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Teaching engineering design through Lego® Mindstorms™

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This paper examines a particular methodology of teaching engineering design to undergraduate engineering students, which relies on Lego® Mindstorms™. A number of important issues are addressed, including the timing of the design module within the programme, prior knowledge required and assessment components. The module, which has been running for three years, was found to have many positive attributes, not only in relation to the core design activity, but also in generating good team-building and engaging students with the degree programme.

1. Introduction

Many engineering degree programmes incorporate some formal learning on engineering design into the syllabus. This is, essentially, the 'engineering' in all the different disciplines, incorporating:

- systematic problem-solving skills;
- creativity and creative design;
- working with constraints and real-world situations;
- requirements assessment and communication of final design to potential clients.

In general, these skills are generic to all engineering disciplines, with perhaps the implementation medium differing from discipline to discipline.

There is little doubt that every engineering programme should engender engineering design skills in its students, but there is considerable variety of opinion on how this should be achieved. The Accreditation Board for Engineering and Technology (ABET) is reasonably specific in that it requires students of accredited programmes to have 'an ability to design a system, component or process to meet desired needs'. ABET (2002) further goes on to define engineering design formally as:

> Engineering design is the process of devising a system, component or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria synthesis, construction, testing and evaluation.

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Perhaps a 'natural' way to include design is through laboratory, assignment and project work, supported by a formal lecture programme that emphasizes creativity and problem-solving. This approach has a number of advantages:

- Time does not need to be taken from the traditional technical subjects.
- Engineering design is, arguably, demonstrated across a variety of technical areas.
- There is no need to search for some 'generic' engineering design problem prior to students having enough technical knowledge to approach a meaningful design problem in a relevant technical area.

There are, however, a number of drawbacks associated with this approach:

- Students may never encounter any formal design methodologies, with reliance on students 'picking up' the general idea.
- Design and creativity are necessarily left until the latter years of the programme, by which time students may be bored with the seemingly endless volume of physics, mathematics and technical formulas.
- The synonymous association of 'engineering' and 'design' may never become obvious to engineering students until they have graduated.

An alternative approach, which abrogates a number of these drawbacks, is to include a specific module (or modules) on engineering design, which illustrates the universality of design, its synonymity with engineering and exposes students to a number of formalized design methodologies. Arguably, any attempt to impose a procedure on the design process potentially stunts true creativity, but the emphasis here should be to expose the student to a set of loose tools which can aid the designer in maximizing creativity while achieving a successful and acceptable final design.

From the last comment, the reader may suspect that these authors are fans of the latter approach – indeed, this is true! However, this approach is not without its own problems, mainly centred on selecting a suitable context in which to place any engineering design module. Arguably, engineering design can be taught in the abstract, but it is the practice of design which is likely to have the greatest impact and engender true creative skills. An issue which impacts the problem of context is that of timing in the programme and finding space in an otherwise busy curriculum. If design is to be taught in the latter years of an engineering programme, then engineering students will have the requisite technical knowledge across a number of technical areas, and the problem becomes one of merely selecting one or, indeed, of deciding on an appropriate combination. If, however, it is desired to expose students to design at an early stage, the context must be carefully chosen, so that students can focus on design aspects, rather then wrestling with the technical minutiae. Clearly, including specialist design material at an early stage is challenging, but offers a number of important possibilities:

- Students are immediately enthused with the creativity that engineering offers.
- There are significant opportunities for team-building that are not, perhaps, present through more traditional subjects.

The context problem, however, still remains, and the ideal solution is one which:

- Provides wide scope in terms of solution options, allowing maximum creativity.
- Is representative, to a reasonable degree, of the general engineering discipline which the students are enrolled on.
- Is representative of a real-world problem which includes well-defined limitations.
- Is as 'hands-on' and visually stimulating as possible.

The remainder of the paper is laid out as follows. Section 2 looks at current perceptions of undergraduate engineering education and outlines the context of the ECE programme at NUI Maynooth. Section 3 documents the specific module in engineering design incorporated into the engineering programmes at NUI Maynooth, with sections 4 and 5 focusing on the assignment task and its evaluation respectively. Finally, conclusions are drawn in section 6.

