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Teaching Innovation at UPC: Linking Space Design Education with Agency Roadmaps for Exploration

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ABSTRACT

Exploration is one of the principal motivations for many space activities, but due to economic, technological or strategic context, exploration missions require long-term funding, planning, development and implementation that far exceed most other mission profiles. Individuals are therefore typically exposed to few such activities in their professional lives. To maintain the perspective of exploration as an ongoing endeavour, top-level strategies are captured as roadmaps, spanning decades. Roadmaps are developed, maintained, and defended by the space agencies on behalf of the industrial and scientific communities, but their importance is perhaps undervalued in other facets of the space sector.

The other end of the space sector experience spectrum is populated by students, to whom exploration roadmaps are colourful illustrations of an exciting future (even if most of the roadmapped future will never arrive). Roadmaps carry an implication that the ideas therein are taken seriously, that missions will fly: that it is possible to be a part of these future projects.

The School of Aeronautics and Industrial Engineering within UPC has prioritised innovation in teaching methods in order to deliver courses that expose students not only to realistic projects, but to real projects that involve external reviewers, consultants, team members, and standards for work.

This paper describes the approach of the authors in creating a new space systems design course for Aeronautics students in Catalonia. Exploration roadmaps provide interest and relevance, and so the course development principle was to associate material with actual projects and real ideas, rather than textbooks. In particular, the NASA and ESA roadmaps proved to be an excellent source for examining a number of disciplines, and joining them together in a consistent way. The course concluded with a team project, which with the help of agency professionals, generated a small incremental step in mission definition for Venus exploration. - directly linked to the Solar System Exploration Roadmap and the VEXAG white paper. This paper presents the course, the links to exploration, a description of the process, a summary of the team project conclusions, and additional examples of the 'strategy of teaching strategies'.

CONTEXT FOR TEACHING INNOVATION

The classical model of higher learning via classroom teaching dates back to the 12th century, with the emergence of guilds for specific skills. Teachers were responsible for apprentices, who followed a rigid structure: approach, reasoned discussion, synthesis of conclusions. The roles were very simple: sage teacher conveys knowledge to disciple student, and despite profound changes to society, the scope and depth of learned material, available technologies, communications, and the actual value of learning, this approach has remained essentially unchanged for 9 centuries.

When university entrance was limited to a few fortunate, this classical model could continue unquestioned. As access to higher education has become extensive, especially in the last 50 years in the Western world, serious weaknesses emerged with the previous approach. The first obvious point of note is that the ratio of sage teachers to disciple students has markedly increased, while the volume of information to be transferred has also grown non-linearly.

Since the option of incorporating an exponentially growing number of scholars to our universities is not really any alternatives, the possibilities that lie ahead to meet the demand for graduates are only those that permit the process of learning in students with lower need for resources and with maximum efficiency.

In this context cooperative learning techniques emerge as one of the most efficient variants of group work. Faced with conventional lectures in which a teacher presents their knowledge from notes and pupils take their own notes for later learning (a process in which information passes from one set of notes to another without any understanding necessary), cooperative learning promotes information flow between teacher and student, student and teacher and student to student. The teacher is no longer responsible only for expounding, but for promoting a dynamic flow of information in what could be a 'catalysis' process for learning.

In the School of Industrial and Aeronautic Engineering of Terrassa (ETSEIAT), within the Polytechnic University of Catalunya (UPC), the methods of cooperative work, active learning peer learning, project-based learning, and blended learning have been in constant use for over 20 years.

In 2000, ETSEIAT created the role of deputy director of Academic Innovation, to promote and coordinate these ongoing efforts and through the outcome of that work, the School has earned various awards and distinctions for Teaching Innovation such as the University Award for quality in university teaching in 2003 and 2009, and the distinction Jaume Vicens Vives, also in 2009). These last two awards were made possible by the efforts of a group of teachers from the school, forming the GID-T (Group for Teaching Innovation in Terrassa). This group has developed many of its activities on the potential of low-cost educational videos as a tool to strengthen the learning process.

Within this innovative teaching context, this paper introduces some features of a new specialisation course in space design for final year students.

COURSE STRUCTURE AND APPROACH

Designing a new course can begin in a number of ways. Structure can be found from established text books, content ideas from resources available online, or curriculum objectives inherited from other courses or existing academic guidelines at an institute.

