Chapter 14
Engineering Design for Mechatronics—A Pedagogical Perspective

Simeon Keates

14.1 Introduction

Since the introduction of undergraduate and postgraduate programmes in mechatronics and related subjects in the mid-1980s, there has been a near continuous debate as to the nature and standing of mechatronics both as an Engineering discipline and in relation to its role within Engineering Design [1–5].

In the case of mechatronics education, what has emerged is a wide variety and range of courses structured around the basic tenets of integration concentrated around the core disciplines of Electronics, Mechanical Engineering and Information Systems or Computing but with a wide range of variation and variety to accommodate local requirements and conditions.

Thus, a course developed and delivered in, say, Detroit [6], is likely to differ significantly from one in place in Singapore [7], while both have entirely legitimate claims and arguments to be considered as mechatronics programmes.

Notwithstanding this difference in emphasis, each course will, in general, seek to conform to the requirements of achieving an appropriate level of integration between the core disciplines, with an emphasis appropriate to the overall requirements of the course.

Here, we examine how innovative and challenging mechatronics programmes structured to meet future needs must still incorporate the basic principles of Engineering Design. However, mechatronics remains a fundamentally innovative field and simple instruction in the basic mechanics of putting the components together is missing an educational opportunity to push students to develop their creative engineering thinking. Mechatronics, being such a diverse field, allows students and teachers to explore genuinely innovative questions and solutions. As such, it is well suited to allowing teachers to set tasks and projects for students

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S. Keates (✉)
Faculty of Engineering and Science, University of Greenwich, Chatham Maritime, UK
e-mail: s.keates@gre.ac.uk

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that break new ground and explicitly support the creation of the new concepts and solutions required to take mechatronics forward.

When looking at mechatronics-oriented degree programmes it is necessary to consider how mechatronics is likely to develop and change in the mid- to longer-term future. The goal of any good degree programme is to not only prepare each student to secure their first job, but also to give them the correct skills and mind-sets to retain employment throughout their entire working life. This goal is a particular challenge in a discipline that is as diverse as mechatronics.

14.2 Learning Objectives of Mechatronics Courses

As the name mechatronics implies, the subject is generally considered to be a merger of both traditional Mechanical and Electrical/Electronic Engineering, often with computing elements. However, while knowledge of both engineering disciplines allows students to understand how mechatronic systems function, it is suggested that an essential component of any mechatronics programme is Engineering Design. Mechatronics students are not typically driven solely by grades, although this is an undeniably important motivational factor for the brightest students in particular. Instead, most mechatronics students are more generally motivated by the desire to solve a problem. Any educational programme should be oriented to support this desire and must not inhibit it through too much formulisation. In other words, mechatronics programmes need to support open-ended active enquiry rather than do-it-yourself flat-pack or pro forma type assembly instructions. It is proposed that the key attributes of a graduate of a mechatronics programme are:

• Confidence	• Skills
• Creativity	• An ability to work in a team

Figure 14.1 [5] shows that Engineering Design can be placed at the intersection of a science-based set of skills, the horizontal element of the figure, and social and artistic skills, the vertical element. To these must be added a wider awareness of a range of issues necessary to convert a concept into a viable system or product, such as aesthetics, manufacture, ergonomics and human factors.

In considering the requirements of a mechatronics course with Engineering Design at its core, the essence remains that of balancing the Engineering and IT content within a design focus that supports both individual and group working. The latter is especially important for mechatronics, which is a confluence of very diverse technical domains and thus any one person is unlikely to be a master of all of the technical skills required to build a successful device or system, particularly within the context of developments such as cyber-physical systems and the Internet of Things. In industry, most graduates will be expected to work in a team and so ought to experience the realities of such co-operative work in their programmes.