2. Current views and practice

Considerable variety currently exists among different universities as to how design is incorporated into engineering programmes. Typically, mechanical engineering departments have more focus on design often relating to physical or visual design. As an example, the Mechanical Engineering Department at the University of Bath in the UK recently recast its MEng programme with design as a central theme (Medland and Culley 1999). However, the incorporation of design into electrical/electronic/ECE programmes is perhaps not quite as straightforward.

Larger US universities, operating fully modularized programmes, typically weight each course in terms of design (and other) points. In order to be eligible for the Bachelor award in engineering, students must have achieved a certain number of 'design points'. No doubt, ABET plays a role in this and MIT, for example, has a set of programme objectives which are entirely consistent with ABET requirements. MIT and Stanford both provide good examples of systems employing engineering design points, with Stanford's Mechanical Engineering Department having a special 'Design Division', with the provision of 126 design-related courses (Books for Designers). A number of these courses relate to visual and graphical design, as might be expected in the mechanical discipline. Interestingly, one of the design courses provides an introduction to robotics, and many of the courses involve group projects. An example of a US university which has a very specific course on engineering design is the University of Washington (Enterline 1997).

On a slightly smaller scale, UK universities present a different picture. As examples, the major UK electronic engineering (EE) schools of Imperial College and Strathclyde University have no specific design courses, though compulsory projects are undertaken in years 1, 2 and 3 of the programme at Imperial. Cambridge, on the other hand, has year 1 courses on structural design and product design, with an integrated design project in year 2, where teams of six compete against each other in a robotics challenge. In some cases, consortia have assembled to provide a concerted approach to electronic design, but many of these seem to be more focused on tools than techniques (Hicks and Noakes 1995).

As a context, the UK accrediting body of the Institution of Electrical Engineers expects that accredited degrees will: 'be taught in the context of design, so that design provides an integrating theme that exposes students to a blend of analysis and synthesis'. However, it is unclear as to how this translates into specific programme requirements though, arguably, it does not identify any need for courses specifically on engineering design.

In Ireland, the accrediting body of the Institution of Engineers of Ireland specifies a requirement of accredited programmes as: 'Design studies will include consideration of general principles of design and of techniques specific to particular engineering products and processes', thus advocating studies in non-technology-specific generic design methodologies.

Among Irish universities which have accredited electronic engineering programmes, there is essentially a dichotomy in how design is incorporated. Only Dublin City University (DCU), like NUI Maynooth, has a specific course on electronic engineering design, while NUI Cork, NUI Galway and the University of Limerick incorporate design into various technology courses. NUI Dublin, though having no specific course on electronic engineering design, have a year 1 course on engineering graphics.

The literature is relatively rich with views on engineering design education, but overall little consensus is reached. Sale (1999) argued for design education through projects, but suggested that educational institutions should structure the design component in terms of clearly identifying inputs and outputs. The paper also contains an interesting classification of gender-specific design domains. Interestingly, a paper by Lee and Messerschmitt (1998) of Berkely, which looks at the future design of engineering curricula, does not appear to advocate the teaching of abstract design skills (rather to teach through technical subjects), though design is surely mentioned 100 times throughout the paper! There is little in the literature in respect to specific introductory design exercises for electronic engineering students. Papers that do address the specific issue of design education for electronic engineers typically focus on design that is integrated with electronic technology at advanced stages of EE programmes (e.g. Croskey 1993).

Usually, real-world design is accompanied by group interplay, with significant emphasis on communications skills through group discussion, report writing and presentation. It is therefore unsurprising that a number of authors place emphasis on assessment of design exercises in engineering programmes, with some useful observations in Safoutin *et al.* (2000) and Webster (2001).