In this case, the starting point was chosen to be real priorities for the sector, and for exploration in particular. This direct linkage hopefully provides some measure of inspiration to replace otherwise unremarkable course structure. The specific approach was to identify a top-level strategy document, for which the Global Exploration Strategy [1] (Figure 1) is an ideal candidate: multidisciplinary, global, concise, and non-scientific. A 'first level' tree of related strategy documents and roadmaps can quickly be identified supporting the overarching theme of global exploration. One theme in particular focuses upon *Inspiration* and *Education.*

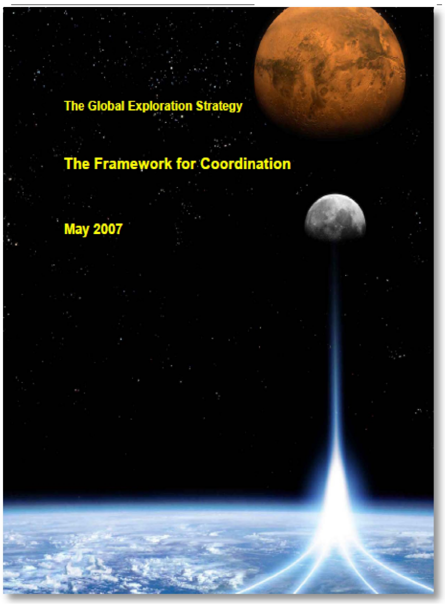

Figure 1: Global Exploration Strategy Document

Exploration is one of the principal motivations for many space activities, but economic, technological and strategic constraints mean that exploration missions require long-term funding, planning, development and implementation efforts that far exceed most other mission profiles. Individuals therefore are typically exposed to few such activities in their professional lives. To maintain the perspective of exploration as an ongoing endeavour, top-level strategies are captured as roadmaps, spanning decades.

To design a new space specialisation course, within an aeronautics context, a number of questions could be asked: What is unique about space systems engineering, distinct from *e.g.* aerospace, telecomms, *etc.*? What are the gaps between 'academic' knowledge, and industrial or agency experience? (confidence, terminology/language, tools, experience, responsibility…) What is possible in a very restricted timeframe? While these are important factors that were considered, we chose instead to start with the more unusual question: can the inspiration value of roadmaps drive learning? Figure 2 from NASA Marshall Spaceflight Center inspired a generation of engineers in the 1960s, depicting 100 people in LEO, with a further 50 on each of the Moon and Mars by 1989.

Courses of 3.6 ("DVE-1") and 4.8 ECTS [2] ("DVE-2") respectively were designed as a single specialisation, with a focus on future concepts, project work, and real challenges in industry rather than on conventional theoretical content. The process for limiting the scope such that it would fit within around 104 hours follows.

1. Assume substantial background knowledge was already available from previous courses, specifically: classical mechanics (structures, stress, strain, vibration, materials, finite element methods); aerodynamics; rotational dynamics; linear and angular momentum; electronics (at least to the level of circuit theory and fundamentals of all basic discrete components); thermodynamics; simulation tools; CAD/CAE tools; modelling and analysis packages; the basics of one or more high-level programming languages; basic orbital mechanics; the equations of motion in an orbit.
2. Next, consider what the students might be missing in the remainder of the typical topics of a spacecraft engineering course. For example, quaternion representation and algebra, despite also being important for aircraft - at least military aircraft which may encounter pitch angles of 90°. Other examples were found, and overall the conclusion drawn that the system-level relevance of any particular technology or subsystem was lacking. In the case of a satellite for example, the relationship between orbit selection and design upon the electrical power system was never explained. Systems engineering is increasingly important, but limited in exposure via traditional courses.
3. The assumptions were presented to the students at the outset, and they enabled a great simplification in the potential scope of the course. The topics mentioned above were therefore excluded at theoretical level, but included in terms of system relevance. In terms of major subsystems of a textbook spacecraft, structures and life environmental control and life support were omitted. There are few indications that there is going to be a sudden need for Europe to start putting new graduates to work on human spacecraft designs.