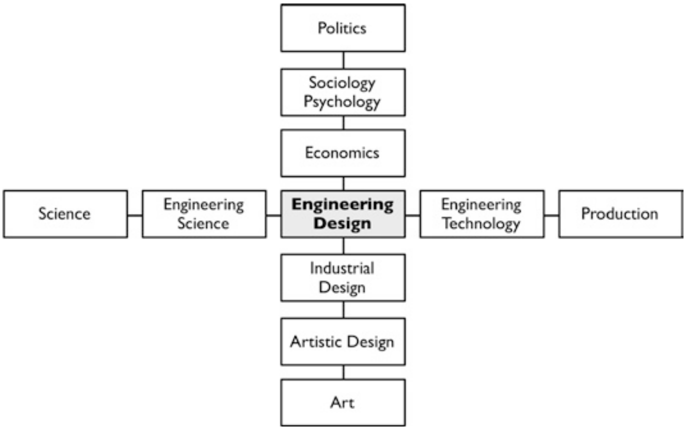

Fig. 14.1 Engineering design issues (after [5])

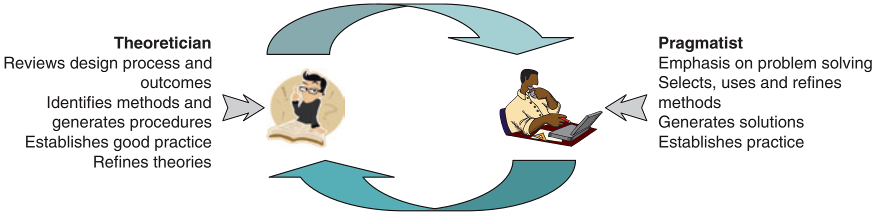

Fig. 14.2 Approaches to design

Key elements here are the need to support communication between members of the group, for instance through computer-based communications structured around the use of digital libraries [8, 9], and to expose students, both individually and as members of a group, to the design process from concept development to implementation [10]. Intrinsic to this is the need to ensure that, particularly in a cross- and interdisciplinary environment, issues of potential misunderstanding through different and differing use of terminology is avoided [11].

Further, it has been suggested [5] that design can be categorised in relation to two broad approaches; theoretical and pragmatic, as illustrated by Fig. 14.2. In practice, these extremes do not exist in isolation, but co-exist along a continuum within the design process. What is perhaps of more significance in relation to course design is that students, inevitably, lack the range of experience associated with established design engineers, and this then impacts on their approach to problem solving [12, 13].

Here, we shall consider issues associated with achieving a design-based input through a combination of project- and problem-based learning linked to mechatronics and looks at these from a range of perspectives including the need to encourage innovation and student perception [14–19].

14.3 The Challenge of Teaching "Innovation"

Innovation and, by extension, the ability to innovate, is a key element of any Engineering Design process and one that needs to be encouraged and developed within a mechatronics course. In the widest sense, the ability to innovate impacts upon issues such as market penetration and the ability to develop, implement and introduce new products to market ahead of competitors, and to maintain that position over time.

Typically, innovation is seen as a continuous and dynamic process involving investigation and feedback across a number of individuals. However, until relatively recently, innovation was considered by many companies as a closed process. An alternative approach, that of open innovation, takes as its goal not simply preserving a current market, but actively seeking to grow and develop other market areas through importing ideas, concepts and technologies as appropriate.

14.3.1 Open and Closed Innovation

Innovation, in all its potential forms, is key to the achievement of new generations of products and systems. In order to develop and take forward the innovative process to meet a new set of challenges, Chesbrough [20, 21] has suggested the need for a shift from the traditional approach, defined as Closed Innovation, with its orientation towards secrecy and the retention of ideas to one of Open Innovation in which ideas and solutions are widely sought from both within and from outside the organisation.

The relationships between these two divergent approaches can be seen in Figs. 14.3 and 14.4. From these, it can be seen that they each represent a significantly different focus on the innovation process, both in terms of the value of ideas