The timing of engineering design is dealt with by a number of studies, with some authors focusing on the need for early exposure to design, with a view to engendering the design ethic in students at an early stage (Parsons and Klukker 1995, Sheppard and Jenison 1996, Courter *et al.* 1996, Tonkay *et al.* 1997, Patel *et al.* 2002). Particular emphasis is placed on motivation and student retention.

Using design competitions as both exercises in real-world experience and as motivational tools had also been examined in a variety of contexts by Titcomb *et al.* (1994), Davis and Masten (1996) and Padgett (1997). In particular, the use of robotics or mobile robots as a design target is documented in Boyle and Kaldos (1997), Avanzato (2000) and Ahlgren (2001).

Though a number of diverse perspectives on engineering design pervade, there is a body of evidence and experience which supports the teaching of engineering design at an early stage in the curriculum through competitive group projects in a variety of domains/contexts, including robotics. This paper builds on these experiences and provides, we believe, further evidence that supports this mode of engineering design education.

Finally, an interesting paper by Smyth and Olszewski (1993) looks at the interplay of the roles of the engineering professor, technical staff and students in engineering design exercises. This relates to the work documented in this paper, since two of the authors are with the technical staff of the Electronic Engineering Department at NUI Maynooth.

For further reading on design and design education, the authors can recommend the excellent range of references available on the 'Joint Programme in Design' website of Stanford University (Books for Designers 1999), while useful texts on engineering design include (Pugh 1991, Hyman 1998, Voland 1999, Dym and Little 2000, Cross 2000, Dominick *et al.* 2001, Salti and Rothery 2002). Pugh (1991), Voland (1999) and Hyman (1998) provide some very nice real-world examples of successful (and unsuccessful!) engineering designs, documenting a number of illustrative case studies. Cross (2000) and Pugh (1991) focus mainly on mechanical design while Dominick *et al.* (2001) and Dym and Little (2000) have what we believe are the most usable procedures for generic engineering design, particularly at the junior undergraduate level. Salt and Rothery (2002) focus on design aspects, with particular relevance to ECE programmes.

3. A module in engineering design

This section documents the rationale for the position of the engineering design module within the BE programme and articulates the pedagogical design and content. In addition to this featured introduction to engineering design (year 1), design features in the technological subjects more strongly in the latter years of the programme, as assessment moves from fairly structured laboratories to more free-thinking design exercises, assignments and mini projects. The (usual) final-year project provides the most significant design exercise of the entire programme. Further details on the ECE programme at NUI Maynooth can be found at http://www.eeng.may.ie/pages/programmes/courses.htm

3.1 *Module timing and level*

Given the inextricable link between engineering and design, it is vital (in our opinion) to highlight this link to engineering students at an early stage. At least one of the authors here can testify to not making the connection at all during his four years of undergraduate education! Furthermore, since design underpins all of the engineering technologies, it is important to give some design methodology to students at an early stage, which can then be utilized in the technological subjects. Further support for early introduction of the module is available in the following points:

- It is desirable to encourage creativity as early as possible.
- The group assignment associated with the engineering design module can be a significant help in improving the social interaction of first-year students and bonding of the class body.
- Given that engineering degree programmes are traditionally perceived as difficult, with a high content of (possibly abstract) mathematics and physics in year 1, it can be beneficial to provide an ‘alternative’ module, which is ‘lighter’ in content, gives a sense of accomplishment, engenders a belief in students that they can, even at a relatively early stage, do useful engineering work, and is enjoyable, and therefore serves to improve retention rates at the critical year 1 stage.

A more minor point, which also supports the introduction of the module in year 1, is to lessen the number of formal examinations at that stage, since the module is exclusively continuously assessed.

3.2 *Pedagogical design of module*

The module in engineering design, unlike most of its year 1 counterparts, has a relatively small amount of formal instruction and relies exclusively on continuous and non-traditional assessment, with no end-of-semester examination. The module is essentially built around the assignment, with supporting lectures and tutorials, and assessment based on assignment outcomes. Arguably, this places the module in the domain of problem-based learning.

