A transformative engineering and architecture education

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***Abstract*—Singapore University of Technology and Design (SUTD) in Singapore was set up in January 2010 to tackle global challenges of the 21st century and beyond. To truly address human-centric issues and problems, a design-focused curriculum using an outside-in approach was adopted in formulating its undergraduate degree programmes in engineering and architecture. This has led to the formation of degree programmes focusing on products, services, systems and built environment which the world needs. To break down the silo mentality and promote multidisciplinary education, SUTD adopts a very forward-looking approach in its academic structure in which majors are offered by four multidisciplinary pillars, supported by two clusters. The absence of conventional colleges, faculties, departments and even divisions encourages seamless and boundaryless collaboration in education and research across all pillars and clusters. With a strong focus on Big-Design (i.e., Big-D) throughout and across courses, semesters and domain areas, undergraduate students are well equipped with skills and attitudes through 20 to 35 team-based Big-D projects during their undergraduate education to provide learning experiences beyond book knowledge, preparing them well with various soft skills such as creativity, critical thinking, teamwork and others before embarking on their career in industry. Coupled with small group-cum-active or peer-to-peer learning in a dedicated cohort classroom environment, the SUTD undergraduate programme further encourages students by having them collaborate with each other across pillars to foster teamwork and a collaborative spirit in formulating and sharing solutions beyond the team. Besides being recognized by the "Global State-of-the-Art in Engineering Education" report commissioned by the MIT School of Engineering [1] as the top of the emerging leader in engineering education recently, the response from industry for the first 5 batches of undergraduates has been very positive.**

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I. Introduction

Based on the report by the US National Academy of Engineering [2], the grand challenges faced by the world in the 21st century are multi-faceted. Their 14 grand challenges range from energy, healthcare, a more liveable environment, safer living, to personalized education. These grand challenges are significantly different from that of the past century and require new approaches to overcome them. Coupled with the aggressive development of new opportunities in Industry 4.0 - which is driven fundamentally by digital transformation, internet-of-things and ultra-high-speed wireless network - the challenges and problems that we face are increasingly inter-connected. Technologies on one hand have provided us with great engineering and architectural achievements and solutions but, on the other hand, have also created many more new and greater challenges for which the solutions are not clear.

Thus, we need to innovate so as to provide human-centric solutions for affordable healthcare, clean water supply and energy, low-cost and abundant power source, reliable transportation systems and security in the physical and cyber worlds. Disruptive technologies such as artificial intelligence (AI), 3D/4D printing, advanced robotics and internet-of-things are taking place at an unimaginable rapid pace to the extent that not only are traditional jobs disappearing rapidly, but new types of jobs are also appearing constantly. To address these challenges and cope with the fast-pace of technological development, we need graduates with new mindsets and skills who are capable of providing practical, sustainable, innovative and even radical solutions that cut across traditional boundaries and new domain areas. Some of these are likely to be beyond our current imagination.

Hence, it is timely for institutions of higher learning to revisit the engineering and architecture education so as to equip future generations of students with the knowledge, skills and attitudes to work in diverse groups and environments, harness the potential of new or untapped technologies and knowledge and find creative and previously unthought of solutions to complex problems. This has led to many new initiatives within higher engineering and architecture education to effectively develop and train our graduates in the required competencies.

In January 2010, the Singapore Government and Massachusetts Institute of Technology (MIT) agreed to establish a new partnership in creating a new research-intensive university called the Singapore University of Technology and Design (SUTD) with a mission to nurture technically-grounded leaders and innovators to serve societal needs through a multi-disciplinary, design-centric education and culture. Its students were to have far-reaching aspirations to create a better world by design, the confidence and courage to try new ideas and approaches, a questioning spirit fuelled by the thrill of multi-disciplinary learning and doing and life-long competencies, especially the ability and appetite to learn and innovate. Mr. Lee Hsien Loong, the Prime Minister of Singapore, in his congratulatory messages [3] at the signing ceremony marking the launch of SUTD, mentioned that "The Singapore University of Technology and Design will provide something different from the existing institutions - a very high quality education, not just an academic education, but one which is going to stimulate students to go beyond the book knowledge, to apply it to solving problems. It will teach students to be creative, not just in the technology and the design part, but also to be creative in bringing ideas out of the academic environment into the real world, into the business arena, into the real economy and make a difference to the world."