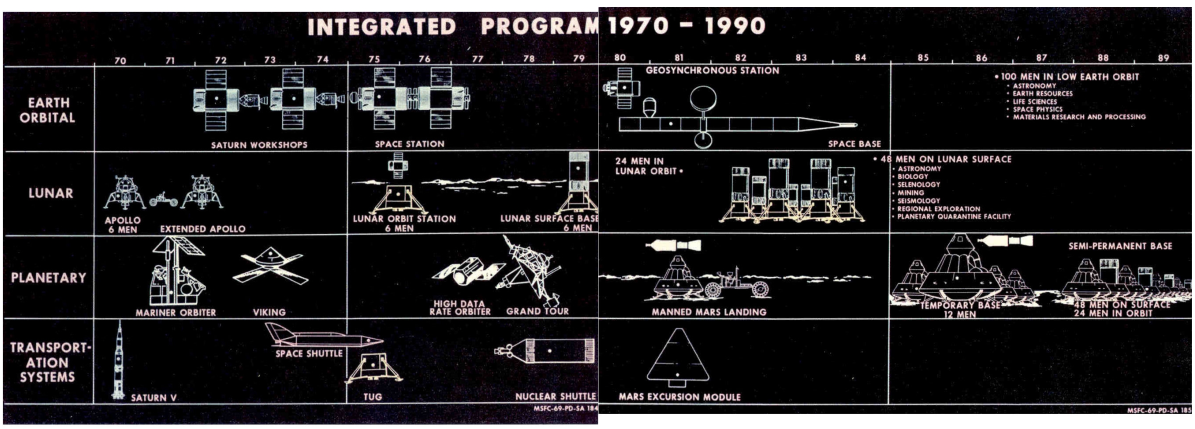

Figure 2: NASA Integrated Program 1970-1990

ROADMAPS AND PROJECTS

Roadmaps are developed, maintained, and defended by the space agencies on behalf of the industrial and scientific communities. Roadmaps are colourful and exciting plans for a future full of possibility and wonderful quests. Their primary objective is to capture long-term rationale at programme level, and thus to secure funding.

Figure 3: ESA's Mission Roadmap within Aurora

The central stripe of Figure 3 shows a series of missions including re-entry demonstration, Exomars, sample return, human landing, and a cooperative human/robot surface exploration activity. Indeed, this sequence of undertakings is logical and necessary, but the illustration carefully omits any indication of relative timing. This is addressed in Figure 4 [3], which when published in 2003 already foresaw launch of a Mars Sample Return mission on or before the 2013 opportunity. Roadmaps are useful tools, but serious documents representing expected plans and activities they are not. They have 2 valuable uses in for educators:

- *Roadmaps capture imagination*
- *Roadmaps highlighting specific technical gaps and challenges*

Published roadmaps, typically with an agency logo or reference, carry an implication that the ideas therein are taken seriously, that missions will fly: that it is possible to be a part of these future projects. This motivation is hopefully captured in the resulting course design, tapping potential and enthusiasm, and developing projects that are invested with a sense of 'roadmap realism', rather than being traditional academic exercises.

Project work carries the highest potential for strong impact on training and education value of a short course for senior students, so using activities shown in roadmaps, we endeavour to expose participants to as much reality as possible. The projects form the core the course, rather than being a closing/consolidating activity.

PROJECT PROCESS

In addition to completing a project of the type described in the following section, the students are also exposes to the language of the space industry, to requirements and their management, to traceability matrices, tradespaces, trade-offs, performance, hidden, critical, and functional requirements, and so on. Through bundling all this into project work, supported by a lecture on requirements, a significant chunk of systems engineering