3.2.1 Formal lectures. Approximately 8 h of lectures on engineering design methodology are given, with introductory material on the centrality of design to engineering science and motivational topics. The following list itemizes the syllabus:

- Introduction to design, centrality, definition.
- Perspectives on engineering design – design (synthesis) versus analysis.
- The design process – a procedural approach.

- Models for design process
  - Hyman (1998) model.
  - Voland (1999) model.
  - Pugh (1991) model.
  - Dym and Little (2000) model.
  - Dominick *et al.* (2001) model.
- Stage 1 – Problem definition.
- Stage 2 – Formulating/conceptualizing solutions.
- Stage 3 – Detailed design.
- Stage 4 – Presenting and implementing designs.

As can be seen from the list, five engineering design paradigms are presented and then followed with a detailed discussion on four generic components, which are essential introductory design material and also relevant to the module assignment. Supplementary sessions are held on:

- presentation skills (in the context of the design assignment);
- report writing skills (in the context of the design assignment).

They are the main modes of assessment. However, the first semester in year 1 contains a half module on communications skills (in Professional Skills), so these sessions just provide some revision and focus on aspects particular to the design assignment.

3.2.2 Tutorials. Tutorials are provided on both Lego® Mindstorms™ hardware and software. The hardware, apart from the RCX™ block (which contains a microcomputer), is fairly intuitive and many students will have met Lego® somewhere in their childhood, so a single 3 h tutorial is allocated to this. The software presents somewhat more of a challenge, but students will already have been introduced to computing in semester 1 (including basic C programming), with a second computing module (more advanced C programming) taken concurrently with the module on engineering design in semester 2. Software tutorials (approximately 9 h in total) tend to focus on variations in the Mindstorms™ programming language, Not Quite C (NQC), from standard C. This includes specific commands to set up inputs and outputs, read from sensors and issue drive commands to motors. Also, multiple tasks can be handled concurrently, using the *tasks* command, which students will have no familiarity with.

3.2.3 Assignment. The assignment is key to the success of the module. Essentially, it is the problem, where the module can be considered from a problem-based learning approach, solved by students in groups of three. As documented in sections 3.2.1 and 3.2.2, tutorial and lecture support are provided in the context of the assignment, with all assessments being assignment based. The assignment occupies approximately 60 h, with two 3 h sessions per week, following the end of the formal instruction. In order to control the amount of time spent on the assignment, students' groups only have access to their Mindstorms™ kits during these sessions. One session per week is 'supervised', with advice being available on aspects of design and the Lego® Mindstorms™ hardware and software. It is also expected that students spend approximately 8 h (during the course of the project) of their own time in sourcing materials and researching the problem. Further detail on the assignment is given section 4.2.

3.2.4 Assessment. The module assessment is broken down as shown in table 1. A number of assessment elements are noteworthy:

Table 1. Assessment breakdown.

Assessment component	Maximum mark allocation	Timing
Project plan	10	Week 5
Practical assessment (competition)	Creativity 10	Week 12
	Performance 15	
Final report	Evidence of structured design 25	Week 12
	Quality of reporting 10	
Presentation	10	Week 12
Workload contribution – peer mark (assigned by other group members)	20	Week 12

- A small amount of instruction on the preparation of the project plan is given, as part of the 'supervised' lab sessions. Students are also asked to review their plan as the assignment progresses and to conclude on the value of their plan in the final report. Plans should indicate how the project workload is broken down between group members, as well as showing the proposed project schedule, usually illustrated by a Gantt chart.
- A single final report is solicited, for which a group mark is given, where evidence of structured engineering design is emphasized. This attempts to ensure that students focus on design aspects in their report (and assignment), rather than becoming experts in Lego® Mindstorms™!
- In the practical assessment, which occurs on competition day, marks are awarded for task completion. However, a prize is awarded to the team which successfully completes the 'course' in the minimum time.
- Presentations, 15–20 min in duration, must include participation from all team members.
- Peer marking is carried out by students, which gives an individual mark component for each student. All students are asked to mark themselves and their other group members in terms of per cent contribution to the group effort. The averaged peer mark for each student is then used to weight the group mark to provide an individual score out of 20.