II. New Design Footprint – A 4D Design Philosophy

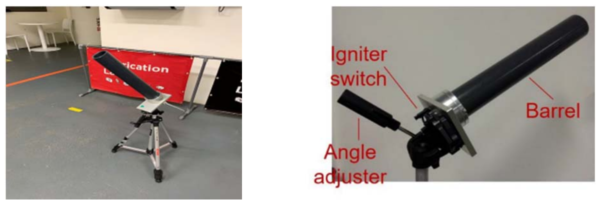
To embrace the ambitious goals and create a very different university, a new design-centric concept called "Big-D" (i.e., Big-Design) was adopted as the backbone for developing an innovative outside-in-approach undergraduate programme. Professor Thomas Magnanti, the SUTD Founding President and former Dean of Engineering of MIT, articulated that Big-D covers technical designs built based upon strong foundation knowledge like Mathematics and Sciences, and covers the full value chain from conception, development, prototyping, manufacturing, operation to maintenance. The whole process from understanding needs and challenges, problem framing, ideation, evaluation, prototyping, modelling, simulation, development and testing is included, and key aspects such as creativity, innovation and entrepreneurship are inculcated and nurtured. This inevitably requires a combination of theory and practice, and of science and art. The Big-D concept is very powerful because it cuts across different domains and disciplines (i.e., subjects), across terms and between university and collaborators in industries. It further compels students to use a human-centric approach, quickly learn from mistakes, and arrive at a better set of possible solutions.

To truly break down the silo mentality and encourage cross- and multi-disciplinary collaboration, SUTD was carefully set up without colleges, faculties, departments and even divisions. Instead, the academic organisation is based on so-called "Pillars": Engineering Product Development (EPD), Engineering Systems and Design (ESD), Information Systems Technology and Design (ISTD) and Architecture and Sustainable Design (ASD) that break down traditional boundaries of specialized fields like electrical engineering, mechanical engineering, industrial engineering and computer science. After a common first year of three terms, each Pillar offers degree programmes over a further 5 terms in their respective area. For example, EPD covers key topics and concepts like structure and materials, feedback and control, circuits and electronics in both mechanical and electrical engineering majors, respectively. This way of formulating the new types of degree programmes using an unconventional outside-in approach by focusing on what the world needs – products, services, systems and built-environment – will ensure that the SUTD undergraduate programme is always forward-looking and ahead of the curve. By emphasising what is needed to do a great job in the 21st century, SUTD believes that the graduates will be able to use a significant amount of knowledge learnt, and skills and attitude developed at SUTD immediately upon joining the workforce after the completion of their undergraduate education.

A. *Approaches for 4D Big-D*

Besides building a strong foundation for all students in critical areas like design innovation/thinking, mathematics and sciences in the first three terms, a 4-Dimensional Big-D (Called 4D Big-D) programme built upon the Big-D concept was also formulated to support the vision of "bringing book knowledge out from textbooks and classrooms and applying to real world". SUTD developed "designettes", which are short-term design challenges, as a platform to support the 4D Big-D programme. Starting from Term 1, students are given opportunities to work collaboratively in groups on designettes within a subject (i.e., 1D Big-D) like mathematics, physics, chemistry and biology as well as designettes that cover knowledge needed from two or more subjects within a term (i.e., 2D Big-D) and across terms (i.e., 3D Big-D). In essence, 2D and 3D projects serve as bridges to further strengthen the inter-connectedness of subjects in the curriculum. Figs. 1 and 2 show some examples of 1D and 2D designettes of the foundation subjects and Fig. 3 shows an example of a 3D designette in EPD. Finally, the 4D Big-D projects such as 2-term integrated Capstone Design projects in senior year encourages collaboration across pillars or domains, between university and industry and outside the classroom among students.