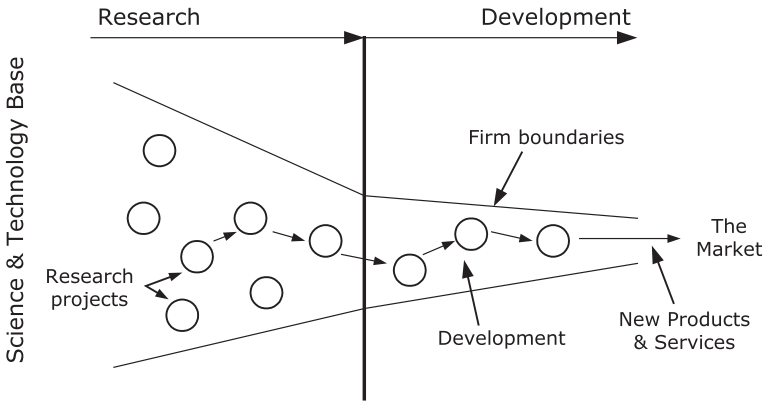

Fig. 14.3 Closed innovation

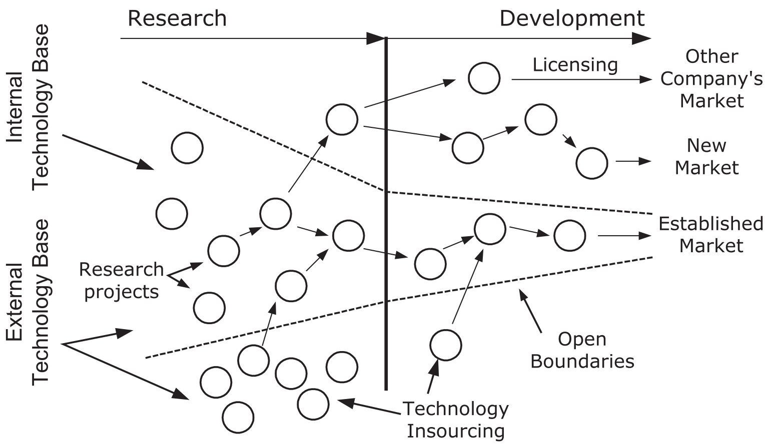

Fig. 14.4 Open innovation

and the ways in which such ideas are to be incorporated into that process. The revised methodology represented by open innovation has been adopted by organisations such as Proctor & Gamble [22] and the US Department of Education [23] to create platforms to develop and take forward new ideas, but perhaps more importantly to bring in new ways of thinking from outside the organisation. Similarly, IBM runs an annual "*Innovation Jam*" as part of its Global Innovation Outlook [24]. Though the underlying motivation, in one case growing company profitability and in the other enhancing an education system, may differ, both are exhibiting a degree of openness by inviting external bodies, groups and individuals to submit their ideas into a central 'pot' for consideration.

14.3.2 Students and Innovation

In 1998, John Prados [25] suggested that Engineering graduates were perceived as having a range of weaknesses, including:

- Technical arrogance
- Lack of design capability or creativity
- Lack of appreciation for considering alternatives
- Lack of appreciation for variation
- Poor overall perception of the project
- Narrow view of engineering and related disciplines

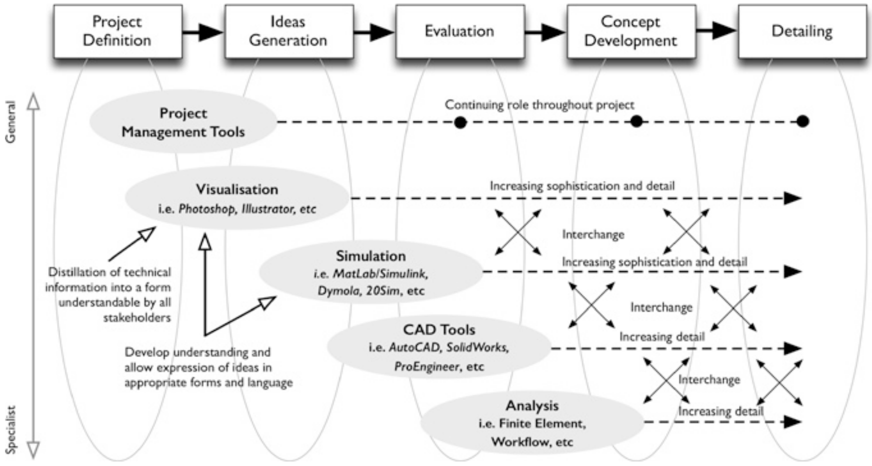

Fig. 14.5 Design support tools

- Weak communication skills
- Little skill or experience in working in teams

In developing innovative thinking by students, all the above issues need to be considered, some of which may well, however, be in conflict with the administrative requirements associated with grading and the ability to differentiate between individual students in assessment schemes [26–32].

There is a range of tools available to support both the design process (Fig. 14.5) and communications between members of the design group [8, 9, 33,34]. In terms of encouraging an innovative approach to design problems, in which the aim is encouraging students to bring forward new and novel ideas, there is a need to create an environment where trying and failing is not considered as a failure in relation to a student’s ability to progress or pass the course or module. This means that students are then free to put forward ideas and pursue options in an environment in which the emphasis is on trying and not on failing, i.e.: “*Try and fail, but don’t fail to try*”.

