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Design and construction of a Formula SAE racecar in a teaching and research framework

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Abstract: *The paper discusses the benefits that have been achieved through the design and construction of a Formula SAE© racecar both as part of mechanical and mechatronics engineering curriculum and as a core element of a research group. The project was seen as an aid to develop life long generic skills and as a means to reinforce management skills via engaged learning. The student group work involved design and development of the racecar from inception to completion over two semesters. Postgraduates, who took the role as team leaders of student groups, were able to use the car as a test bed for developing intelligent systems. Both the undergraduates and postgraduates were able to reinforce engineering management principles during the project. Since the exercise was challenging, authentic, and multidisciplinary it proved an effective tool to extend formal lectures while also providing a resource for research in the School.*

Keywords: *SAE Formula, racecar, project base learning, collaboration, research.*

Introduction

The School of Engineering at the University of Tasmania integrates the engineering disciplines of civil, mechanical, mechatronics, electrical power systems, electronics and communications and computer systems engineering. This is done through the use of a common Year 1 and a common Semester 1 in Year 2 for all disciplines. Other synergies are obtained by sharing many Year 3 and Year 4 Units across two or more disciplines.

In 2000 the School was presented with the opportunity to introduce some new teaching and learning techniques, when it undertook to review all programs. At the same time that new units were being formulated, a mechatronics discipline was introduced. This, and the existing mechanical engineering discipline, were selected to trial a new group based learning project. The project was designed to involve collaboration between undergraduates at a peer level, and between undergraduates and postgraduates. As part of the third year engineering course, a core mechanical and mechatronics engineering unit was re-structured in 2001 to cater for the development of a Formula SAE© racecar (KNE353, Manufacturing, Maintenance and Quality). As part of the project, the students had to design and build a racecar from inception to completion in a specified time. The project was intended to be a teaching tool to help impart modern engineering management principles, and to reinforce engineering principles via engaged learning (Jones et al 1994).

The Formula SAE© competition was originally established for the Society of Automobile Engineering (SAE) student members to conceive, design, fabricate and compete with small formula-style racing cars (SAE 2001). There are several restrictions imposed on the car frame and engine performance so that the knowledge, creativity, innovation and imagination of the students are challenged. The competition initially involved participation of several engineering schools around the USA, but has grown to become an international event (Van Zanten 1995). Teams build the cars over a period of about one year and the teams can attend an annual international competition for judging and comparison with other vehicles from universities throughout the world. The University of Tasmania competed in the event for the first time in Melbourne in December 2001 in a field of 19 that included 2 vehicles from England, 3 from Europe and one from the USA.

Objectives of the project

Teaching

An extensive amount of scientific principles and technical expertise are built into a car, which makes the Formula SAE© racecar an ideal project for engineering students. One way of preparing students for the unknown of their future careers, is to let them face and deal with novel problems, an approach adopted for the project. The system adopted lets students deal with a limited number of types of problems, using a limited range of parameters, which is very good for solving predictable situations (Marton and Trigwell 2000). Traditional training methods teach students what to think and the obvious and better alternative is to teach students how to think (Candy 2000). In an environment of inquiry such as applied project work, all students must talk to one another and juggle concepts and ideas. The students pose questions, hypothesise, experiment, test and review the outcomes. The learning and teaching outcome is that the students are capable of finding things out for themselves through disciplined inquiry (Candy 2000).

The project-based learning described here is aimed at reinforcing basic concepts of design in the areas of manufacturing technology and mechanical engineering. A collaborative team approach is encouraged with an emphasis on self-paced learning and project task completion. Each team has an excellent exposure to the engineering management skills such as effective communication, team-based collaboration and management. Some of the specific aims of the project were to:

1. Reinforce the use of basic engineering science, mathematics and physics in engineering design and computer modelling.
2. Provide students with an alternative learning process, with particular reference to students from non-English speaking backgrounds.
3. Encourage engaged learning within the student body via collaboration within teams and between teams.
4. Support the teaching of management principles by having students develop a project management plan complete with critical milestones.
5. Develop an appreciation of the need for economic judgement and provision of effective documentation in engineering projects.
6. Encourage inter-disciplinary collaboration between students in the mechanical and mechatronics specialisations.