4. Assignment

The assignment task must be carefully chosen to provide a sufficient (but not too extreme) level of challenge for students, while exercising planning, hardware and software abilities. Over the three years, a variety of assignments have been used, which have provided some experience upon which to pitch the degree of assignment difficulty.

4.1 *Assignment design*

A number of issues are considered in the specification of the assignment task:

- A solution must be possible using a standard Lego® Mindstorms™ kit, containing three motors, two light sensors and two touch sensors.
- A wide variety of Lego® Mindstorms™ robot designs are documented on the Internet and elsewhere – ideally an assignment domain should be found which has few, if any, ready-made solutions.
- There should be considerable freedom in how the task can be solved, in order to encourage diversity in design approaches.

- The assignment task should also have a number of real-world limitations which, in this case, manifest themselves as: (i) *Time*: access to materials is only given for 60 h; *Human resources*: group of three with no outside (personal) assistance; and *Components*: only the Lego® pieces in the standard set may be used.

Clearly, Lego® Mindstorms™ provides an excellent platform on which to base the assignment, since:

- the number of ways in which parts can be combined is virtually infinite;
- an enormous variety of devices can be constructed, including a wide range of autonomous mobile robots;
- Lego® has excellent intuitive and visual appeal;
- the software and hardware abilities required in synthesising Lego® designs are entirely consistent with engineering science;
- exactly the same kits can be used from year to year, with virtually no repetition in design features.

4.2 *Task description*

Three different tasks have been used over the brief history of the design module:

- *Year 1*: drink-can collection on a single table (task 1).
- *Year 2*: drink-can collection over two tables connected by a bridge (task 2).
- *Year 3*: activation of an electronic beacon over two tables connected by a bridge (task 3).

The following are common to all tasks:

- Performance is calculated over two robot runs.
- A run is prematurely terminated if: (i) the maximum run time of 10 min is exceeded; (ii) any user intervention is required or rendered; or (iii) the robot falls off the table!

4.2.1 Task 1. This task was used the first time this module was delivered and therefore was possibly not as well thought out as those that followed. Essentially, the task here was to build a mobile robot to collect three drink cans in a square area (a single table) and return them to a start/finish area. Most groups completed this assignment, which perhaps indicated that it was a little too simple, but it nevertheless produced a wide diversity of approaches. Principal design decisions here were:

- *Traction mechanism*: choice of wheels or tracks, appropriate gearing and speed command.
- *Navigation*: choice of light sensors to follow tape on table, or a contact sensor, which can be configured to detect table edge.
- *Can pick-up mechanism*: some designs used a large 'sweeper' arm (e.g. figure 1), others used an active collecting (harvesting) device, while one group built a mechanism to pick cans up and stow them.

4.2.2 Task 2. The objective of this task is to build a mobile robot which, starting on table 1 (figure 2), is able to negotiate some obstacles on table 1, negotiate the (hump-back) bridge to table 2, retrieve a drink can (painted white and randomly placed) from table 2 and return it to the start area.

