EXPLOITING HAND SKETCHING IN EDUCATING 'MECHANICALLY ORIENTED' ENGINEERING STUDENTS

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ABSTRACT
It is well known that even though Computer-Aided Design (CAD) systems are available, sketching is still widely used in design synthesis. Mechanical engineering students must therefore be cultured and trained to exploit sketching during this crucial activity in the basic design cycle. However, in our years of experience in training such students we found a strong tendency that due to the overall knowledge transfer they receive, these future engineers tend to be oriented in mainly thinking and presenting details of their design solution. Whilst clearly design solutions need to be eventually described in detail for their successful realization, good detailed design solutions do not make up for poor solution concepts generated. In this paper, we therefore present the overall pedagogic approach adopted at the University of Malta in exploiting sketching both for expressing working principle solutions and also for early form design. In addition, this paper outlines how a prescribed sketching language was developed to enable co-located students to quickly express and exchange 3D CAD models of their sketches, all this helping in making 'global design' truly feasible even at the early design stages.

Keywords: pedagogic approach, global design, sketching languages, design synthesis

1 INTRODUCTION

Due to the *Bologna Process* [1], which is aimed at establishing academic degree standards throughout Europe, certain mechanical engineering degree programmes have become more focused towards pure mechanical engineering. Consequently, tools and methods supporting students during *design synthesis* [2] are either omitted or perhaps not given sufficient depth. Sketching is one of the oldest methods used by designers to visually support the development of ideas [3] and hence during synthesis. 'It is interesting to watch how a designer, when given a 3D design problem, instinctively reaches for a pencil and paper' [4]. Traditional sketching is still very popular amongst designers, as it provides an efficient means to instantly capture ideas [3]. It is only when designers develop their ideas by sketching them on paper that they resort to the computer [5]. A survey carried out by Roemer *et al.* [6] with 106 designers shows that sketches are significantly more used than other means including physical and CAD models for solution development. The study carried out by Song and Agogino [7] also reflects such a trend. It was only towards the late design stage that the 57 mechanical engineering students involved in this study produced a reasonable amount of CAD drawings. Traditional sketches were the prevailing representations used throughout the design process. The above practices and studies collectively suggest that even though CAD systems are available, sketching is still widely used in design synthesis. They reflect also that students must be cultured to exploit sketching during this crucial activity in the basic design cycle [2]. Thirdly they highlight the importance that mechanical engineering students are trained to acquire adequate sketching skills before working in industry.

Within this context, the rest of this paper is organized as follows. Section 2 discloses how hand sketching forms an integral part of the pedagogic approach employed at the University of Malta to train students in expressing working principles and for developing form design solutions. Section 3 presents a *Prescribed Sketching Language* (*PSL*) aimed at enabling students and designers, irrespective of their cultural background and sketching skills, to quickly transform their early form design solutions sketched on paper into three-dimensional (3D) CAD models. Section 4 discusses the pedagogic approach adopted and *PSL*. Future research directions are also recommended. Conclusions on the contribution of this paper are made in Section 5.

2 SKETCHING – AN INTEGRAL PART OF THE PEDAGOGIC APPROACH

The bachelors engineering degree offered by the *Department of Industrial and Manufacturing Engineering* at the *University of Malta*, is spread over a period of four years.

2.1 Year 1: introducing sketching in engineering drawing

Given the importance of drawing in the design process [8] and since we strongly believe that drawing is the language of an engineer, we retained the manual engineering drawing study unit in the first year of the new curriculum, instead of replacing it with CAD. It must be mentioned that the former syllabus of this unit was focused mostly on techniques required to draw detailed mechanical components in orthographic views, isometric projections and accurate drawings of cams, loci and development patterns only. Whilst keeping the majority of the aforementioned techniques, given the importance of sketching in design synthesis as argued in Section 1, basic sketching skills have been added to the new curriculum. In the first lecture of this study unit, the advantages of manual drawing over the direct use of CAD in conceptual design are highlighted. In this manner, students are made conscious of the importance of sketching as early as from the first week of their degree course. Furthermore, the different types of drawings used in the four main stages of the design process (Figure 1) are explained.

