systems and industrial robot system architectures. It should look at the nature of the components that make up a robot system, what size a component should be, how its functionality is defined, what inputs it accepts, what outputs it gives, and so forth. These are crucial for the practical realisation of robot systems.

How does one build a robot system?

Whether pursuing experimental robotics or building applications, robot systems need to be put together in a practical, real form. It is important to understand two key aspects of building robot systems: firstly, that robot systems scale anywhere from the very simple, where the robot incorporates two-state sensors (on/off), one step-circuitry (Boolean logic gates) and simple reactions (turn left/right) to the very complex where the robot incorporates a sophisticated real-time operating system, many-faceted sensors and controls, and performs under the management of a suite of software that was possibly developed by a team of hundreds; and secondly, that a robot system integrates many facets of engineering, from mechanical through electronic to computational; from design through simulation to programming.

Students need to appreciate all of these elements, perhaps focusing on one or a number of them:

- For mechanical systems they need to understand control. For electronic systems they need to understand measurement and communication. For computational systems they need to understand algorithms and software. All three require as well a basic understanding of computer systems.
- Building robot systems involves the integration of many sensor, actuator and control devices. These have operational characteristics that the robotics engineer needs to comprehend. Additional operational characteristics and capabilities are often available when devices are combined.
- Building robot systems requires programming skills. These include the ability to design and simulate robot systems, program and control robot devices, program in low and high-level languages, understand programming environments and systems, know how to build program libraries, and the ability to translate models of intelligence into hardware or software implementations.
- Building robot systems requires integration skills. These include the ability to translate a robot architecture into a real implementation. For software the engineer needs to determine whether to use monolithic or component-based software, object-oriented or process-oriented software models, and single or multi-agent implementation of intelligence. For hardware the engineer needs to determine the requirements for fixed or reconfigurable digital circuitry, microcontroller based operations or a full computational system. Allied to both hardware and software the interfaces between each need to be determined, whether network or bus-based, via function calls or message passing.

The engineer in addition needs to be able to assess trade-offs between all of these options and to understand the nature of reliability and optimality in system design and implementation.

The above touches briefly on a wide range of current topics in robotics and in doing so provides the material that should be covered in an introductory module on robotics. The development of more substantial programmes can build from these foundations, but will be greatly assisted if a body of knowledge statement is available for robotics. Such statements have been produced, and have been of great value, for the field of computing [23]. A similar statement is now required for robotics.

SUMMARY AND CONCLUSION

Robotics is both a growing and a changing subject. It has reached a level of maturity now where it can stand on its own as a discipline. Degree programmes that are robot-centred need to be added to the traditional engineering programmes that treat robots as an application of engineering principles. The teaching of robotics needs to be brought forward into a set of first-degree programmes. While those programmes should be robot-centred they should, nevertheless, turn out capable graduates. Robotics programmes which offer less mathematical and control-oriented introductions to robotics, leaving the in-depth treatment of these subjects for more advanced levels (perhaps even masters) are also needed. Such considerations are appropriate for computing and IT degree programmes, and for multidisciplinary programmes within natural and biological sciences. Finally, while there are now a wide range of robot systems and kits available at an introductory level, there remains a poor match to the requirements of a first degree programme in robotics. The most urgent need at present, however, is for the establishment of a rigorous statement of the robotics body of knowledge.

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