Fig. 1. An electric guitar resulting from a designette in an advanced physics course. The designette of 1D Big-D requires students to use Faraday's Law and the wave concept in physics to make a simple electrical guitar.



(a) (b)

Fig. 2. (a) A launcher resulting from a 2D Big-D project. This design activity, aimed at the application of chemistry and physics taught in the common terms, through a scaled-down model of a launcher to launch a projectile. Shown is the solution of a team that came up with a chemical solution, showing their first year knowledge, creativity, modelling and prototyping skills. A combustion reaction between methylated spirit and oxygen generates a sudden and large increase in gas pressure built up in a closed chamber, resulting in rapid gas expansion and ejection of the projectile out of the launcher. The trajectory of the projectile is then modelled by Physics laws. (b) Details of the launcher.

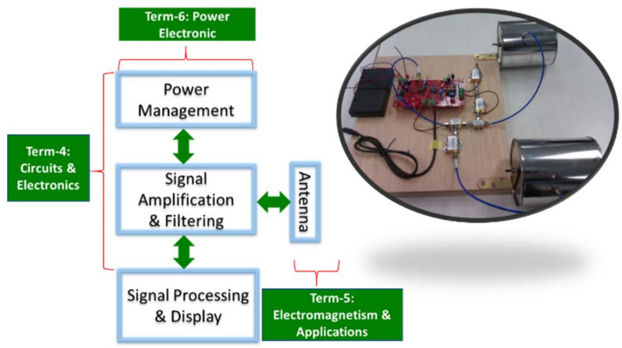


Fig. 3. An example of a 3D Big-D project on a radar system for detecting car speed that links vertically across terms by connecting foundation knowledge with more advanced concepts. In this example, the design of a circuit board of a detection system in Term 4, of an antenna in Term 5 and a power management design of the entire radar system in Term 6.

B. *Integrated Capstone Design Project*

Under the 4D Big-D framework, an integrated Capstone Design project in the senior year brings students from different disciplines (i.e., ASD, EPD, ESD and ISTD pillar) together again in teams to use the in-depth knowledge and design skills learnt in their respective discipline to formulate holistic and advanced solutions and to develop design prototypes for projects sponsored by companies, start-ups, SMEs and governmental organisations from diverse fields. A Capstone project starts with a short problem description and ends with a showcase of a working prototype. Modules on specific topics, as well as skills including professional ethics, teamwork and communication, project management, and health & safety, complement the design projects. This is unlike traditional senior-/final-year projects that fall within a single discipline: each team has to consist of students from at least 2 pillars.

Fig. 4 shows an example of a capstone project. The task was an "automation of outpatient pharmacy" in collaboration with Singapore Changi General Hospital that optimises workflows and improves medication safety of an outpatient pharmacy system. Working together in a cross-discipline team, ESD and ISTD students focused on optimising the throughput of the delivery system used for packaging and dispensing drugs, while EPD students developed the system used to consolidate, buffer and deliver drug prescriptions. ASD students studied the optimal space arrangement of the outpatient pharmacy and how the equipment could be best arranged in the given spaces. Eventually, with their combined team knowledge and skills, the Capstone team designed an optimal pharmacy layout incorporating systems and technologies that proved capable of catering to the high operational throughput.

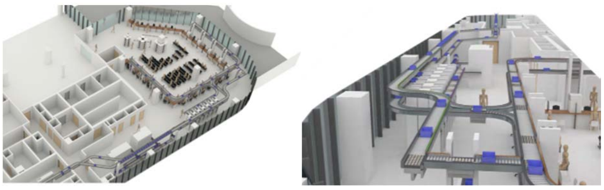


Fig. 4. A 4-pillar capstone project to automate an outpatient pharmacy of a general hospital in Singapore.

