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Innovation and Failure in Mechatronics Design Education

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Abstract: Innovative engineering design always has associated with it the risk of failure, and it is the role of the design engineer to mitigate the possibilities of failure in the final system. Education should however provide a safe space for students to both innovate and to learn about and from failures. However, pressures on course designers and students can result in their adopting a conservative, and risk averse, approach to problem solving. The paper therefore considers the nature of both innovation and failure, and looks at how these might be effectively combined within mechatronics design education.

Keywords: Engineering Design, Innovation, Failure, Education, Curriculum Design.

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1. INTRODUCTION

'*Creative breakthroughs always begin with multiple failures*'
James Dyson[1]

The design of all engineering artefacts and systems is essentially a goal driven problem solving exercise in which the aim is to satisfy user requirements through the appropriate use of available technologies and materials while taking account of applied constraints. Throughout the history of engineering, this combination of challenges in which the designer seeks to optimise outcomes within the available solution space has driven a search for innovative and creative solutions. However, in this search for innovation, some solutions that come under consideration must inevitably fail to provide the desired outcomes [1,2]. Notwithstanding such failures, these solutions often contain within them information essential to driving forward understanding, which is then embedded into future solutions. In this context, it is therefore important that failures are not simply discarded, but are subject to rigorous analysis and evaluation so that the embedded knowledge is transferred to other engineers and other projects. Creating an effective engineering design curriculum that expects its graduates to be innovative designers who learn from failure requires the course designers and the delivery team to overcome a range of challenges, not the least of which are external pressures such as those imposed by quality reviews.

It is also necessary to recognise that within the context of the paper the use of the term '*failure*' does not automatically imply or suggest negativity, either from the perspective of the instructor or the student. Rather, it is used to express a universal feature of the engineering design process which if treated correctly, has major and significant educational benefits [3,4,5].

The authors therefore argue that engineering students should be encouraged towards attempting innovative, and hence risky, solutions, even though some may ultimately fail to meet desired criteria. This then implies that the imposition of inherently artificial constraints, as for instance such as might be associated with grading and marking, does not result in students adopting an inherently conservative approach to engineering design problem solving.

The paper thus begins by considering the nature of innovation and its links to the design process before looking at the nature of failure within design, development and implementation, including an examination of different types of failure as exemplars influencing engineering design learning. Having established the background, approaches to encouraging innovation are considered in terms of their implication for both the student and the course designers. Issues such as communication and interaction within the design innovation process are considered, including how such communication can be supported by appropriate technologies and techniques.

It is recognised that an approach to assessment within a framework where it is acknowledged that some designs will fail will, in some cases, require a shift away from current processes of evaluation, marking and grading.

The paper concludes by looking at models for engineering design courses in which design innovation, and hence risk taking, are encouraged, and considers how such courses could be assessed.

2. THE NATURE OF INNOVATION

The first challenge when considering innovation is that of understanding innovation itself. Dictionary definitions are typically structured along the lines of:

1) *The action or process of innovating*
    1.1) *A new method, idea, product, etc.*

Other definitions range from the simple and straightforward such as:

> *Innovation is significant positive change* [6]

to the more complex:

> *Innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace.* [7]
>
> *Innovation is production or adoption, assimilation, and exploitation of a value-added novelty in economic and social spheres; renewal and enlargement of products, services, and markets; development of new methods of production; and establishment of new management systems. It is both a process*

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[1] In reviewing Syed M, *Black Box Thinking*, John Murray, 2015

> *and an outcome.* [8]

The Organisation for Economic Co-operation and Development (OECD) meanwhile provides 4 different definitions dependent on context [9]:

Product Innovation - A good or service that is new or significantly improved. This includes significant improvements in technical specifications, components and materials, software in the product, user friendliness or other functional characteristics.

Process Innovation - A new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software.

Marketing Innovation - A new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing.

Organisational Innovation - A new organisational method in business practices, workplace organisation or external relations.

Indeed, surveys by Baregheh, Rowley & Sambrook [7], Crossan & Apaydin [8] and Edison et al [10] have suggested upwards of 40 definitions currently in use, many of which are situation dependent.

In the context of the paper, with its focus on engineering design education, it is proposed to take the OECD definition of product innovation above as the underlying concept, while not neglecting other aspects, such as the multi-disciplinarily aspects embedded or implicit in the various definitions.