However, students often focus on the requirements necessary to achieve a particular grade, which in turn tends to lead them to be conservative in their approach as they attempt to ensure that they achieve the necessary marks for the target grade. This conservatism then runs contrary to the requirement to encourage innovation at the expense of an occasional failure to achieve set goals. Thus, insistence on the allocation of a grade, and of differentiating between students, can have a negative impact on the level of innovation.

In this respect, consider student reaction to the essay topic: "*Eli Witney and the origins of mass production*", which was posed in a manufacturing course. Students were told:

- That there was no predefined or predetermined content required to achieve a particular grade.
- That the emphasis was to be on their ability to source, organise and interpret data available from a variety of sources.
- That in order to obtain a passing grade they were required to demonstrate that they had carried out a level of research and analysis associated with basic information gathering.
- That to achieve a higher grade they were required to demonstrate that they could organise and arrange the information to tell a specific story of their choice using the title as guide.
- The length of the paper.

A comparatively small number of students took advantage of the flexibility to develop a case while the majority took the conservative approach of ensuring they did what was required to pass but then did not feel that they wished to take on what they perceived were the potential risks associated with the achievement of a higher grade.

14.3.3 Choice of Tools

Once a design brief has been given to students, they are then typically given access to a workshop or laboratory for construction of their solutions. The equipment and construction components they are given access to will influence their design process. For example, it is common to use standard components such as Arduino boards and associated sensors [35] or Lego Mindstorms [36] in first or second year mechatronics projects. The choice of which of these components are available will push students down particular design paths. While such provision may simplify the project for the students, as well as keep costs down, it does come at the expense of a level of restriction on design creativity.

One possible solution to the cost issue is the use of computer simulations of components through the kinematic modelling of their properties. An example of such an approach was the variable fidelity prototype developed for the Interactive Robotics Visual Inspection System (IRVIS) [37], which was an accurate model of both the size and kinematic response of robot with five motors and five degrees of freedom—see Fig. 14.6a, b. Such a virtual prototype can be reconfigured, redesigned and completely altered with a few lines of code for absolutely no cost.

The advantages of using a working model that can be adjusted quickly and for comparatively little resource cost when trying to teach innovation are obvious. Students are encouraged to explore different options, because the effort involved

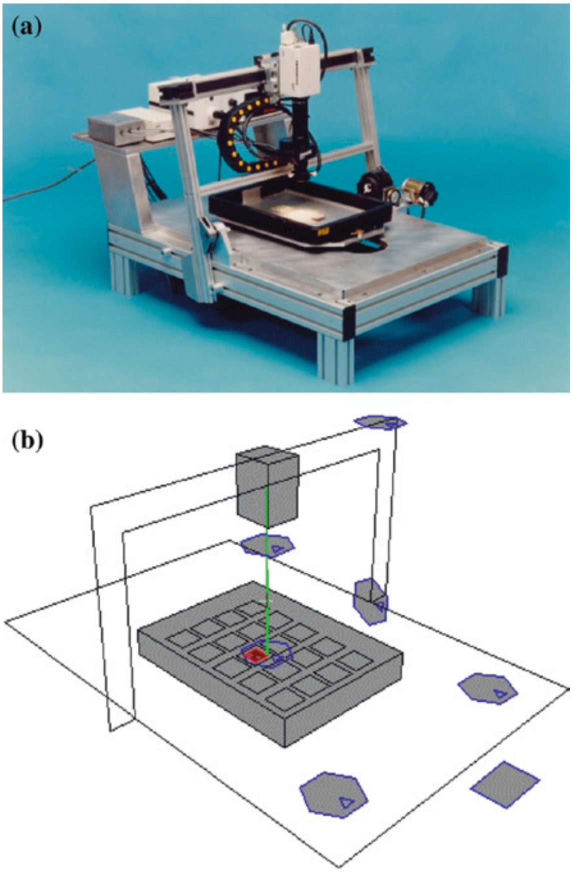

Fig. 14.6 Virtual prototyping in design education, **a** interactive robotic visual inspection system (IRVIS) consisting of a camera mounted on a gantry above a moveable tray of microcircuits. The robot has 5 degrees of freedom. **b** the variable fidelity prototype—a virtual model of the IRVIS robot with authentically modelled kinematic performance

in creating alternative options is minimal and the feedback on the success or otherwise of their design is very quick. However, the model does need to be flexible enough to support more radical design solutions, otherwise what may be intended as a tool to promote innovation may itself become a limitation on that same innovation if students cannot explore and examine all of the design variations they can conceive.