Research

It has been recognised by many engineering academics around the world that both undergraduate and postgraduate students can be a valuable asset in the construction of a research base. This is especially applicable where an academic has very few other avenues and opportunities to develop their research. The integration of student work into an academic's research activities could be as depicted in Figure 1. Undergraduates can assist by identifying and establishing worthwhile research within a School, which can then become an ongoing source for supporting future research activities.

Clustering and sequencing projects around a common research theme accelerates research development, especially in the presence of postgraduate students. Sequencing projects involves running a series of very similar projects over a number of years, each year gradually building on the previous foundation. Typically, sequencing only lasts for around three years after which the work tends to become outdated and stale. Clustering projects involves more than one group of students working on different aspects of the same project. This can create a synergy among groups, as all groups can access the combined body of work, while still restricting their reports to their own selective subset of the total project.

Obviously, sequencing and clustering can be combined. However, the work required to coordinate activities tends to denigrate the benefits of the work being carried out by the students and the role of the academic may reduce to that of a project manager. With the Formula SAE© project the student groups fitted the clustering model with integration being achieved via a cooperative approach between the postgraduate group leaders.

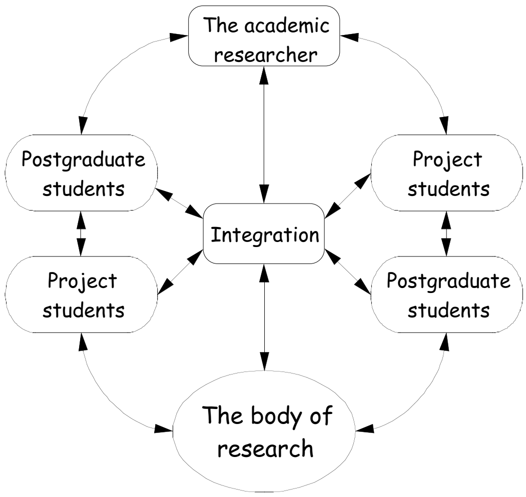


Figure 1: Integrating teaching and research

A longer term aim would be to have students with superior academic ability adopt the postgraduate group leaders as role models and stay or return to the University in a postgraduate role. This completes the circle as new postgraduates can then assist with more undergraduate project supervision, interact at peer level and serve as role models for the next cycle of potential researchers. The topics being researched as part of the overall Formula SAE© racecar project include the following.

- Estimating Spring Travel and Brake Forces Using Intelligent Sensor Fusion
- Using Artificial Intelligence for Torque Estimation in Engines
- Applications of Computational Intelligence to Predict On-line Dynamics Using Sensors.
- Automotive Traction Control Using Neural Networks
- Machine vision integration for traffic speed detection
- Control of HC emissions for better environment

Racecars and engineering management

There has been an increased emphasis on the inclusion of engineering management in degree programs over the last decade. The teaching is often fragmented, spanning areas such as environmental management, project management, financial management, factory management and production management. Recent efforts to re-address engineering curriculum by the Institution of Engineers, Australia (IEAust) have directed efforts to the application and management of technology rather than a conventional approach that specialises in the theoretical aspects of management (Palmer 2000). The IEAust does not specify the way courses should be taught and suggest that Schools should devise their own approaches and subject arrangements. One approach is to integrate as much of the management content as possible within other studies (Karri and Walker 1996). This is a convenient way of achieving the scope and extent of management studies that should be covered in a normal undergraduate engineering course. The IEAust objectives recognise the need for competence in management, business and social responsibility as a part of the engineering profession. The need for continuing self-education to enable graduates to perform professionally in times of rapid change, and to improve further studies in management after graduation is also highlighted in the policy (Karri and Walker 1996).

The IEAust is encouraging Engineering Schools to reduce contact hours to allow students more time for more self-paced learning (IEAust 1999). Thus with an increased emphasis on specialisation, formal management course content is constantly threatened in the engineering curriculum. As a consequence management content is 'squeezed' or merged into other technical subjects for 'indirect teaching'. The management courses are then divided into 'direct management units' and 'indirect management units'. Units such as *Engineering Economics*, *Financial Management* and *Project Management* are taught as direct management units. On the other hand, mechanical engineering units such as *Manufacturing, Maintenance and Quality Control* and *Advanced Manufacturing* (UTas 2001) can be considered as units that contain much information where the students are indirectly exposed to management.