2.1 Elements of Innovation

The previous section established that innovation is a complex and multi-faceted process which involves consideration of markets and opportunities as well as technologies. It is necessary therefore to establish those contributory elements of the innovation process which determine its outcomes.

Innovation through Evolution or *'Standing on the Shoulders of Giants'* [2]

Innovations do not in general spring into life fully formed, they evolve incrementally over time through a process of experiment and evaluation, in which an understanding of the nature of failure plays an important part. Numerous examples of this process can be found in engineering applications where earlier developments, and failures, supported by developments in associated technologies, provide the basis for next generation systems [11].

For the course designer, this implies a need to establish a sound technical base.

Communication & Networking or *'The Water-Cooler Moment'*

The cross-fertilisation of ideas is crucial to innovation, and often comes from apparently random discussions resulting from informal interactions in environments with very low cultural barriers to communication [12]. To encourage such interaction, organisations have increasingly organised office space to force such interactions. For instance, Steve Jobs of *Apple* & *Pixar* argued that:

> "*If a building doesn't encourage* [collaboration]*, you'll lose a lot of innovation and the magic that's sparked by serendipity. So we designed the building to make people get out of their offices and mingle in the central atrium with people they might not otherwise see.*" [13]

and at *Pixar* redesigned the workspace, which had originally provided separate buildings for computer scientists, animators, and everyone else as a campus where random encounters would take place. The design focused on an atrium that Jobs intended to house the only restrooms on campus to force people into a space where they would encounter others!

For the course designer, this implies a need to support individuals in developing personal, along with presentational, communication skills, which of course must include the ability to listen to others.

Concept Development or *'The Idea'*

The nature of innovation in the modern era is such that the idea of the solitary inventor emerging with a fully formed product or system probably no longer exists, if indeed it ever did in reality. This was recognised by Thomas Edison in his creation in 1876 of the research facility at Menlo Park. Though Edison was generally the person to whom the inventions that emerged were legally attributed[3], in the main they resulted from the research staff working under his direction.

The reality is that majority of innovations emerge over time as individuals gather information about need, requirements, problems, potential outcomes and solutions along with consideration of the target market, which itself is likely to impact on the nature of the final product or system. Thus, the Sony *Walkman* evolved not only out of its underlying technical considerations, but out of the belief and understanding that it could be used to create a new market, in this case for a portable music player [14].

For the course designer, this implies a need to support individuals in developing recording and note taking skills to put in place the structure of the innovation and to support the identification of the skills, tools and resources required for its implementation.

Serendipity or '*Recognising the Opportunity'*

A key aspect of innovation is the ability to identify and develop concepts that have originated in other ways and from other areas and to recognise that they have a potential application in relation to the specific problem for which a solution is being sought. This implies an open-minded approach in which no concepts or ideas are rejected simply because they do not fit a pre-conceived model of a solution[4].

Perhaps the best known of example of a serendipitous innovation is that of the sticky or *Post-it*® note. In 1968, Dr Spencer Silver, a chemist working at 3M, developed a low adhesion adhesive that could be repositioned without leaving a mark[5] but for which no application could, at the time, be

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[2] By Isaac Newton in a 1676 letter to Robert Hooke but its use as a metaphor extends back before that.

[3] Edison's name is carried by 1,093 patents.

[4] As might be expressed by the '*not invented here*' mind-set.

[5] He was actually hoping to find a high-strength adhesive!

found. A few years later, Art Fry, a colleague of Dr Silver's, and a member of a local church choir, was looking for a way to stop markers falling out of his hymnal and remembered this adhesive and tried some on his bookmarks. The rest, as they say, is history…![6]

For the course designer, this implies creating opportunities for the cross-fertilisation of ideas and exposing individuals to different means of thinking about, and solving, problems.

Interdisciplinary Working or '*The Other Technologies'*
Recent decades have seen an increasing integration in technologies at the system level through the introduction of concepts such as those of mechatronics, Cyber-Physical Systems (CPS) [15] and the Internet of Things (IoT) [16]. Such systems, which are often context dependent and dynamic in nature, are dependent not on a single technology but on a combination of technologies to support their operation. In consequence, the innovator needs to have access to support and expertise across the range of necessary technologies required for the final system.