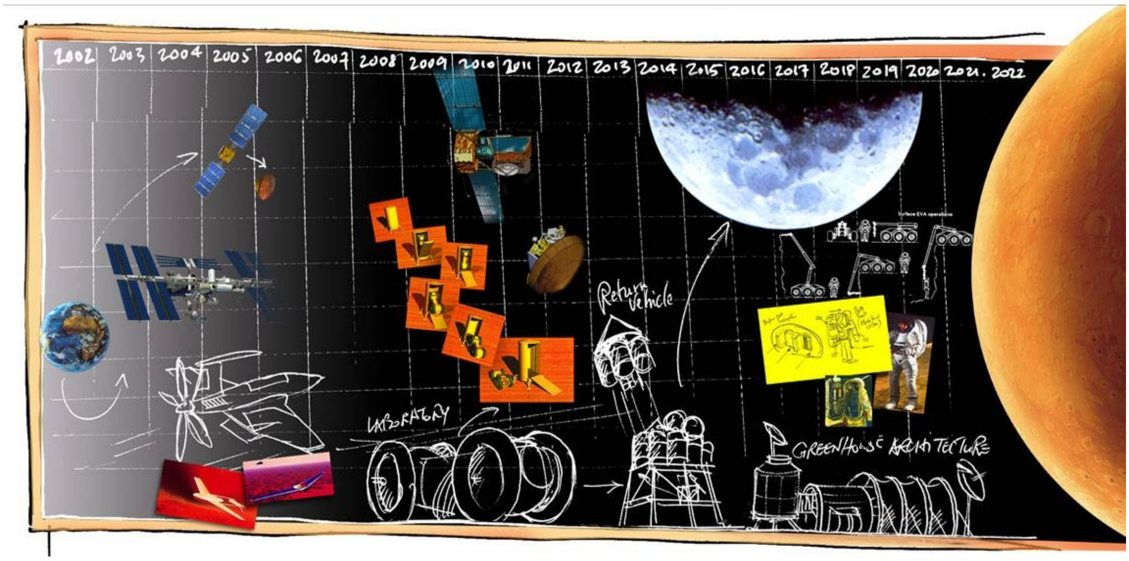

Figure 4: Aurora Timeline

thinking is delivered without taking too much time in the classroom. The principles for project work in this course at ETSEIAT are:

- *Do Something Real, No Matter How Small*
- *Take responsibility for defining objectives, work plan, required resources, deliverables, schedule, etc.*
- *Somebody in the real (agency, industry) world should want to read the output of the project.*
- *Explain how the project is relevant to some bigger picture: in technology, in concept, or in a roadmap.*

The Team Projects are designed to be intentionally almost impossible within the time allocation, but also to induce high motivation in the students. The teams are not asked to work on a typical academic exercise, but to work with industry and agency experts to identify a problem in a current or future mission design, however small, and work on it.

The goal is a team project experience that delivers something useful to the external community. It thus has to be of a high standard, no matter how small the scope. It may be as limited as "determine the wire gauge needed for connection X to payload Y in spacecraft Z". However, the team knows know that somebody in the real world actually wants this wire gauge calculation, that X, Y and Z are real, and they would feel some responsibility for the work, and for communicating it professionally.

Finally, the challenges undertaken are rather more complex than wire gauge analysis.

TEST CASES

1. Veloonus

A development project to take a small step in making balloon mission concepts for Venus exploration a reality. The reference missions of VME [4] and EVE [5] are used to identify possible project activities.

For this team project, the mission designers for future in-situ Venus missions were asked about their design challenges, or what was the "next step". The students discussed the needs with engineers, and then defined a project they felt they could take responsibility for, and have reasonable chance of success.

The team decided that they would work on trajectory modelling for a balloon in the Venusian windfields [6][7] of a super-rotating atmosphere, modelling aerodynamics and thermodynamics (necessary for a balloon since they are interdependent) in a coupled simulator. They produced a Matlab tool that propagated 3D balloon trajectory over time from any given starting point, and delivered a report and the tool to contacts at NASA JPL (VME) and the University of Oxford (EVE).

The project will also be presented at the 7th International Planetary Probe Workshop in June 2010. The cover of the report appears in Figure 5.

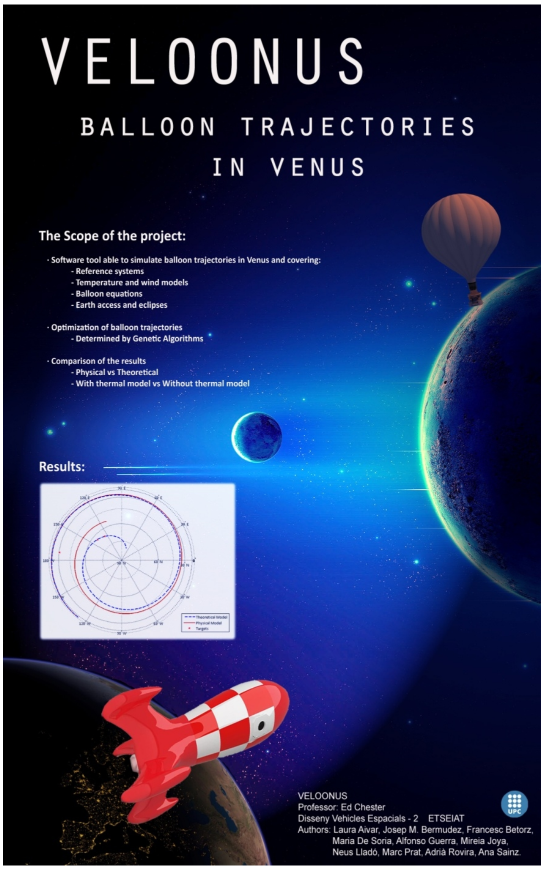

Figure 5: Veloonus

2. Marmot

The Marmot project is an individual project also related to exploration, in particular surface science of Mars in preparation for ISRU demonstrators. There are several existing designs for microrovers, of which the most well known is the Nanokhod [8], developed by vH&S of Germany.