14.4 Approaches to Assessment

As design is generally a group or team exercise, it is sensible to incorporate a group design exercise within a design-oriented mechatronics course. This, however, leads to issues of ensuring that the marks and grades reflect the contribution of the individual members of the group. Strategies that have been used include:

Flat marks	Each member of the group receives the same mark irrespective of their contribution to the final report. This can work if balanced by the internal peer pressures of the group ensuring a balanced level of activity across all members
Individual contribution	Assessing an individual student's contribution could typically involve an agreed introduction and conclusion for which each member of the group would be awarded a shared mark. The individual contributions to the overall project would then be identified and the sections of the report associated with particular responsibility and activity graded separately This approach generally works best where group members have either identifiable skills or worked on clearly demarcated components. The classic example is the development of a robot for following a white line where students can be allocated responsibility for building (i) the robot chassis; (ii) the sensor array; and (iii) the control code
Combined marking	An alternative approach is to couple the project work with an examination that is designed to establish a student's overall depth of knowledge of the project. For example, students are first asked to write a group project report, which is then graded for the whole group. The group is then invited to make an (ungraded) presentation on the report summarising the key findings. The students are free to decide who presents what. This presentation is then followed by individual oral exams, where the group project marks can be increased or decreased by up to one grade Such an approach gives the students an incentive to work well as a group, because they all benefit from a high initial report grade. However, the students feel some degree of confidence that weaker members of the group will be found out in their individual exams and so there is an element of correction in the final grade. Similarly, very able and diligent students also have the opportunity to improve their grade if there had been a problem elsewhere in the group
Peer assessment	Peer assessment can be used in association with either of the above but with a proportion of the marks being held back to be allocated by members of the group to the other members of the group to reflect their perceived contribution Each of the above has been used in association with group projects in design, and each has been met with various degrees of scepticism by students. However, the general view was that the overall marks awarded reflected the contribution by the individual group members A further approach used where groups were competing on the same project brief, as for instance representing individual design groups tendering for a project, was to distribute the reports to other teams prior to marking and asking for a critique of the these to be submitted. These critiques were then graded, with the grade then contributed a percentage of the overall grade. The results from these critiques were generally very interesting, as the majority of teams did not set out to attempt to destroy the other's case, but to genuinely perform a critical analysis of the proposal. Two instances are of particular interest: • One group commented that they wished they had thought of an idea put forward by another group and followed this up with a detailed analysis to demonstrate why they still thought that their solution was superior • Another group commented to the effect that after doing the critique remarked on "*the problems of grading such reports*" and that they had never appreciated these previously

14.4.1 Measures of Success and Success Criteria

The challenge of how to grade such reports is interesting. In any design activity, one of the earliest considerations is that of what measures of success are to be used. Put simply, if two designs are to be compared, what evaluation criteria are to be used? Again there is a range of possible strategies.

For example, consider the classic Civil Engineering student design problem, that of building a structure to span a gap supporting a specified weight at the mid-point. Typical measures of success are (i) whether the structure supported the load; (ii) the weight of the structure; and (iii) the "*cost*" of the structure, which is usually calculated based on the cost of the components and the labour time for fabrication. Most students typically design a traditional truss-type structure, usually a Pratt or Warren truss, because that is what they automatically assume will be the most effective structure. In reality a Waddell-type truss, i.e. a very large triangle design is usually the most cost-effective solution.

A typical mechatronics project is substantially more complicated than this and thus less straightforward to assess, not least because it will necessarily involve multiple Engineering disciplines and multi-skilled teams.

14.5 Teaching Mechatronics—An Example

We have comprehensively overhauled the entire Engineering undergraduate experience at the University of Greenwich. As with many newer universities, the focus of Engineering programmes had typically been on the acquisition of technical knowledge. Consequently, the entire pedagogical experience had been focused on technical instruction, typically in the traditional forms of equations and laws, delivered through lectures supported by laboratory sessions. Assessments were largely exam-based, with traditional mathematically heavy questions where answers were typically either correct or incorrect. Exploration of problem and solution spaces is difficult to encourage in this context.