For instance, a modern vehicle system is structured around a series of individual mechatronic components such as engine & drive train management, traction control, driver assistance (lane control, smart cruise control, smart lighting, etc.) environmental controls and entertainment systems which are then integrated through software to create a Cyber-Physical System in the form of the vehicle itself. Finally, through communication at the level of the IoT the vehicle can support traffic management and routing as well as diagnostics and reporting, leading ultimately to self-driving vehicles.

For a mechatronics course designer, this implies a need to create opportunities for group working and the development of systems level concepts applied across a range of technologies.

Learning through Failure or '*Things Break*'
In engineering, failures occur on a reasonably regular basis, and are generally traceable to a specific cause or causes. The requirement therefore is that of being able to understand the nature of failure, and to mitigate against possible failures, throughout the design, development, construction and operational phases of the life cycle of a product or system.

The ability to analyse failure and identify the underlying cause is therefore an important part of the innovation process. In this context therefore, consider the following:

On the BBC *Radio 4* programme '*Learning from Life and Death'* broadcast on 9 July 2017, Dan Cobley of Blenheim Chalcot, and formerly CEO of Google UK, commented that 6-year olds who immediately begin a sequence of play and experiment and proceed through a process of trial and error can often outperform MBA students in the spaghetti and marshmallow tower challenge as they repeatedly try and fail but observe, and learn from, their failures while the MBA students will often attempt to go directly to a final solution without intermediate trials, and hence have no evidential failures to learn from.

Experience or '*Time on the Job*'
In comparing the performance of expert (or experienced) and novice scientists Feist [17] noted that:

1. Expert scientists are more willing to modify or discard hypotheses than novices.
2. Experts demonstrate more cognitive complexity when they discuss their domain.
3. Novices solve problems and evaluate evidence based on more common-sense representations; experts form abstract representations.
4. Experts use chunking and mode-linked representations of large quantities of domain knowledge.
5. Experts work forward from the information given; novices work backwards from a possible solution.
6. Experts are more likely to discover useful analogies.

This suggests that the behaviour of the expert is tempered by experience, including that of failure, and that a course designer needs to properly consider the underlying experience of their students.

3. THE NATURE OF FAILURE

To more fully understand the relationship between innovation and risk, the following exemplars serve to illustrate the range of different types and causes of failure.

Communication Error – Mars Climate Orbiter
Following the initiation of its orbital insertion manoeuvre in September 1999, the *Mars Climate Orbiter* lost radio connection as it passed behind Mars 49 seconds earlier than expected, and communication was never regained. It was established that the spacecraft was at a lower altitude than intended and broke up in the Martian atmosphere. The main underlying cause lay in a communication failure between two systems groups with the result that part of the software, supplied by Lockheed Martin, produced results for the thrusters in pound-seconds while the trajectory calculation software which used these results was expecting them to be expressed in newton-seconds. Discrepancies between calculated and measured positions had in fact been detected and reported, but were ignored [18].

Moral – Communication is key.

Construction Error – Hyatt Regency walkway
In July 1981, two suspended walkways collapsed into the lobby of the Hyatt Regency in Kansas City, killing 114 and injuring 216. It was established that problems in construction had resulted in a design change that significantly increased the load on the connections at the upper walkway. The new design was just capable of supporting the static load of the structure, but not the live load of the people using the walkway at the time of its collapse.

As designed (Figs 1(a) & 1(b)), the walkways were suspended from steel tie rods, with the lower walkway directly under the upper walkway. The upper walkway was suspended from cross-beams in the ceiling by steel rods retained by nuts. Investigators later determined that this design only supported 60% of the minimum load required by local building codes. The contractor responsible for manufacturing the rods objected to the original design as it

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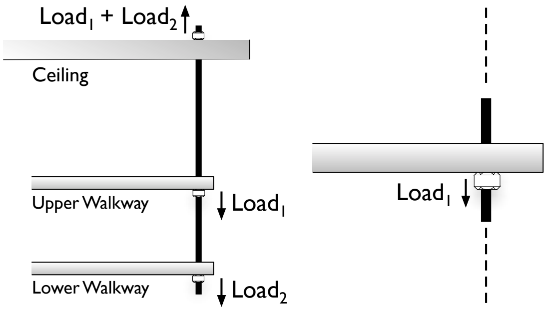
[6] 3M, along with Google, IBM and others, allow employees time to work on their own projects. In the case of 3M, many of their major product developments came from this freedom to explore concepts and ideas.