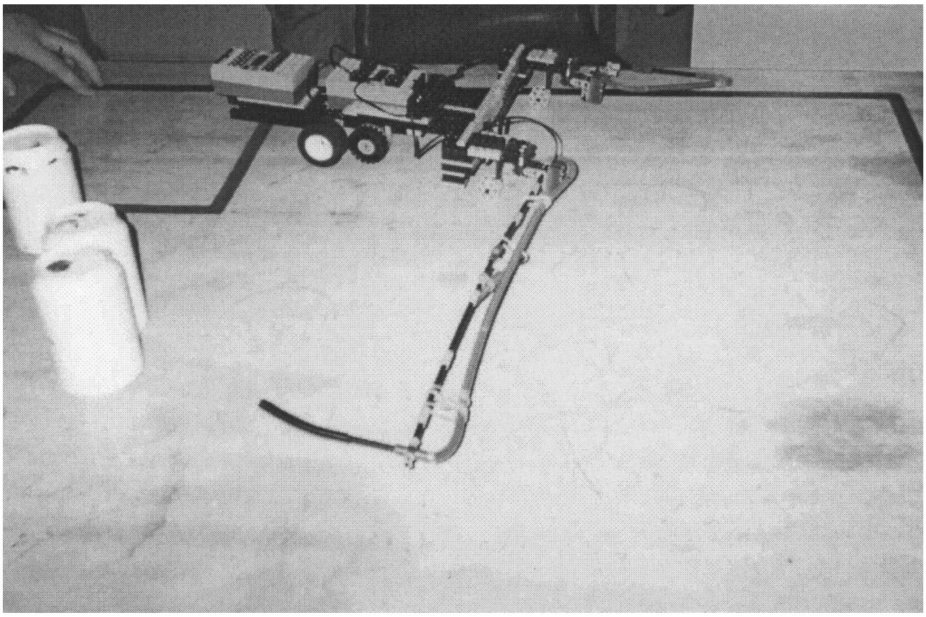

Figure 1. 'Sweeper' robot for task 1.

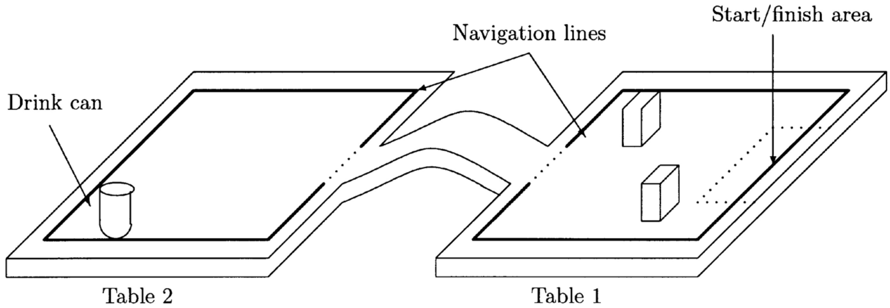

Figure 2. Task 2 course.

This task places emphasis on robot navigation and design of an effector which can grasp and secure a drink can. The main reason for the introduction of the bridge was to give more challenge to the navigational exercise and to force students to consider the torque/speed trade-off in selection of gearing.

Total marks for performance were distributed as shown in table 2.

For task 2, a graded mark of up to 15% (of performance) was awarded for speed.

4.2.3 Task 3. This task utilized the same basic course as in task 2, with the following exceptions:

- no obstacles were present on table 1;
- two 'obstacles' were introduced to table 2;
- the navigational tape was overhauled, with green navigation lines replaced by silver, to improve colour discrimination.

Table 2. Task 2 performance mark breakdown.

Task no.	Task description	Score (%)
1	Pass obstacle line	5d
2	Get robot onto bridge	15d
3	Successfully cross bridge	10d
4	Locate can (physical contact)	5d
5	Secure can	15d
6	Robot back onto bridge	10d
7	Successfully cross bridge	10d
8	Pass obstacle line	5d
9	Stop (self-stop) in start/finish zone	10d

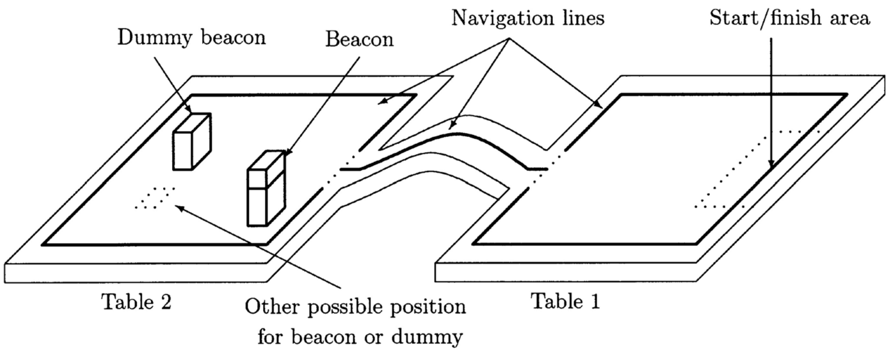

Figure 3. Task 3 course.