While the acquisition of technical knowledge is clearly a key requirement of any undergraduate programme, the pedagogical focus on this somewhat narrow goal tended to miss the wider objectives of preparing the students for professional practice. In particular, important skills such as innovation, creativity and engineering "*instinct*", the ability to look at a design and have a realistic view of its merits and weaknesses, were not typically taught. This apparent oversight was not because the academic did not appreciate the value of such skills, more that the programme structure and assessment practices did not lend themselves to supporting them, for the reasons discussed earlier in this chapter. Furthermore, the programmes were delivered in a heavily silo-ed approach, which made the delivery of strongly interdisciplinary subjects such as mechatronics inherently difficult administratively.

Given that we believe that with the rise of notions like the Internet of Things [38], the traditional silos are increasingly archaic, we took the step of completely re-thinking all of the programmes. A number of new degree programmes were introduced, such as Design, Innovation and Entrepreneurship—to help encourage the next generation of entrepreneur–inventors—and Engineering for Intelligent Systems—which is, in effect, a degree in mechatronics.

A new common first year, focusing on the fundamental principles of Engineering Science, was introduced for all Engineering students, whether studying on traditional programmes, such as Civil or Mechanical Engineering, or the newer programmes. The new first year consists of four double-courses:

Engineering mathematics	Students explore a range of engineering problems through which relevant Mathematical skills are taught
Practical and experimental skills	Students are provided with the lab sheets at the start of the year, complete with theoretical primers that are to be completed prior to the lab sessions. The lab sessions then focus on "*learning by doing*", i.e. verifying the theoretical answers through replication in the labs
Engineering professional skills	Students are taught the wider aspects of becoming a professional engineering, such as communication (including essay writing, critiquing, how to précis and presentation skills), risk assessment and management (including the study of engineering failures), ethics and management, among other skills
Design and materials	This consists of some traditional Materials instruction coupled with an introduction to Engineering Design. These complementary topics are then combined into a group design, build and evaluate mechatronics exercise.

An example challenge is to build a remote-control boat. The students are given a budget of £50 and are allocated a material out of which to build their hull. These materials can vary from newspaper to plastic drinks straws or ice cream tubs. A series of challenges for the boats to complete are set, around attributes such as speed and manoeuvrability. For example, in any one year the challenges may include:

- Build the fastest boat.
- Complete the obstacle course in the fastest time and with the fewest penalties.
- Be the most aesthetically pleasing.
- Be the best value-for-money.

Students then have to decide for which challenges to prioritise with their designs.

A possible grading scheme could be developed by attaching values to each of these factors and a simple algorithm implemented to calculate a total "score" for each group. However, once the students become aware of how the scoring algorithm works, this knowledge will axiomatically influence how they approach the design process, thus potentially stifling their creativity. For example, should encountering an obstacle be more heavily penalised than, say, time to complete a traverse, then the students will begin to prefer slow, but steady solutions.

DARPA addressed this issue in its self-driving car challenge [39] where the criterion for success was simply that the first vehicle to cross the finish line wins. A consequence of this approach is a wide variety of highly innovative entrants. Similarly, the *Robot Wars* television programmes had an equally direct approach to establishing the "better" design—a fight until only one robot remained and all opposition had either been immobilised or ejected from the arena. Again, there was a similarly wide variety of innovative designs among the entrants. We are in the process of working with the team behind Robot Wars to establish an outreach programme to local schools to inspire the next generation of mechatronics students by helping schoolchildren design and build robots to compete in Robot Wars.

The solution that we use was inspired by the role of the jury on Robot Wars where a panel of external experts is used to assess each finished design against each of the stated challenges and category champions identified. Those champions then progress through to a final round and a "*champion of champions*" is named as the design that, in the opinion of the experts, best meets as many of the challenges as possible.

14.5.1 In Summary

Engineering Design is a major element of mechatronics and can form the unifying theme throughout such courses. However, the requirement to encourage innovation is often in conflict with the requirements of "quality" and of the need to assign grades to all forms of student-based activity, even when doing so encourages a conservative approach to design. Instead, the aim should be to encourage innovation, and even failure, as to reward students for the adoption of an innovative and a novel approach.