However, while this robot has been well developed and analysed for operations on Mars, Moon and Mercury, there are few studies dealing with its delivery, deployment, and operational support in situ. This was identified as a gap in the roadmap planning for ISRU and surface robotics, and so a detailed, but top-level, design study undertaken to consider the tradespace for delivering multiple microrovers to their exploration target.

Figure 6 shows a preliminary concept from a mid-point of the project (upper panel), and a descent and landing trajectory analysis using a realistic atmospheric model for the designed entry vehicle. Again, this project was "delivered" to external 'clients', and also presented (with ESA scholarship support) at the 60th International Astronautical Congress in 2009 [9], and will also be included in IPPW-7 [10].

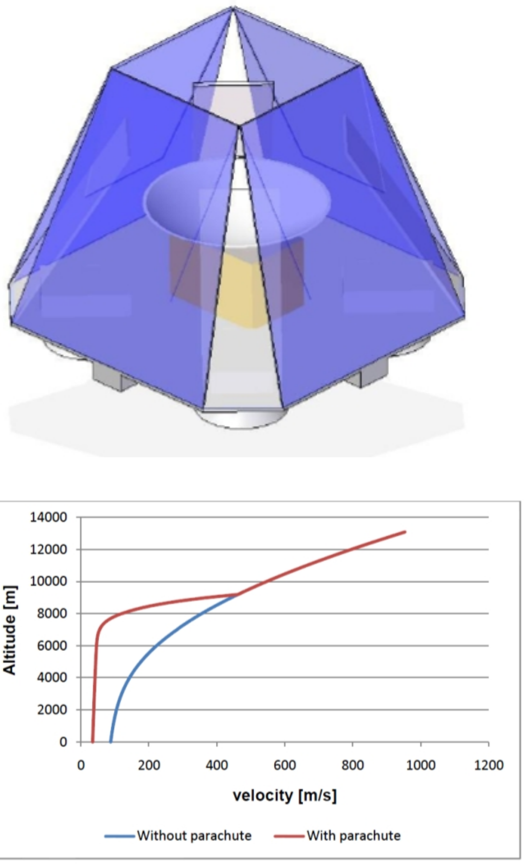

Figure 6: Marmot

3. GA/SMD

A combined aerospace and software project was also developed based on the course, as a final thesis project by an individual participant. The objective was to reverse the remote sensing mission design process using evolutionary algorithms. Rather than perform a conventional trade-off of launch capability and cost to establish a mission, and then evaluate candidate orbits for mission utility, this project sought to automate orbit design based upon targets of interest. The inputs are regions for observation, and the outputs are candidate orbits with coverage metrics used for assessing mission utility. The project objectives are summarised as:

- Develop a tool that can understand remote sensing objectives, and automatically produce orbit designs that maximise mission utility.
- Integrate the tool with a visualisation and analysis package.
- Relate the optimisation of remote sensing missions to priorities and budgets in upcoming initiatives (Sentinels, private EO mini-constellations, *etc.*)

This was completed through an integration of commercial off-the-shelf software, using educational licenses provided by ETSEIAT. Specifically, MathWorks' Matlab, AGI's STK, and custom 'glue' software were integrated to create a seamless orbit optimisation tool. Again, the project was present at IAC in 2009, and welcomed external experts as customers.

4. School Project – Lunar Albedo

A challenging extension of the approach to developing a range of realistic space vehicle engineering projects was to consider the level of work that could be performed by motivated high school students with minimal specific knowledge. The 'L'albedo' project was performed by a student of 16 years age at the outset, with the following complex objectives:

- Investigate the viability of mapping lunar albedo by indirectly monitoring solar panel temperatures
- Establish the relative importance of albedo for thermal design for different target orbits
- Consider the science value of engineering housekeeping telemetry

In this case, the 'client' is the future lunar spacecraft currently being assembled by IRS in Germany, BW1. Interest and support for the idea of 'free science' was provided by project leaders at IRS, and this sense of value and realism directly enhanced this school project.