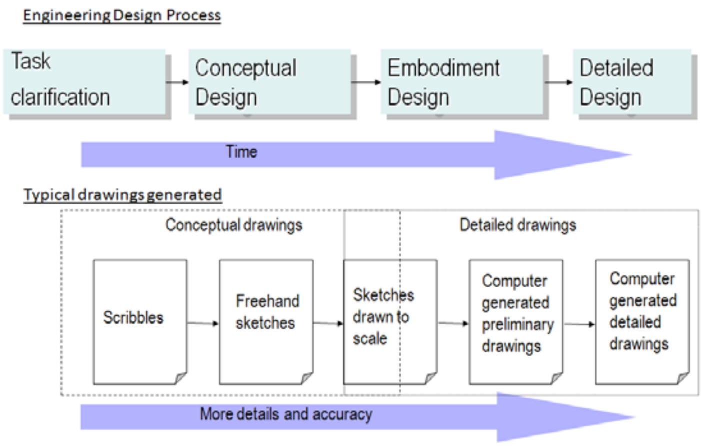


Figure 1. Diagram used to explain to first year students the types of drawings used in the design process – adopted from [9]

In the eight lecture, basic sketching techniques are taught to the students, including perspective projection which is widely used in industrial design sketches [10], the spiral technique to draw objects of rotational geometries [11], lineweights, cross-sections, shading and representation of material of the components constituting a product (e.g. transparent plastic covers and textured gripping surfaces). After the theoretical part, the students are assigned a series of exercises in which they have to sketch freehand objects of various geometries (e.g. rotational, lofted etc.) in perspective projection. Figure 2 illustrates sample sketches drawn by students in these exercises. It is stressed that the sketches should be drawn without the use of any drawing instruments.

Figure 2. Sample freehand sketches drawn by first year students

It must be mentioned that in the former engineering drawing curriculum, students were assessed on a number of individual assignments and a larger project in which they have to generate detailed engineering drawing of a mechanical product (e.g. a pump). Whilst keeping the individual assignments, a new approach has been adopted as regards to the larger project. The students are divided into teams of six, in which they have to first select an existing physical object. Each team is instructed to generate sketches of the selected object and detailed orthographic views. At the end of the study unit each group has to submit an A0-size poster illustrating the different types of drawings produced. The focus of this project is not on the use of sketching in design synthesis but rather to teach students to appreciate how a design solution evolves from conceptual to detailed stages, via drawings, besides other tools and methods.

2.2 Year 2: use of sketching in a global design exercise

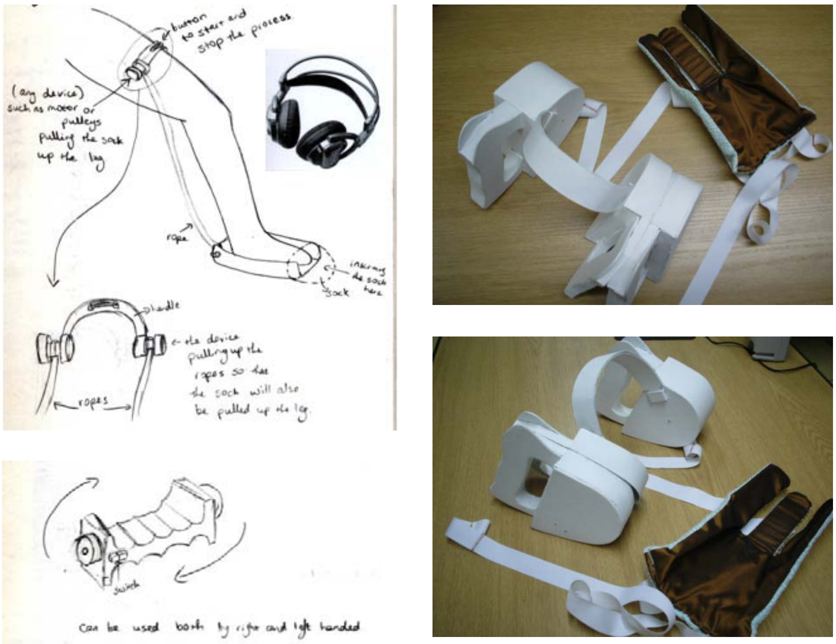
Given that nowadays it is a common practice that product development activities are carried out in different places around the globe [12], the second year students in Malta taking up the *Computer-Aided Engineering Design* (CAED) study unit are engaged in a synchronous collaborative design group exercise with students at the *University of Strathclyde*, in the UK. It introduces students to the particular tools and practices necessary to complete the design of an artefact in a distributed environment. The exercise is spread over a period of four weeks, where the students take part in three videoconferencing sessions, one each week. In the first week they review the design brief and gather background research, in the second week they generate and discuss concepts and select one, and in the third week they refine the selected concept and prepare presentation. In the fourth week a reflection session is carried out in which the students share their experience after completing the exercise. The exercise is designed to be a hands-on experience which highlights the real issues of sharing and communicating design information with technological constraints. Students make use of information storage tools (e.g. *Google Docs* and *Wetpaint*) as well as conferencing tools (e.g. *Polycom* and *Skype*). The use of digital sketching tools is strongly encouraged both as means of communicating working principles as well as to express the form of the evolving solution. For example we suggested that students use *Skrbl* (www.skrbl.com), an online multi-user whiteboard, allowing users to sketch, write text and share files and *Google SketchUp* (http://sketchup.google.com) which allows users to quickly create 3D models.