Task 3 focused on locating an electronic 'beacon' (constructed using an RCX™ block and connected to a shake sensor) on table 2. This beacon, upon being activated by a sharp bump, transmits a code which must be read by the competing robot and later displayed. Table 2 also contains a 'dummy beacon', which has no in-built intelligence, as shown in figure 3. Three possible positions for these two beacons are available, with the actual layout specified only on competition day, after all final adjustments have been made to the robots. Task scoring, for this task, was as shown in table 3.

4.3 *Originality and creativity*

In order to engender the creative spirit, 10% of the module marks, exclusive of robot performance, are awarded for creativity (see table 1). The possible difficulty of copying of designs is circumvented by a rule which allocates marks only to original designs. If, for example, two different designs demonstrate inescapable similarities in hardware and software, then the

Table 3. Task 3 performance mark breakdown.

Task number	Task description	Score (marks)
1	Cross bridge from start zone	4
2	Locate and activate beacon, recording correct number	5
3	Cross bridge after contact with beacon	4
4	Play a 10 s musical tune	2

groups share the marks for that *single* design, with the sharing proportion being decided by the students concerned. Over the three iterations of the module, there has been no necessity to implement this rule! Interestingly, some students prefer to sacrifice potential performance points (i.e. deliberately choose a particular sensor/actuator configuration which may not be non-optimal) in an effort to be original. This is not seen as being detrimental to the module objective, since it ultimately encourages a wider variety of designs.

4.4 *Race day!*

Race day, the day on which the performance (and creativity) of each robot is evaluated, is a busy and exciting affair! Each robot gets two runs, with all adjustments to robot software being completed before the final course is announced. This helps to ensure that robots are autonomous, rather then preprogrammed with a fixed set of moves. The best of the two runs is taken, with scoring according to the breakdown in section 4.2. If necessary, course changes are made between runs, with no adjustment to robots allowed, other than replacing any pieces which may have fallen off in the first trial. The ‘race day’ is usually well attended by students of later years, keen to see the current challenge and how the robots can cope with it, in addition to staff and postgraduate students. Students taking the design module generally learn a lot from watching the performance of other robots, in addition to their own, including:

- the trade-off between speed and reliability;
- robustness of the design, both physical and in sensitivity to course variations;
- effects caused by variation in lighting conditions on the day,[1] or new batteries causing more torque/speed then expected;
- frequently, the designs with the greatest potential fail to complete the course, due to poor reliability and/or robustness.

5. Module evaluation

5.1 *Questionnaires*

Questionnaires were used to elicit student opinion on the value of course aspects and suggestions for improvement. The questionnaires have both multiple-choice questions (MCQs) and ‘free-format’ sections.

5.1.1 MCQs. The averaged MCQ results are shown in table 4, indicating a good level of satisfaction with the course, and would also indicate that, despite its alternative format, the degree of difficulty of the module is perceived as comparable with other year 1 modules.

5.1.2 Free format. The following is a summary of typical free-format responses:

- More spacing between different assessment components.
- Course could not be improved.
- Good course, interesting.
- Nice break from more traditional subjects.
- Prefer groups of two.
- Prefer individual assignment.

Table 4. MCQ results.

Question	Mean	SD
Lectures on design were useful	2	0.6
Lecture on reporting/presentations was useful	1.7	0.6
Tutorials on Mindstorms™ hardware/software were useful	2.5	1.0
Our team of three worked well together	2	0.9
I would prefer an individual assignment	4	1.2
Groups should be chosen by the course leader	2.8	1.3
The assignment is a good test of engineering design skills	1.7	0.6
The course was difficult in comparison with other EE courses	2.3	1.2
I am now clear on what structured engineering design is about	2	0.7
I have become more interested in engineering as a result of this course	1.9	0.6
Overall rating of course	2	1

Key: 1, strongly agree; 3, uncertain; 5, strongly disagree.