Around a third of the capstone projects are student-initiated, i.e., a group of students from at least 2 pillars proposes a topic and finds a company interested in sponsoring. To cultivate more entrepreneurs and students with entrepreneurial mindsets, ca. 10% of the Capstone projects are so-called entrepreneurship projects. Student teams from different pillars follow a series of entrepreneurship trainings provided by the SUTD Entrepreneurship Centre and pitch their ideas to a group of venture capitalists. The teams that are selected will be provided with 70% of the required funding by the Entrepreneurship Centre. The remaining 30% they will have to raise from elsewhere. Upon completion of the Capstone entrepreneurship projects the students will be equipped with entrepreneurial competencies to bring a product, service, system or architectural design from conceptualisation to commercialization. At the end of the programme, the teams are encouraged to form start-ups and get opportunities to pitch their working prototypes to investors. So far, more than 40 start-ups have been formulated by the undergraduates and some of which were successfully continued from the entrepreneurship capstone projects. More recently, one social innovation capstone project has been specially selected each year to further embrace bringing innovative design solutions to tackle social problems.

Through these design projects, students further strengthen their skillsets in creative thinking and reasoning, problem solving, social and emotional competencies, empathy and communication. It is also believed that design projects can cultivate a strong passion, collaboration, growth mindset, challenging the status quo, willingness to take risks and fail, and even a "can-do" spirit. The Big-D concept uniquely defines the design footprint of SUTD and differentiates itself from other design curriculum around the world. As Big-D spirit is present at every stage of the undergraduate study, it becomes a cornerstone in defining and shaping a strong culture within the university environment that naturally leads to fostering a mindset of design thinking and innovation, creativity and system integration across many disciplines. With the strong presence of entrepreneurship and can-do attitude transferred from MIT, it inevitably serves as a catalyst for solutioning and boosting the commercial viability of products, services and systems in the start-up space.

C. *Human Centric Design*

Like MIT, SUTD has deliberately included a significant proportion (22%) to Humanities, Arts and Social Sciences (HASS) courses that enable students to acquire reflection, critical thinking, problem solving and communication skills. To be a good innovator and designer, SUTD believes that students need to be more aware of the ethical, environmental and societal impacts of technology and their design solutions. Besides two core HASS subjects in the common terms, students must take 5 more HASS electives in each term from Term 4 to Term 8 to meet the graduation requirement, which is significantly higher than typical engineering and architecture programmes. The HASS requirement strengthens human-centric design, which is extremely important in the disruptive digital design era.

D. *Freshmore Terms to Build Common Foundation*

To further ensure that all SUTD students are equipped with strong technical fundamentals, students undergo a broad-based three-term foundation curriculum before focusing on a major in one of the "Pillars" that offer degree programmes. The foundation curriculum, called "Freshmore" which is a combination of three terms of the Freshmen and Sophomore year, consists of core courses in sciences, mathematics, design innovation, programming, computational thinking and HASS. In Term 3, through the courses Digital World, Systems World and Physical World, students are able to cross-link basic theories and knowledge to real-life technologies and applications. By leveraging on the 3-term collaboration opportunities via 1D/2D Big-D projects, the Freshmore programme provides a common human-centric professional language for all students..

III. Unique Cohort-Based Pedagogy for Design

To foster more interaction, bonding and integration among students, classes for the Freshmore subjects are commonly conducted in 200m^2 cohort classrooms. Each such classroom is home to up to 50 students who have full access to their room round the clock for the 3 Freshmore terms of common study. Each classroom contains basic fabrication tools such as 3D printers, digital cameras, mechanical hand-tool sets, and even relevant texts and reference books for the Freshmore subjects. The rooms are designed with a flexible configuration of chairs and tables and multiple whiteboards and projectors to cater to various requirements and expectations of subjects like cohort lessons, design projects, group discussion, problem solving, 1D/2D projects, quizzes/tests/exams and small group critiques cum seminars. Students take full advantage of the classrooms for various learning activities outside formal instructional lessons such as hackathons, self-study and group discussion. Together with mandatory on-campus hostel residency for the 3 Freshmore terms, this unique environment further fosters social integration and bonding by leveraging on peer-to-peer support, collaboration and cooperation.