2.3 Year 3: introducing sketching logbooks in the engineering design project

In the third year students undertake the *Engineering Design* study unit. This is divided into two parts; in the fifth semester they are taught engineering design methods to solve a design problem in different stages of the basic design cycle. Examples of synthesis tools which are taught include *SCAMPER*, synectics and morphological charts. In semester 6 students are assigned a group project aimed at developing an innovative product, in which they have to apply the design methods learnt. To ensure that students have exploited sketching to develop the working principles and form geometry concepts, as one of the deliverables, they have to submit an individual log book containing a record of ideas generated. This concept was introduced in the new curriculum, as in the previous years students tended to focus on detailed design solutions. Figure 3a illustrates excerpts from a student's logbook showing the development of working principles and exterior form of the automatic stocking wearing device. Students are instructed to include pictures of existing objects in their sketches as means to facilitate the use of *SCAMPER* during synthesis. For example, the sketch in Figure 3a shows a picture of a pair of headphones from which the student has adapted the form of this physical object to the evolving form of the automatic stocking wearing device. In addition, given the importance of modelling in design [13], besides the log book, each team has to build a simple physical model showing the working principle and the basic form geometry of the selected concept (see example in Figure 3b). Simple physical models are also widely used in design [6].

2.4 Year 4: sketching in the final year engineering project

Thoroughout their fourth year students undertake the final year engineering project, where they have the opportunity to apply their knowledge and to exercise the skills learnt throughout the course. In projects where students have to design and manufacture a component or an assembly of components, the use of freehand sketching, rather than the use of CAD, during the conceptual design stage, is strongly recommended. It is explicitly requested that students include sketches of working principles in their dissertation, besides the detailed drawings of the final solution.



(a) (b)

Figure 3. (a) Excerpts from a student's logbook (b) cardboard model of automatic stocking wearing device

3 A PRESCRIBED SKETCHING LANGUAGE (*PSL*)

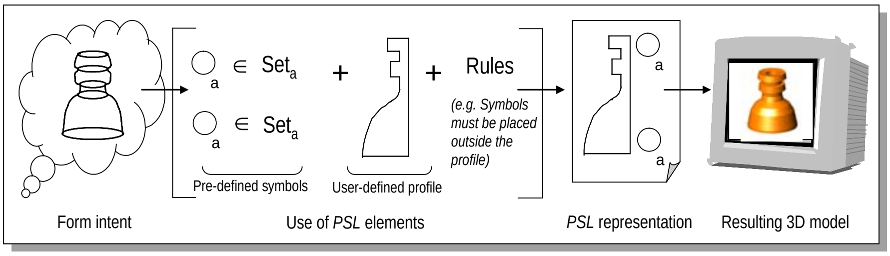
3.1 Rationale for *PSL*

In order to assist students and practising designers to automatically transform their form concepts sketches on paper into 3D CAD models, a sketching approach was developed. The rationale behind the development of this sketching approach is described next. CAD systems have a number of limitations which make it difficult to automatically transfer early form paper-based sketches in 3D models. A survey conducted by Lim *et al.* [14] with 82 design students and 9 research staff members highlights a series of weaknesses of CAD systems in conceptual design, including 'too time consuming with slow feedback', and 'too complicated for design thinking'. At the same time, CAD systems possess a number of advantages (e.g. 3D visualization) which can be exploited in early design. Within this context we argue that a means is required to combine sketching with CAD.