The principal difficulty encountered was to explain the phenomena involved and why they were important, but further, to explain and to conduct the project without the use of integral calculus. Despite expectation, the student excelled in producing a numerical model of heat effects of albedo for lunar orbiters, and subsequently invested months in running the model for different orbits, look angles, sun angles, and so on.

A report with detailed model was completed, and three awards won at regional and national level for outstanding school project work. The student is now an undergraduate at ETSEIAT.

Figure 7: L'Albedo Project Cover

5. Team Project 2010: TREX

After completing a number of individual trials of 'real' projects, another team development is underway until summer of 2010. In addition to having a real client, NASA JPL, the team is also required to work in a bilateral arrangement with the University of California in a similar model to industrial bilaterals. This time, they are to re-design a concept vehicle for the exploration and in-situ science of gas giant Trojan moons, with the following objectives:

1. Conduct an international collaborative project as a bilateral mission design
2. Develop a concept design with principal system budgets for L4/5 exploration of Trojan bodies in gas giant orbits
3. Relate the mission design to existing roadmaps for solar system exploration, especially the 2006 roadmap and the science priorities in the 2010 decadal survey

The relevance to the community must be demonstrated through reference to the science plans, and presented at a suitable conference. The main objective to bring innovation to the project work in this academic year was to require international collaboration, and to introduce an agency-level customer for the deliverables. This leads to a strong pressure on the students, but with appropriate support it achieves the goal of substantially increasing motivation and thoroughness. Naturally in the case of UPC, it also provides valuable repeated opportunities to practice technical written and spoken English. Specific challenges arose in different aspects:

Project Setup

- Identifying and obtaining support and permission from outside clients
- Balancing freedom with over-constraining the project scope

Project Execution

- Prioritising project time without impacting lecture syllabus or delivery
- Establishing sufficient resources and knowledge for an advanced challenge, to avoid frustration, and excessive efforts

Academic Assessment

- Individual assessment must remain possible throughout a team project. This is addressed by requiring the team to adopt industry standards for project management, especially WBS (work breakdown structures) and WPD (workpackage descriptions) with tasks assigned to named people. Not only does this facilitate assessment, it trains the students to understand, produce and follow standards.

LECTURE COURSE

The remainder of the course is very limited in terms of the technical detail across certain disciplines. Rather than attempt to cover all aspects of space vehicle design, we focus on the interfaces, behaviour, relationships between elements, and overall systems level performance and how it affects the overall design process.

In particular, the dependency upon orbit design for nearly all subsystems is emphasised strongly. The assignments in each topic are designed to be developed as calculations within a tool, and the students are encouraged to integrate all their assignments into a simple MS-Excel based tool that can be used for tradespace analysis, preliminary Phase-A designs, etc.

DVE-1	*DVE-2*
3.6 ECTS	4.8 ECTS
• Individual Project • Orbits • Spacecraft Design • Systems Engineering • Manoeuvres • Launchers, Propulsion and Staging • Power Subsystem	• Team Project • Thermal Control • Interplanetary Mission Design • Entry, Descent and Landing • Attitude Determination and Control • Communications Systems, TT&C • Operations and Ground Segment • Payload Configuration • Future Concepts

Table 1: Course Contents

CONCLUSION

Traditional teaching meets a strong challenge when faced with highly technical subjects and ever-diminishing resources. Project work of all kinds can help mitigate this challenge, and lead to a wide variety of different teaching modes. This paper has briefly toured some examples of student-driven learning in ETSEIAT, with the support of the dedicated resources for Innovation in Teaching.

Further, the practice of imbuing projects with an element of reality – of external customers, of using applicable standards for both technical work and for project management, delivers a number of important lessons outside and beyond the conventionally limited academic scope.

Some next steps to be considered are the business aspects of bidding for project work, and familiarising students (especially non-native English speakers) with the language of the aerospace industry.

Agency roadmaps are powerful things, but they should be understood within the context of the political and financial context of agency strategy, rather than as statements of intent regarding future activities. However, they can provide considerable value to educational undertakings, as a source of inspiration (for both educators and students!) and as powerful motivation to contribute, in some tiny way, to the possible future steps in exploration.

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