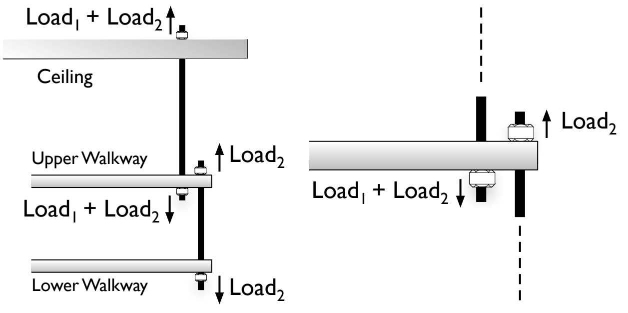
required the whole of the rod below the upper walkway to be threaded to screw on the nuts holding the upper walkway in place. An alternate was proposed (Figs 1(c) & 1(d)) using two sets of tie rods, one set connecting the upper walkway to the ceiling cross-beams, and the other set connecting the lower walkway to the upper walkway.

In the original design, the connectors for the upper walkway were only required to carry the total load (*live + static*) of the upper walkway, with the total load of the lower walkway being entirely supported by the rods, the connectors for the lower walkway then carrying only the load of that walkway. However, in the revised design, the upper walkway connectors were now required to carry the total load of both the upper and lower walkways. The resulting redesign could now only carry 30% of the mandatory minimum load, resulting in the collapse of the walkways [19].

Moral – Design changes need to be checked and verified.



(a) Intended configuration *(b) Connection as designed*



(c) Revised configuration *(d) Connection as built*

Load_1 = 50% of total load on upper walkway
Load_2 = 50% of total load on upper walkway

Fig. 1. Hyatt Regency walkway.

Design Error – Space Shuttle Challenger

The Space Shuttle *Challenger* broke apart shortly after launch from Cape Canaveral on 28 January 1986, resulting in the deaths of five astronauts and two Payload Specialists. The root cause of *Challenger*'s disintegration was the failure of an O-ring seal in the right solid rocket booster (SRB) shortly after lift-off. The O-ring was not designed to fly under the unusually cold conditions experienced prior to and at launch and its failure resulted in a loss of containment at the SRB joint. High-pressure burning gas was then released onto the SRB aft field joint attachment and the external fuel tank, causing a catastrophic failure after which aerodynamic forces resulted in the break-up of the shuttle.

The original design of the SRB joints and the O-ring seal (Fig. 2) meant that on ignition of the SRBs, the joint would rotate, allowing gasses to bypass the primary O-ring and reach the secondary O-ring, where burning had been observed on previous launches. The Rogers Commission also found that NASA's own organizational culture and decision-making processes had been contributing factors to the accident, and that the agency violating its own safety rules in permitting the launch to take place [20].

Moral – Never rely on assumptions where safety is concerned.

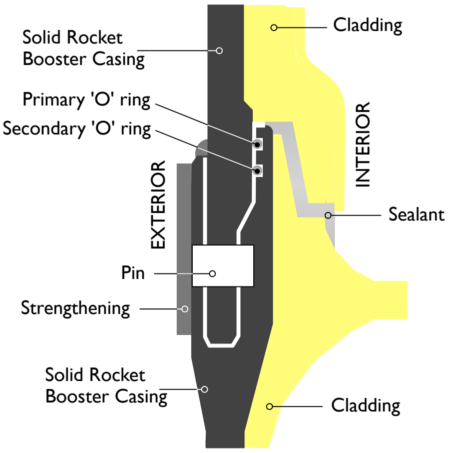


Fig. 2. Original design of SRB joint.

Human Error – Kegworth Air Crash

In January 1989, a Boeing *737-400* operating as British Midland *Flight 92* was en route from London Heathrow to Belfast when a fan-blade broke in the port engine. Smoke entered the flight-deck, leading the flight crew to assume that the problem was with the starboard engine as previous 737 models had ventilated the flight-deck from the starboard engine. They were unaware that this was not the case with the *-400* which took air from both engines. This was compounded by changes to the engine vibration gauges for which the flight crew had not yet been trained as there was no *737-400* simulator in the UK. As a result, the flight crew shut down the starboard engine while increasing the power on the port engine, which burst into flames. Of 126 aboard, 47 died and 74 sustained serious injuries.