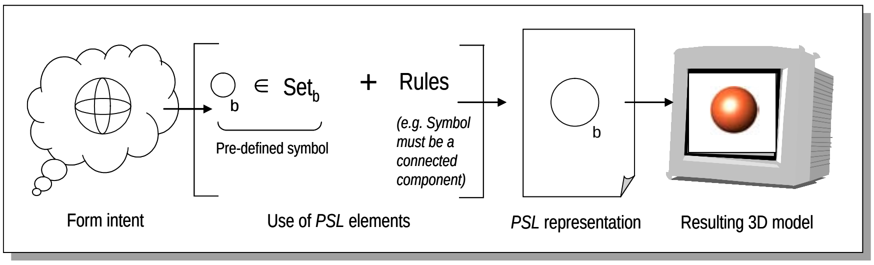
However, computer recognition of paper-based sketches is a non-trivial task. The sketching style varies from one individual to another [15], even if the form concept being conceived is the same. A sketching style is typified by the type of graphical representation, sketching media, rendering techniques and the use of notes and of drawing instruments [9]. It is also common that sketches contain different types of information [14] such as annotation and geometric information. Such a characteristic complicates the processing of paper sketches as the required geometric information is not extracted in real-time [16]. Geometric vagueness is another issue; information which is expressed vaguely in sketches gives rise to multiple interpretations [17]. Thus, to address these issues, a prescribed sketching language was developed to robustly communicate the same form concept in sketches produced by relevant stakeholders into one 3D CAD model.

3.2 *PSL* alphabet

PSL exploits symbols representing 3D CAD modelling functions. These symbols map two-dimensional (2D) form descriptions on paper into 3D CAD models. The type of mapping depends on the particular class of symbols. For instance, a class of these symbols operates on 2D profiles, mapping them into 3D models (Figure 4a). Other symbols are directly mapped into the corresponding 3D primitives, e.g. a sphere (Figure 4b).



(a)



(b)

Legend: Set_a = {○, ⬡, △} (a) Set_b = {○, ⬡, △} (b)

Figure 4. 2D-to-3Dmapping obtained by symbols in PSL

In view of the underlying principle of *PSL*, fundamental 3D operations utilized in CAD systems were referred to. Such operations represented by symbols in *PSL* (see Table 1) cover extrude, sweep, revolve and loft. The 3D mapping accomplished by each of these operations when applied on 2D cross-section profiles is illustrated in Figure 5. The sweep operation requires a user-defined sweep path to accomplish mapping, whereas the revolve operation, an axis. With loft, two or more sections can be blended with either a linear or a curved transition.

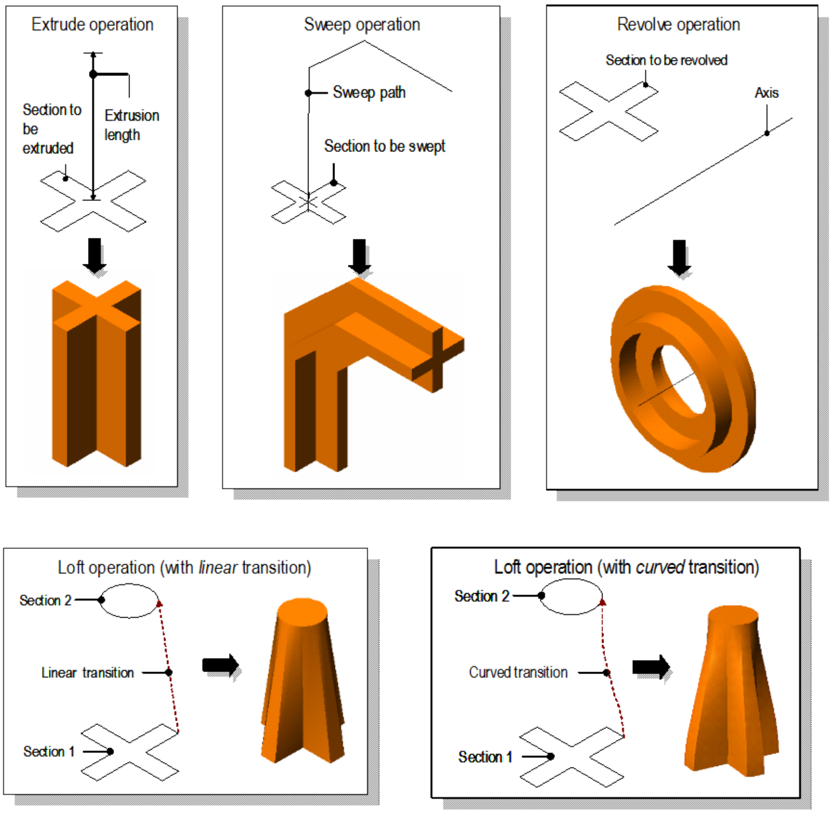
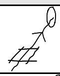
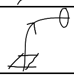