- Assignment groups should be chosen by lecturer.
- Representative of a real-life team situation (do not get to choose co-workers).
- Could be weighted, so that each group has a range of ability levels.
- Larger range of Lego® pieces and more sensors, including trading of pieces.

The above raise a number of interesting points. Though it would be desirable to space out the assessment more, it is difficult to see which assessment component could be moved forward. Final reports, peer mark and performance assessment should all (ideally) be based on the full module work, while having the presentation at the end helps to ensure confidentiality of designs. Interestingly, many students would prefer a group to be selected for them, this being more representative of the real-world setting. Such a selection policy can also be used to integrate different class groups, e.g. international students. The issue of group size is a moot one. Overall it is felt that three is a good size as it provides for richer group dynamics than two, and provides a number which guarantees a definitive outcome to democratic decisions! In relation to the range of Lego® pieces, it is felt that the current provision gives adequate flexibility, while providing a real-world limitation, which is consistent across groups, on components and being relatively economical (approximately €260 per set).

5.2 *Overall impressions*

This course has been a very positive experience for the course leaders since its inception. Having run the course for three years, we now have a good idea of an appropriate level to pitch the assignment problem for year 1 students and we are constantly encouraged by the abilities that first-year students can demonstrate. This, we feel, is justification for the inclusion of such a module in year 1 and confirms that the use of ‘generic’ engineering technology as a base (e.g. Lego® Mindstorms™) enables students to engage in structured (and sometimes complex) engineering designs without the need for a vast knowledge of (electronic) engineering technology. Truly, we were very impressed with what freshmen students could achieve in a 60 h assignment.

The maturity that students displayed was also very encouraging, both in the manner in which the design exercise, reporting and presentation was approached as well as the honesty displayed in the peer marking. In general, there was a high consistency in the peer marks awarded from other group members compared with the self-assessed figures.

Having delivered the module for three years, most of the teething problems have been ironed out. These related mainly to:

- offering the right level of formal instruction and support;
- elimination of most of the variability associated with the light sensors, through: use of blackout curtains and artificial light only; and use of only black, white and silver navigation lines providing maximum discrimination;
- pitching the assignment problem at the correct level.

6. Conclusions

This paper advocates the inclusion of explicit design instruction in undergraduate engineering degree programmes along with the use of design exercises within the technological subjects. The use of a generic engineering technology like Lego® Mindstorms™ allows use across a wide range of engineering disciplines but, more importantly, it allows for the introduction of design skills at a very early stage of engineering programmes, which:

- engenders the creative spirit at an early stage;
- demonstrates the essence of engineering to freshmen students, which may not become obvious through the normal range of technological subjects for some time;
- is an enjoyable practical experience, which can assist with student retention at a crucial stage;
- provides a meaningful group exercise, with all the characteristics of a professional engineering project (teamwork, communication, etc.), which can help to bond the class body and integrate disparate student groups.

On a wider scale, bodies which accredit undergraduate engineering programmes have, and continue to play, a role in how engineering academics incorporate design in their syllabuses, with some diversity in approach being evident on different sides of the Atlantic. ABET is somewhat more direct in its requirements for design, which may be partly responsible for more emphasis on the incorporation of explicit design modules in US engineering programmes, compared to Ireland and the UK.

Lego® Mindstorms™ offers, in our experience, sufficient flexibility to implement an enormous range of designs for a variety of problem domains. It is highly visual and intuitive, since it is based on a learning toy which many students will already have some familiarity with, while the ability to incorporate 'intelligence' through software is both attractive and characteristic of most modern engineering applications.

Based on our experience with this design module, we can unreservedly recommend the approach described in this paper. Further information on our module entitled 'Introduction to engineering design' is available from http://www.eeng.may.ie/jringwood/undrgrad/lectpage.htm, which contains course material and more photos [i.e. ... MAY.IE/~JRIN...] of the various robots over the course of the module.

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Note

1. Most of the variability in light conditions has been eliminated by using black-out curtains and completely artificial light, and shadows are largely eliminated by ensuring a clearance area around the competition area.

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