The inquiry attributed the blade fracture to metal fatigue caused by heavy vibration in the upgraded engines, which had been tested on the ground but not under flight conditions, the latter not being mandatory at the time for an upgrade [21].

Moral – People make mistakes.

Maintenance Error - Continental Express *Flight 2574*

In September 1991, an Embraer EMB 120 *Brasilia* (Continental Express *Flight 2574* operated by Britt Airways) was on route from Laredo International Airport to Bush Intercontinental Airport (IAH) in Houston when it crashed, killing all 14 people on board. The National Transportation Safety Board (NTSB) investigation discovered that the cause of the crash was some missing screws on the horizontal stabiliser. The screws had been removed when the aircraft was undergoing maintenance the night before the accident and, following a shift change, had not been replaced.

NTSB report [22] noted that:

> "*The failure of* Continental Express *maintenance and inspection personnel to adhere to proper maintenance and*

> *quality assurance procedures for the airplane's horizontal stabilizer de-ice boots that led to the sudden in-flight loss of the partially secured left horizontal stabilizer leading edge and the immediate severe nose-down pitchover and breakup of the airplane. Contributing to the cause of the accident was the failure of the* Continental Express *management to ensure compliance with the approved maintenance procedures, and the failure of FAA surveillance to detect and verify compliance with approved procedures*."

Moral – Procedures are there for a reason.

Materials Failure – Purity Distilling Company
The Boston Molasses Flood of 1919 occurred when a tank containing some 8.7 x 10^6 l of molasses collapsed, releasing an 8m wall of molasses travelling at over 50 kph, which killed 21 people and injuring around 150. The tank was poorly constructed and testing was inadequate and the initial failure probably occurred at a manhole cover when a fatigue crack reached criticality. A modern study established that the steel was deficient in manganese, making it more brittle, and was only half as thick required for the pressures involved [23].

Moral – Proper testing is vital.

Operating Error – Three Mile Island
The Three Mile Island accident of March 1979 was associated with failures in the non-nuclear secondary system and a stuck-open pilot-operated relief valve in the primary system, resulting in the escape of reactor coolant. The investigation revealed both human factors and user interface issues with the operator's control panel. In the case of the relief valve, though this was stuck open, an indicator light on the control panel appeared to indicate that it was in fact *closed*. This came about because the indicator light did not indicate the actual position of the valve, only if the valve solenoid was powered. This led the operators to assume that the valve itself was closed.

The situation was compounded by the operators not having been properly briefed on the ambiguous nature of the indicator and the need for additional confirmation of relief valve closure. There was in fact a downstream temperature gauge which would have shown the temperature in the tail pipe was higher than if the relief valve was shut. This was not however one of indicators intended to be used for this purpose, and the operators had not been trained to interpret it.

Following a shift change in the control room, the temperature increase was noted and a backup used to shut off the coolant flow, but not before some 120,000 l of coolant had been released from the primary loop [24].

Moral – Avoid ambiguities.

Software Error – F22A Raptor
In February 2007 a flight of *F-22A Raptor*s were deploying Hickam AFB in Hawaii to Kadena AFB in Japan. When the aircraft crossed the International Date Line (IDL), on-board computer systems crashed. When attempts to reboot the systems failed, the *F-22*s had to be led back to Hawaii by their escorting tanker aircraft.

In an interview with CNN, retired Airforce Major General Don Sheppard stated that [25]:

> *"... at the international date line, whoops, all systems dumped and when I say all systems, I mean all systems, their navigation, part of their communications, their fuel systems. They were — they could have been in real trouble. They were with their tankers. The tankers – they tried to reset their systems, couldn't get them reset. The tankers brought them back to Hawaii. This could have been real serious. It certainly could have been real serious if the weather had been bad. It turned out OK. It was fixed in 48 hours. It was a computer glitch in the millions of lines of code, somebody made an error in a couple lines of the code and everything goes*."

The problem was essentially instantaneous transition from 179.9°W to 180°E on crossing the IDL, something which no-one had thought about.

Moral – Check, check and check again.

Cascade Failure – 2006 European power outage
A cascade or cascading failure occurs in an interconnected system when the failure of an individual node results in a failure in succession of other nodes as they attempt to compensate for the failed node. These nodes may then fail in turn, resulting in the collapse of the system.