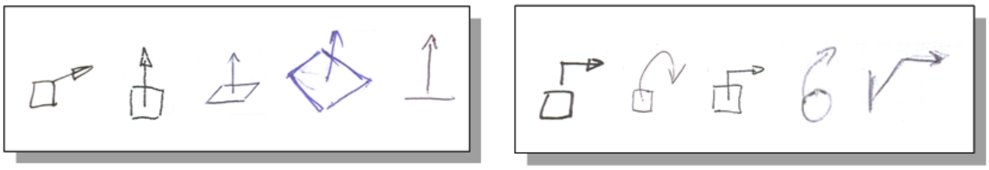
Figure 5. Mapping obtained by the 3D operations in PSL

To make the symbols simple to understand, they were designed so that their structure reflects the skeletal representation of the corresponding geometric meaning they convey. The extrude symbol, for instance, is composed of a square section and a vertical arrow line suggesting the length of extrusion. A common feature in the symbols in Table 1 is the arrow. This feature was included following results of a survey conducted with 106 students of different cultural backgrounds. The survey was carried out in US, UK, Denmark, France, Germany, India and Malta. The students were studying product design, had a mean age of 23 and an average of 3 years using CAD systems. It resulted that arrows were *commonly* suggested as means to improve the preliminary set of symbols proposed (see Figure 6).

Table 1. PSL symbols representing 3D operations

Symbol	3D operation
	*Extrude*
	*Sweep*
	*Revolve*

Symbol	3D operation
	*Loft_linear_transition*
	*Loft_curved_transition*



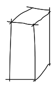
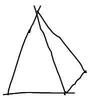
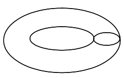
(a) (

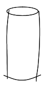
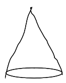
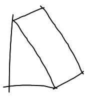
b)

Figure 6. Examples of suggestions proposed for (a) extrude (b) sweep symbols

Another sub-set in the *PSL* alphabet consists of 3D primitives. Table 2 shows the set of symbols developed to represent this type of geometry. To make the symbols simple to understand, their basic structure reflects the shape of the corresponding 3D entities. From the survey referred to previously, it emerged that the students, irrespective of their cultural background, suggested a complete description of a 3D primitive instead of the skeletal representation proposed originally. At the same time, only the front geometry is considered to make the symbols quick to draw; hidden edges (e.g. in the cuboid) are excluded. Figure 7 depicts an example of a 3D CAD model generated automatically by the prototype tool supporting *PSL*, from the corresponding paper-based sketch annotated with *PSL*.

Table 2. PSL symbols representing 3D primitives

Symbol	3D primitive
	*Cuboid*
	*Sphere*
	*Pyramid*
	*Torus*

Symbol	3D primitive
	*Cylinder*
	*Cone*
	*Wedge*

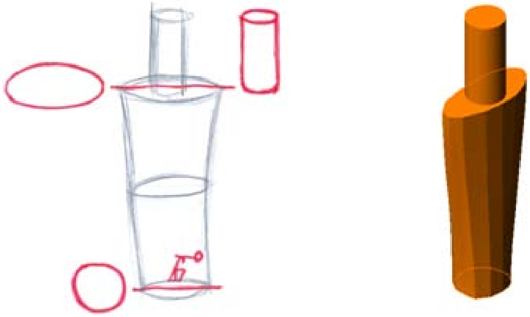


Figure 7. Example of a 3D CAD model generated from a paper-based sketch annotated with PSL

4 DISCUSSION & FUTURE WORK

We argue that the strength of our pedagogic approach lies in the fact that sketching is still given the importance it merits in design synthesis. Studies, such as the one described by McGown *et al.* [18] demonstrate that students who produce a large amount of sketches are in a better position to obtain a better final design solution than students who produce less sketches. In addition we argue that our pedagogic approach allows students to first understand well the language of engineering drawing via the manual exercise in year 1 and then to gradually take it up a step further by the use of CAD. We strongly believe that it is useless that students learn CAD without solid foundations of the engineering drawing language. Another strong point of our pedagogic approach lies in the global design exercise. Our students have the opportunity to collaborate with students of totally different cultures coming from Asian countries; some of the students in UK were reading for an *Erasmus Mundus* M.Sc. course on *Global Innovation Management* (http://www.globalinnovationmanagement.org/). After completion of the exercise, students from both institutions exhibited a positive attitude towards this exercise as they were exposed to different problem-solving approaches. In addition, they underlined how useful sketching was to communicate and exchange ideas.