It was seen that important management aspects such as team working, communication, leadership and public speaking could be incorporated into collaborative projects such as the Formula SAE© racecar to expose the students indirectly to managerial skills.

Benefiting NESB students

The School has one of the highest percentage levels of Full Fee Paying Overseas Student (FFPOS) in Australia. In 2001 the School was provided with 172 domestic (DETYA) EFTSU by the university and assigned a target of 89 FFPOS. The School ended 2001 with 202 EFTSU and 102 FFPOS. Students come with advanced standing from Thailand, Vietnam, Malaysia and Singapore and the number of FFPOS in some classes exceeds 50% in Years 3 and 4 of the degree programs. The vast majority of the FFPOS are from a non-English speaking background (NESB). This provided an added stimulus to the project as it has been largely recognised that NESB students learn more effectively via project based learning (Mulligan and Kirkpatrick 2000). The high level of FFPOS students in the School places special demands on both staff and students, due to the different learning processes required for each group of students. These learning differences were shown by Mulligan and Kirkpatrick (2000), who carried out a survey resulting in the return of 414 questionnaires consisting of 198 NESB and 216 ESB. Most NESB students surveyed were from Malaysia, Indonesia and Singapore. This student distribution is very similar to the School's. The data in

Table 1 is the response to the question ***"Over all how did you understand this lecture?"*** The data provides an indication of the need to develop alternative teaching mechanisms. An obvious alternate is project-based learning such as involved in the construction of a Formula SAE© racecar.

Table 1: Student response to understanding lecture material showing differences between NESB and ESB students

Question	NESB	ESB
Understood very well	9	34
Understood fairly well	68	58
Did not understand at all	22	8

An additional issue with the NESB students is that they often fail to recognise metapragmatic signaling when lecturers change topics or emphasis and indicate those changes by change of tone, modification of delivery, change of expression or body language (Mulligan and Kirkpatrick 2000). Similar problems occur with respect to identifying lecture macrostructure, note taking and conceptual understanding. Much success has been achieved with real life examples that both ESN and NESB can relate to rather than text book examples. The project described in this paper addresses the issues referred to above.

Benefits from Building the Formula SAE© Racecar

Collaboration in design and construction

During design, the students are required to assume that a manufacturing firm has engaged them (as a team) to produce a prototype car for production evaluation. The students must collaborate with each other and other teams via their postgraduate team leaders. The car must be designed for very high performance in terms of acceleration, braking, and handling but also must have low maintenance and be reliable. In addition, marketability must be enhanced by other factors such as aesthetics, comfort and use of common parts. The design must be checked at each stage through established software. Computer aided design (CAD) skills are also taught as part of this objective. Figure 2 shows a typical CAD drawing of frame of the School's racecar and a finite element analysis of the front suspension.

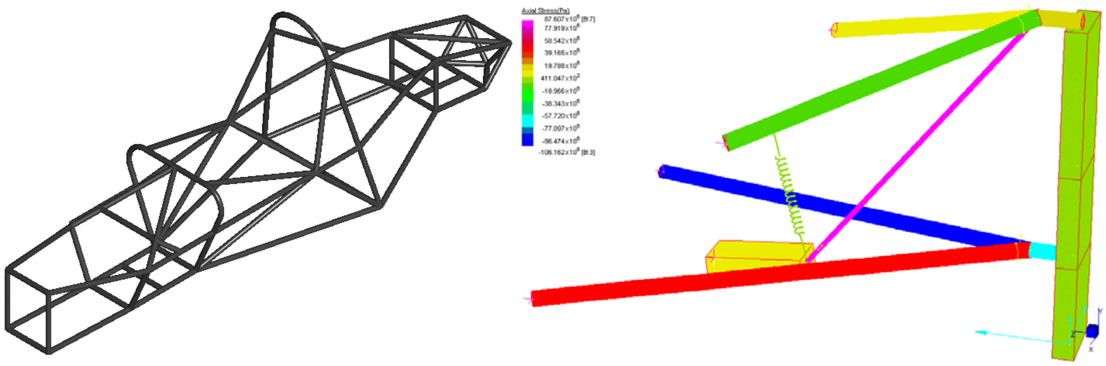


Figure 2: Frame drawing of the racecar and a Finite Element Model of the front suspension