To make the lessons "lively", each cohort lesson is conducted by three instructors - two faculty members and one upper-year student serving as a teaching assistant. This teaching ratio of about 16:1 (i.e., 50 students against 3 instructors) is almost ideal for facilitator-led lessons. Through careful courseware design and coordination among the 15-20 faculty instructors of a teaching team of the Freshmore subjects, a typical lesson will start with a high-level overview of key concepts based on the flipped-classroom format followed by group discussions of problem sets and questions. At times, 1D projects are included to enhance learning and faculty instructors occasionally perform high-risk or expensive demonstrations to stimulate learning. The lessons will typically end with simple quizzes for the students to reflect on what they have learned. For some lessons, individual quizzes followed by group quizzes are adopted at either the beginning (for blended learning) or towards the end of a modular session of about 30 to 45 minutes. Upon completion of a cohort lesson, students will typically walk away with a good understanding of a concept and how that can be applied in the real world. This "learn, engage, apply and make-prototype" approach has become a cornerstone of SUTD's unique pedagogy which is an important building block of the students' upper year of study. More importantly, each Freshmore subject teaching team consisting of different instructors (10 - 20) is led by a lead instructor whose main responsibilities are to ensure coordination and synchronization of lesson delivery. Hence the SUTD cohort-based pedagogy is very unique in providing a learning environment that is not only very effective but also fosters working relationship among instructors and among students.

IV. Design and Artificial Intellengence

To build strong digital capabilities in preparation for the AI-driven digital economy and to support the Singapore Smart Nation initiative [4], SUTD further aims to create a new breed of designers and innovators who are able to harness the power of artificial intelligence to enable design and innovation in the space of products, systems, services and built environment. SUTD believes that "AI for better applications" is needed as many companies face challenges in deploying AI applications effectively and at scale. SUTD has the unique advantage and strength to set up a multi-disciplinary programme in AI-enabled design innovation since "Design" is its DNA and AI is as one of the focused fields of SUTD study and research in its Phase 2 growth. This new Design and AI (DAI) degree programme would encompass the ability to i) apply AI to design innovation in the space of products, services, systems and built environment, ii) value-add to business processes and services via a systems-approach, iii) improve human experiences using digital technologies, iv) create start-ups and v) critically assess the ethical, environmental, organisational and societal effects of their AI-enabled solutions or innovations during the design process.

Besides design and AI-related courses, business-related courses will be tightly integrated as an important part of the curriculum to make the students understand the importance of value creation in AI-driven designs. Like SUTD's other undergraduate degree programmes, HASS courses such as digital humanities, AI and ethics, and design ethnography, are an essential part of the curriculum to equip students with the ability to critically assess the ethical, environmental, organizational and societal effects of their AI-enabled solutions and innovations. In every term of the junior and senior years, DAI students will work on an industry- and AI-driven design project in a design studio setting so that applied learning occurs in the context of a real-world problem. The design studios will involve company-sponsored design projects across a wide range of growth sectors like built environment, healthcare, media and services using real-life data. These design studios are envisioned to take place at dedicated project spaces that will be modular and adaptive to individual as well as team-based collaborative work through the SUTD Big-D framework. By graduation, all DAI students would have a comprehensive design portfolio of industry projects to show to prospective hiring companies.

Conclusion

Since SUTD launched its first class in May 2012 and graduated the pioneer batch in August 2015, SUTD has graduated 5 batches of undergraduate students and 4 batches of students from its Master in Architecture. The performance of the SUTD graduates has been encouraging; they have found employment in more than 70% of the key industries in Singapore – a recognition that our graduates are versatile in adapting to the demands and expectations of today's industries. SUTD graduates have also enjoyed a higher employment rate (about 94% in year 2018) after 6 months of graduation. The self-reflection of our graduates in their surveys conducted by an independent party engaged by our Ministry of Education showed that SUTD graduates acknowledge multidisciplinary, teamwork, creativity and innovation as key differentiating factors which separate them from their peers. About 5% of our graduates have started their own companies while about 10% pursued further graduate studies. SUTD has also received very positive feedback and encouraging remarks from industrial partners that SUTD graduates are not only Industry 4.0-ready but also World- and Future-ready. We strongly believe SUTD's pedagogy and educational approach can be an appropriate model for the next few decades.

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