Such a collapse occurred in Europe in 2006 when more than 15 million clients of the European Network of Transmission System Operators for Electricity lost supply for some two hours. The cause of this blackout was the planned, and routine, disconnection of the Ems powerline crossing in north-west Germany for the passage of a ship. However, a change in timing was not passed on to all operators in time to enable a full system analysis of the change to be carried out.

The result was that when the disconnect was implemented, the power on connected lines began to increase. It was thought that closing a tie would decrease the load on these lines. In fact, the opposite effect and lines began to trip out. Over some 28 seconds, the outage cascaded across Europe [26].

Moral – Expect the unexpected.

As systems become increasingly self-organising, and hence more complex, as for instance in association with the development of Cyber-Physical Systems and the Internet of Things, the potential for such failures will inevitably increase.

3.1 Innovation & Risk

From the above it is clear that innovation generally implies operating at, or in some instances beyond, established boundaries, and that it carries with it an element of risk regarding outcomes. For this reason, within the engineering design, implementation and operating environments, tools such as Failure Mode, Criticality and Effect Analysis (FMECA) have been developed as a means of both identifying and dealing with risk [27].

Within the context of the paper, risk is essentially concerned with the decisions made at the level of the concept design to utilise solutions which attempt to take full advantage of available technologies. The alternative is a conservative approach relying on demonstrably proven options.

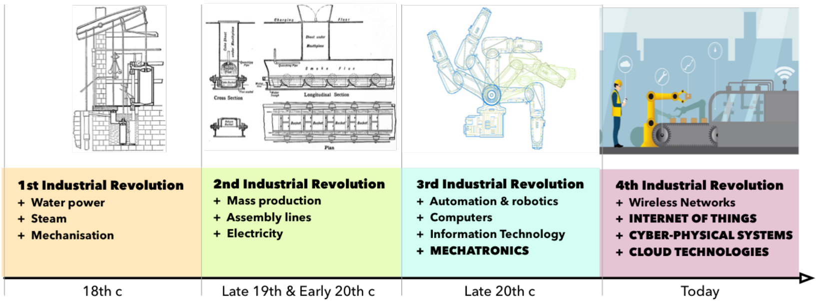
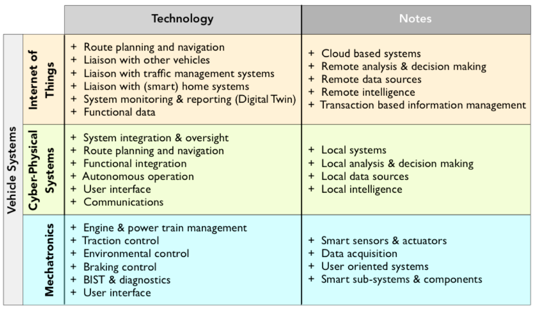


Fig. 3. Timeline of Industrial Revolutions.



		Technology	Notes
Vehicle Systems	Internet of Things	+ Route planning and navigation + Liaison with other vehicles + Liaison with traffic management systems + Liaison with (smart) home systems + System monitoring & reporting (Digital Twin) + Functional data	+ Cloud based systems + Remote analysis & decision making + Remote data sources + Remote intelligence + Transaction based information management
	Cyber-Physical Systems	+ System integration & oversight + Route planning and navigation + Functional integration + Autonomous operation + User interface + Communications	+ Local systems + Local analysis & decision making + Local data sources + Local intelligence
	Mechatronics	+ Engine & power train management + Traction control + Environmental control + Braking control + BIST & diagnostics + User interface	+ Smart sensors & actuators + Data acquisition + User oriented systems + Smart sub-systems & components

Fig. 4. Vehicle system configuration.

4. ENGINEERING DESIGN ISSUES

The engineering design process has been well documented and has resulted over time in the development of various design support tools which can be deployed to support the reduction of the initial solution space, containing all viable solutions, through the application of appropriate constraints to one which contains the chosen solution when relevant external factors are considered.

4.1 Mechatronics, Cyber-Physical Systems & the Internet of Things

Referring to Fig. 3, it is seen that mechatronics was a major driver of the 3rd industrial revolution. However, the 21st century and the growth of cloud-based systems such as the Internet of Things and Cyber-Physical Systems represent a 4th industrial revolution [28] presenting new challenges to the designers of mechatronic systems in areas such as privacy and security [29] as well as in the more conventional areas of integrating electronics with mechanical engineering.