Building a racecar from inception requires dedicated teams working on many aspects. Identifying specific areas of major work and assigning team leaders for each area promotes collaboration. The teams need to communicate across several nationalities, which greatly assists the students to later fit more easily into an industrial environment (Karri 1993). It can be seen from Table 2 that the teams must cater for anything from obtaining sponsorships to manufacturing the frame, engine and suspension. Cooperation must exist across all the groups for the overall project to succeed. There is a pressing need to synchronise activities, which exerts a psychological pressure on student teams to 'keep up' with progress. This is a situation common in real life manufacturing. Development of the ability to lead, relate to people from varied backgrounds and to solve problems through collaboration meets many of the objectives of the project.

Table 2: Specific teams working on varied tasks of building the racecar

Marketing	Finance	Frame	Suspension	Engine	Shell Design
Sponsorship	Cost Report	Design	Suspension	Cooling	Logistics
	Planning	Seat	Brakes	Exhaust	
		Safety Belt	Intake		
		Steering	Engine Control		
		Pedals	Drive Train		

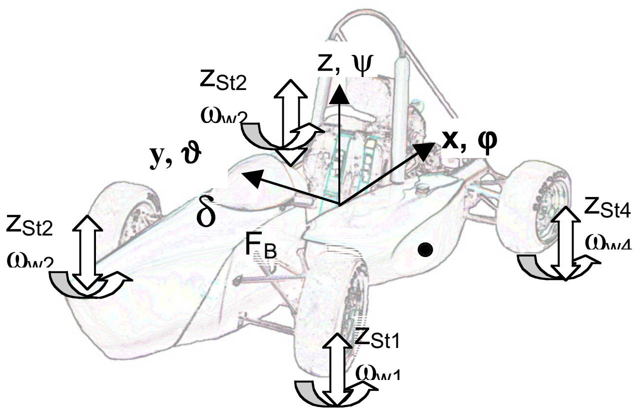
Project management and completion of milestones

Project management, although taught formally in the curriculum, has little direct application to modern industry. This is because there is a lack of specific case studies that reflect reality. Building a racecar is an authentic task, with several groups contributing to various aspects of the overall project, all within a detailed project plan with rigid milestones and completion dates. Third year students with sufficient computer background from their first 2 years successfully generated a conservative project plan using Microsoft Project software. Within the project plan the students constantly monitored the completion milestones. This encouraged the teams to achieve technical milestones while synchronising their work to meet the overall progress.

Upon completion, the cars are judged in a series of static and dynamic events including inspection, engineering design, solo performance trials, and high performance track endurance. The challenge to the design team is to design and fabricate a prototype car that best meets these goals and intents within a limit of US$30,000. At the competition each design is compared and judged with other competing designs to determine the best overall racecar. This means that there is a challenge for students to produce a car that is both competitive and economical to manufacture. The groups monitor cost effectiveness of manufacture by continual appraisal of the cost of parts and equipment and also by the quality of the equipment procured. Students develop a competitive spirit and work hard in collaboration to build their racecar and participate in the international event. Systematic documentation is mandatory via regular progress reports and oral presentations.

Inter-disciplinary interaction and collaboration

While Industry has very discipline specific technical requirements it also expects graduates to be multi-disciplinary. Engineering students are forced to improve their multi-disciplinary skills over and above the prescribed academic curriculum to enable an immediate successful start in industry. One of the major objectives of this project is to cater for this need to develop multi-disciplinary collaboration. Modern automobiles are becoming ever more computerised and electrical engines, step motors, sensors and actuators are increasingly used. The project demonstrates how computer systems engineering and mechatronics principles can be coupled with traditional mechanical and electrical engineering.