A preliminary analysis on the impact of introducing sketching as from the first year of the course was carried out. It consisted of firstly observations made during meetings with students carrying out their third year engineering design project and secondly a measure of the amount of sketches generated in their logbooks. During meetings, students commented that sketching helped them to explore as much as possible the solution space, instead of rushing to CAD at an early phase. This is supported by the amount of sketches produced by the cohort who enrolled for the new curriculum. It resulted that these students produced approximately 30% sketches more than the amount of sketches produced by students who undertook the old curriculum, in which sketching was not introduced in the first year. It must be also pointed out that the logbook helped the tutors to track design progress as also demonstrated by the study conducted by Rodgers *et al*. [19].

PSL was evaluated in a survey conducted with a sample of 58 second and third year mechanical engineering students. The students were divided into four groups of approximately 15 students each, who were first given a verbal presentation of *PSL*. Students were shown how the construction of the form of three physical objects is represented with *PSL*. Based on their impressions, the students were then asked to fill in a questionnaire. To measure the attitude of the students '7-scale response' type questions were utilized; the lowest rate in the scale implied a strong positive attitude, whilst a rate of 7 indicated a strong negative attitude. Thus, a mean rating (*M*) of 4 implies a neutral opinion. Students were urged to comment on the ratings given. Some questions, e.g. question 4 (Q4), were negatively worded to lessen response bias. Figure 8 illustrates the key results obtained.

With reference to Figure 8, it can be observed that the students tend to agree using symbols in sketches to represent form ($M = 4.83$, *Standard Deviation*, $SD = 1.57$). Note that Q4 was negatively worded. The most commonly reported reason was that symbols facilitate the robust communication of the form concept to the computer. Results also revealed that students found it easy to understand the overall underlying principle of *PSL* ($M = 2.62$, $SD = 1.04$). As reflected by the qualitative data gathered, the students' knowledge of using a CAD system facilitated their understanding of how *PSL* works. Students also exhibited a positive attitude towards our suggestion of teaching *PSL* in the mechanical engineering course ($M = 3.02$, $SD = 1.4$). It was commonly suggested that *PSL* is taught as part of the CAED module, as its underlying principle assimilates to 3D modelling principles found in CAD. This is supported by qualitative results of another independent evaluation on *PSL* carried out with various design practitioners [20]. This is reflected in following comment made by an educator in 3D CAD modelling:

> *"...I saw it (PSL) as a way to understand how CAD systems work. Maybe I could use it when I'm talking about how a CAD system works by using some examples like these (the physical objects used in the evaluation)".*