The mechatronics design engineer is now increasingly in a situation where they are responsible for smart components and sub-systems which will be integrated within a larger, and essentially unknown at the time of design, system which may well be capable of self-configuration depending on context, as is suggested in Fig. 4 for a vehicle system. Referring to this figure, the mechatronic elements constitute the bulk of the on-board systems. These then come under the control of the cyber element to create a CPS in the form of the vehicle. The IoT then provides the link between the individual and the wider world to support interactions between vehicles and systems such as those engaged in traffic management. Each of these systems has associated with it a potential for failure which must be accommodated, including issues such as privacy and machine ethics [30,31]. This suggests that any Mechatronic Design oriented course needs to consider:

- Integration of the computation and physical processes.
- Product life-cycle management.
- Design methods.
- Tools for modelling and simulation [32].

5. MECHATRONICS COURSE DESIGN

For the mechatronics course designer, the above implies introducing the concepts of engineering design while providing access to the necessary tools along with an understanding of their use, operational implications and limitations. Specifically, there is a need to ensure that students are ultimately able to:

- Manage the ambiguities that arise in the concept stages of design. These tend to be associated with the need to combine divergent thinking considering multiple potential outcomes, and fact-based convergent thinking.
- Place ideas within the context of desired outcomes and the associated systems concepts and dynamics. This is particularly so where different teams are working on different aspects of the same problem.
- Manage the uncertainties associated with the engineering design process that are associated with incomplete and imperfect models, incomplete information and potentially ambiguous objectives.
- Estimate outcomes based on the identification of key design parameters. This is supported by statistical tools to assess the sensitivity of the design to variations in these key parameters, and is closely associated with experimental design and testing of prototypes.
- Manage communications between the members of a design team. These can take a variety of forms including:
    + *Verbal* (spoken) and *written* (textual) communication involving formalised syntactical forms of expression.
    + *Diagrams* to provide a visual description and representation of design artefacts.
    + *Models* representing specific behavioural aspects.
    + Parametric or numerical *data* associated with discrete-valued information.

In context of the above, Froyd *et* al [33] identified the five major developments in engineering education over the 20th and early 21st centuries as:

- A transition from hands-on and practical experience to engineering science and analysis.
- A transition to outcomes-based education and accreditation.
- An increasing emphasis on the role and contribution of engineering design.
- The application of education, learning and social and behavioural sciences research.
- The integration of information, computational and communications technologies within education.

Froyd *el al* also established the main considerations for engineering courses as:

1. The establishment of a sound technical base including an

understanding that engineering design is not purely about technology, but is an interdisciplinary area of study.

2. Provision of support for individuals in developing personal, along with presentational, communication skills, including the ability to listen to others.
3. Support for individuals in developing recording, note taking and diagramming skills.
4. Concept development and the creation of opportunities for the cross-fertilisation of ideas and to expose individuals to different means of thinking about, and solving, problems.
5. Group working and the development of systems level concepts applied across a range of technologies with an emphasis on design & innovation.
6. Encouraging innovative (and hence risky) approaches rather than conservative alternatives.
7. Embedding an understanding of risk and failure within innovation and providing the tools to be able to analyse failures to establish cause.
8. Developing an understanding of user aims and goals.
9. Access to and the sharing of information structured around electronic means.
10. Legislation, as for instance that on privacy, and its impact on the design process.
11. Grading schemes for joint projects involving groups of students, perhaps with disparate skills.
12. Quality mechanisms and their operation.

A principal role of mechatronic designers at each stage of product lifecycle is to make decisions, often involving engagement and consultations with experts from other fields. In general, decisions are determined by knowledge from many sources (and disciplines) involving integration across a range of taught and practical courses. Fig. 5 then shows a possible structure for a mechatronics course relative to product life cycle [34].