One possible way of accomplishing this is to simplify the criteria or measures of success as much as possible—ideally to a single such metric, e.g. the fastest or the lightest. It is also suggested that all mechatronics programmes focus not only on the development of working solutions, but also on how the solutions fit within the wider environment of use, including their users.

14.6 A Final Note—Do not Forget the User

A common failing among many mechatronics projects is a focus on the technical capability of the device or robot being constructed. This failing is not restricted solely to students; it pervades many mechatronics industrial and research projects. For example, the first iteration of IRVIS project [37] discussed earlier failed to produce a usable robot. The development team had spent 3 years developing the robot and ensuring that it functioned. The interface received scant attention until almost the very end of the project such that when the robot was taken to the industrial test site, the interface was a barely developed version of the testing interface used to drive the motors individually. The final user acceptance test was a failure, because although the user could move each of the motors individually, the visual inspection task required complex simultaneous motor control, which the interface simply did not support.

A second three-year development cycle was required to address these shortcomings. The original development team was replaced and their parting advice to the new team was that the acceptance trials failed because the robot was under-specified and needed a (very expensive) complete overhaul. The new development team instead focused on developing a working interface by focusing on the end tasks of the user. A more complete, task-focused interface was developed and the user acceptance trials were completed with no significant shortcomings being identified. No overhaul of the robot itself was required. The deficiencies in performance suggested by the first set of user trials was a result of the motors not being driven effectively—one at a time instead of combinations together.

The experience of this project is unfortunately common among many such mechatronics projects. In a very insightful paper, Buhler examined the success of several of the major EU TIDE Rehabilitation Robotics projects in the 1990s [40]. His conclusion was that only one of the projects that he evaluated (the MANUS project [41]) had achieved its original design objectives and had achieved a respectable degree of success. All of the other projects were considered failures and the most common reason for failure that was identified was a focus on the technology to the exclusion of almost all other considerations.

Clearly, any mechatronics programme must bear this in mind and ensure that students are aware not only of how to develop such systems, but also how they interact with the wider environment, including their users. Such considerations are routinely taken into account in other specialist domains, such as medical device design and it is suggested that mechatronics students are made aware of such broader approaches to Engineering Design.

IRVIS, as a mechatronics product, was very basic compared with the capabilities of modern systems, such as RoboThespian, shown in Fig. 14.7. RoboThespian has been designed explicitly to mimic human movements and appearance. Final year students are taking up projects to explore how people may wish to interact with the robot and it is straightforward to code and implement lifelike responses. At the same time the success of the IBM Watson system in answering unstructured questions in the Jeopardy!^{TM} challenge [42] shows that "*artificial intelligence*" is developing apace.

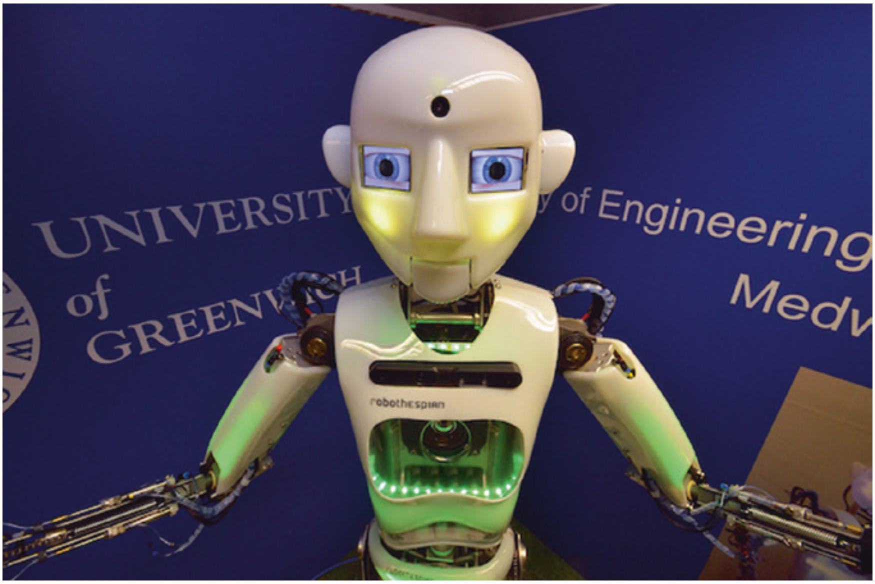

Fig. 14.7 RoboThespian

14.7 The Future

Mechatronics is moving to a future where the design of complex physical components is becoming commoditised, i.e. it is becoming easier to find complex products off-the-shelf, meaning the real area for innovation is in exploring innovative ways to use such capabilities to interact with people.