Parameter		
ω_w	1/s	Wheel speed
d	m	Distance
v	m/s	Speed
a	m/s^2	Acceleration
ψ	°	Yaw angle
ϑ	°	Pitch angle
φ	°	Roll angle
δ	°	Steer angle
z_{St}	m	Spring travel
F_B	N	Brake force
Chassis geometry		
γ	°	Chamber angl
σ	°	Kingpin Inclina
τ	°	Caster angle
r_s	m	Kingpin offset
l	m	Wheel base
b	m	Wheel track
	%	Transfer

Figure 4: Parameters of the test vehicle

The influence of sensors on systems like engines, transmission, brakes and steering can also be studied and the racecar development enhances student understanding of signal processes in modern automobiles. The project helps develop a multi-disciplinary approach by requiring students to understand systems such as Anti-lock Braking Systems (ABS), Electronic Stability Programs (ESP), Electronic Suspension Systems (ESS) and Anti Slip Control (ASC) all which use many sensors (Inagaki et al 1994, Shibahata et al 1992). Figure 4 shows the numerous sensors and associated parameters that have been incorporated into the test vehicle.

Outcomes of the task

A significant outcome was that some students from the School of Engineering had an opportunity to race their newly completed car against 18 other participants from around the world. Competition in the event demonstrated completion of the design task. The event was organised at the Holden proving grounds at Lang Lang, Victoria between the 6^{th} and 9^{th} of December 2001 and was based on static and dynamic events. The static events included a detailed design report, a cost report of the car and a professional presentation by the team. The dynamic events consisted of a series of skid pad tests, acceleration events followed by an endurance event. The participation of universities from the USA, UK and Germany added an international flavour to the event and also formed a basis for future links and technology liaison for the Australian universities competing in the event. Some of the following significant outcomes achieved could be listed as:

- Students benefited from the engaged learning with the performance based assessment approach being well received.
- All involved developed their ability to organise and focus team strengths through collaboration within teams and between teams.
- Management teaching was reinforced by the authentic task of managing the design and construction of the racecar.
- Undergraduate and postgraduate students had to liaise and interact with international universities and become familiar with international state of the art technology.
- Technical skills were developed via the design and construction process and by liaison and discussions with other participants.
- Research in the application of neural networks in vehicles was promoted and has become a key research area within the School.

Many of the skills outlined above are those inherent in the day to day activities of a good professional engineer. Participation in the SAE Formula race appeared to be an excellent means to cater for developing those generic skills that are otherwise not normally covered in a conventional engineering curriculum. As a means of gauging the student's learning experience, some specific statements for evaluation were included in a Student Evaluation of Teaching and Learning (SETL) that was conducted for the unit KNE353, Manufacturing, Maintenance and Quality. The outcomes from the SETL are summarised in Table 3. The statements in the SETL are evaluated by students on a scale of 1 to 5, where a ranking of 1 indicates total agreement.

Statement to be evaluated by students	Mean Response	Standard Deviation
The practical project was a useful learning experience	1.27	0.6
Practicals were a useful learning experience	1.28	0.5
The group project was a good learning experience	1.40	0.5

Table 3: SETL outcomes for the unit KNE353

While the use of a SETL is recognised as a simplistic approach for evaluation of the project's success the ranking by the students indicate that they considered the design and construction of a Formula SAE© Racecar a useful learning experience. A more detailed review of the outcomes is planned for 2002 when the project will be repeated.

Conclusions

The Formula SAE© competition appears to be an excellent tool to help develop management education through classical engineering. Although it was originally established on a technical basis for the Society of Automobile Engineering student members, many universities around the world now participate in the event for both technical and management benefits. A preliminary review via a SETL indicates that the task returned significant benefits to third year mechanical and mechatronic engineering students. In addition to facilitating the acquisition of good technical skills, the project was instrumental in developing the other equally important generic skills and life long learning.

The project helped to integrate the School's ESB and NESB student population through collaboration and greatly assisted the learning process of the FFPOS cohort within the School. The demands on both academic and technical support staff were reduced due to the self-paced approach and student ownership, which underpin the project. The engaged learning allowed postgraduates and staff to become facilitators.

Although originally intended as a teaching tool the Formula SAE© racecar quickly became the core purpose of a research team consisting of 4 research master's students, a research fellow and a senior academic. The team is expected to grow in 2002 to include students undertaking doctorates in the area of neural networks and artificial intelligence.

As in most special teaching projects the cost effectiveness of the project must be questioned. Savings generated by some reduced formal laboratory and tutorial classes were more than offset by the material and labour cost associated with the racecar construction. In most cases Universities can only afford to enter and participate in the SAE competition with sponsorship support from large corporations. In the School's case the costs associated with the racecar were partially offset against the future research quantum likely to be generated by the postgraduates involved.

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