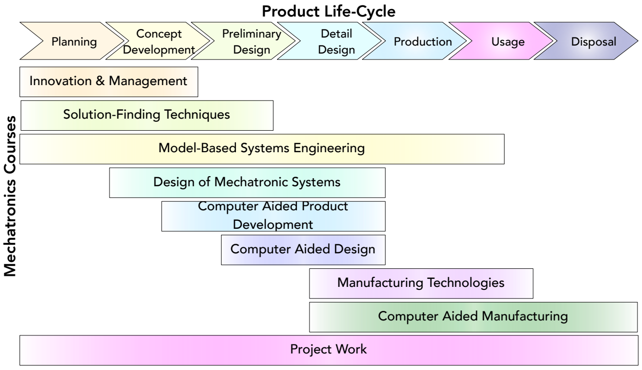


Fig. 5. Mechatronics product development course structure.

5.1 Risk in the Curriculum

> "*The greatest teacher, failure is.*"
> *Jedi Master* Yoda[7]

To be effective, the curriculum and its delivery need to develop transformational learning to enable students to engage in risk taking to create innovative solutions, to understand the iterative nature of learning from failure, and to accept failure as an integral part of the learning process. However, the context of formal education is often driven by the need for grades to equate to perceptions of success; high grades are then derived from the provision of perceived '*correct*' answers. Within such a learning context, the low risk option for students is to practice for assessments, and to find out what is deemed to be a *correct* answer. However, in engineering design terms there usually exists the possibility for numbers of *correct*, in that they satisfy the design statement of requirements, solutions. The designer must then select their preferred solution, which may often be based on contextually peripheral but functionally significant considerations such as aesthetics.

Educators can contribute to this risk-averse approach and reinforce the conservative nature of learning. Indeed, it is possible to argue that it is not just engineering students who are becoming risk averse, but that educators are also seeking risk-averse solutions as a practical response to the numerous pressures placed upon them to meet set targets in delivering a curriculum. The intention within the curriculum and the associated course design strategy and process must therefore be to ensure that students are rewarded both for innovation and risk taking within the design process, and an ability to determine causes of failure should they occur. This implies discouraging the adoption of overly conservative solutions structured around the requirements of whatever grading system is in place and instead challenging students to go beyond their comfort zone.

The drivers of curriculum change are graduate employability and the skills agenda, teaching–research relationships, changing understandings about teaching and learning, educational technologies and flexible delivery. The curriculum also must acknowledge and cope with the learning experience and expectations of entrants while covering an increasing diversity of skills and knowledge base from national and international curricula where available learning technologies and methods of delivery will vary.

6. CONCLUSIONS

In their 2004 report *The Engineer of 2020: Visions of Engineering in the New Century* [35] in response to the question:

> "*What attributes will the engineer of 2020 have*?"

The US National Academy of Engineering suggests that:

> "*He or she will aspire to have the ingenuity of Lillian Gilbreth, the problem-solving capabilities of Gordon Moore, the scientific insight of Albert Einstein, the creativity of Pablo Picasso, the determination of the Wright brothers, the leadership abilities of Bill Gates, the conscience of Eleanor Roosevelt, the vision of Martin Luther King, and the curiosity and wonder of our grandchildren*."

Designing an effective engineering design curriculum that expects its graduates to be innovative designers who satisfy these criteria requires the course designers and delivery team to overcome various challenges encompassing:

1. The adoption of teaching, learning and assessment methods to develop the necessary knowledge and values to understanding and experiencing failure and to apply this knowledge to future problems.

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[7] In *Star Wars VIII – The Last Jedi*

2. The creation of environments within the curriculum in students may expect and experience failure to develop skills such as persistence, dealing with uncertainty, critical thinking, analytical thinking at all stages within a multi-disciplinary context.
3. Provision of all necessary support to facilitate communication between individuals engaged in groups design activities. This will include the use of technology to support the effective transfer of information, and hence of knowledge generated.
4. The implementation of methods of delivery and assessment methods that meet the requisite measures for success but which include competitive elements and the scope for failure. Working in teams, an essential feature of design optimisation, has mixed measures of success for teaching, learning and assessment practice.
5. Designing a curriculum that enables graduates to achieve design optimisation and innovation itself requires the taking of risk; those delivering and assessing the curriculum need to have the academic freedom to design and implement and review the solution and then reflect/amend as per the process of engineering design to achieve the optimum solution.
6. Quality assessment procedures influence curriculum design and delivery and can lead to conservative and less effective courses.

However, if these issues can be managed and accommodated, there are opportunities to develop an innovative approach to engineering, and specifically mechatronic, design resulting in courses that are well suited to meeting the challenges faced by Mechatronics in the age of the 4th Industrial Revolution.

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