As we have seen, mechatronics is necessarily a cutting edge discipline where technology is changing rapidly. Humanoid robots, such as RoboThespian, that were the stuff of science fiction only a decade or so ago are now available to purchase. Their cost is still prohibitively expensive for many degree programmes, but similar technologies have shown that an order of magnitude decrease in price is eminently achievable over a relatively short time span as the technology becomes increasingly commoditised.

Indeed, this process of commoditisation is changing much of Engineering and Technology education, as increasingly complex functions do not typically need solutions to be custom built from scratch. Instead, increasingly powerful modular components can be brought together as an assembly, and with the correct settings and control coding can accomplish complex tasks without students needing to reach for the soldering iron.

While it is still very necessary that students understand what goes into each modular component, how they are designed, and what their capabilities and limits are, there is also a growing challenge in terms of the opportunities that are now opening up. The power and potential of these systems means that engineers and designers are now on the verge of being able to think very ambitiously about what they would like their device or system to accomplish, almost unlimited and unrestricted by the capabilities of the hardware. We are not quite there yet, but the capability of the technology is now only a small step behind that of the imagination of the typical Engineering student.

The impact of the next generation of mechatronics devices is already being felt. Take, for example, the rise of 3D printing. In the 1960s and 1970s, companies began to realise that labour costs in the developing world were very much less than in developed countries. The notion of offshoring was born and the following few decades saw the manufacture of low added value products in particular being transferred from countries such as the US and UK to the Far East and elsewhere. However, it is highly likely that the "*no labour*" costs of 3D printers will undercut even those low labour costs, and also have the added advantage that the products can be made at the point of demand and do not need shipping halfway round the world. Once 3D printers and other similar technologies become sufficiently commonplace, the money to be gained in manufacturing will move from those who can make the product most cost effectively to those who can design the most useful or desirable product.

Similarly, the Internet of Things is also an increasingly important development that has the potential to change the world in which we as much as the Internet itself has done since the early 1990s. Again, technologies that are already available are capable of supporting many exciting innovations. However, it is still looking a little like a solution in search of a problem. The only innovations that have thus far gained any notable traction in the market place are somewhat mundane, with elements of home automation, home security and heating applications initially being the most pervasive Internet of Things solutions in the marketplace. Such applications are only scratching the surface of what the technology can support. However, designers and developers are still struggling to find the "*killer application(s)*" that will lead to sufficient homeowners investing serious money in the necessary Internet of Things infrastructure in their house.

Changes in the general population also need to be considered. Many countries in the developed world already have populations that can be considered aged, rather than ageing. There is a clear need for more technology to help support people in retaining their ability to maintain independent living in their own homes [43]. Mechatronics will underpin much of the new developments in telehealthcare, assistive technologies and support for the activities of daily living [38]. However, designing for older adults or those with disabilities involves particular design challenges because of the variety of user functional capabilities [44] that may be encountered as well as different user priorities and goals [45]. Consequently, future mechatronics engineers will need to understand as much about consumer wants, needs and aspirations as they will about, say, different types of motors.

To reiterate what was stated in the introduction to the chapter, The goal of any good degree programme is to not only prepare each student to secure their first job, but also to give them the correct skills and mindsets to retain employment throughout their entire working life, requiring educators to consider how mechatronics is likely to change in the mid- to longer-term future, and how these changes are likely to impact on course content, structure and delivery. This is a particular challenge in a discipline such as mechatronics with all its diversity. The solution must be to aim for a balance between:

- Technical knowledge—Providing sufficient content about the technology of today.
- Underlying fundamental technical skills—Skills such as Design and Mathematics will support graduates throughout their working life.
- Personal skills—These encompass lifelong learning, adaptability, problem-solving and open-mindedness that together make up a flexible and adaptive mindset, open to new challenges.

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