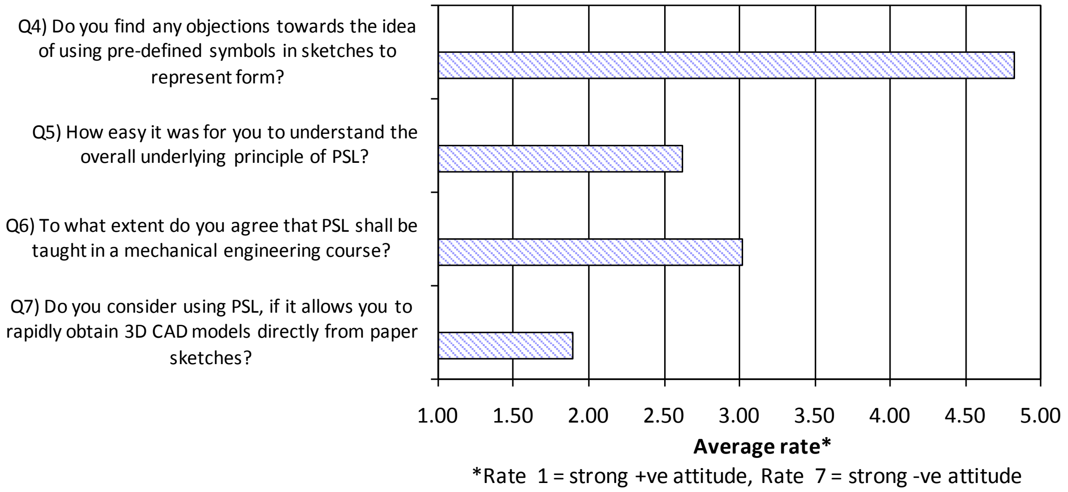


Figure 8. Key survey results on PSL

Interestingly, from the analysis of the qualitative data collected, it emerged that students suggested introducing *PSL* in the course, once it is taken up in industry. From the results obtained for Q7, it is clear that students would consider using *PSL*, provided that it allows them to rapidly convert paper-based sketches into 3D CAD models (M = 1.9, SD = 0.83). The main benefit reported by students concerns the facility of quickly showing clients how the form design solution will look like. On the other hand, the main concern reported regarded the accuracy of the 3D CAD models obtained and the fact that *PSL* does not support assembly of components. These concerns also emerged from qualitative data gathered from another survey conducted with practising designers [9]. Results show that *PSL* would be more suited for industrial form design rather than for mechanical engineering design, which often involves more than one component.

We argue that the *PSL* alphabet contributes a step towards setting up drawing standards for early form paper-based industrial design [21]. Whilst drawing standards for detailed design exist, no such standards are available for early design [21]. Another potential application of *PSL* lies in exchanging and sharing 3D CAD models in a global design environment; a framework was developed allowing users to exploit a cameraphone to remotely obtain a 3D CAD model from a *PSL* sketch [22] (see Figure 9).

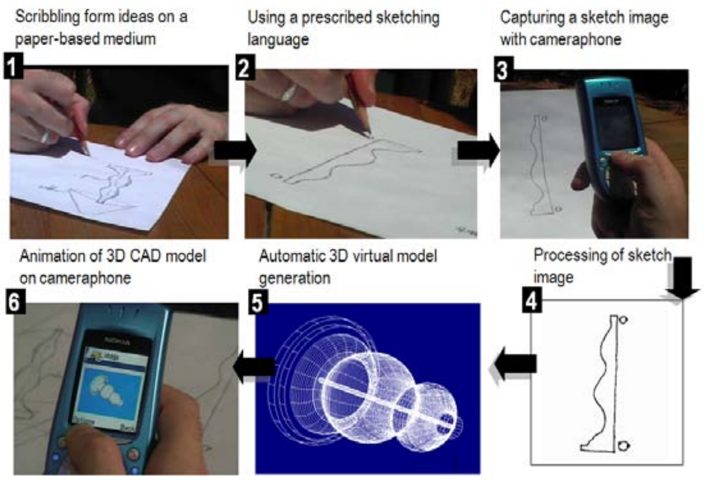


Figure 9. Use of a cameraphone to generate CAD models from PSL sketches

Despite the positive impact that our pedagogic approach had so far in educating mechanically oriented engineering students, future work is required to improve it further. For instance, we are suggesting a study unit which is offered jointly by the University of Malta and another university in which students are engaged in a collaborative design exercise over a longer period of time; the current four weeks sessions do not allow sufficient time for students to exercise their sketching skills. One possibility could be that the engineering design project in the third year is run with students in the UK who are involved in *product design partnerships* (PDPs), whereby a design problem in industry is addressed. It is also suggested that *PSL* is used at the outset of the CAD practical sessions to help students understand how they can covert form sketches into 3D models. Given that the survey results are based on the students' impressions of *PSL*, it is also recommended that the language is assessed via a real design problem. In view of the advancements being registered in devices supporting digital sketching (e.g. *Apple iPAD*, *SMART* whiteboard), it is also suggested that digital logbooks and interactive whiteboards are employed. This would allow students to record all the ideas generated, especially during group brainstorming sessions. Additionally, the exploitation of commercial devices to draw and record ideas, anywhere and anytime, would potentially contribute to promote the sketching culture amongst mechanical engineering students.

5 CONCLUSIONS

In conclusion this paper contributed a pedagogic approach, characterized by individual, project and collaborative based learning. Central to this approach is manual sketching, a fundamental tool in design synthesis. It is concluded that the importance of drawing in the design process is adequately emphasised throughout the four years of the course, this also leaving a positive impact on mechanically oriented engineering students. It is also concluded that *PSL* contributes a step towards the development of a standard sketching language, enabling students and designers to obtain 3D CAD models directly from paper-based sketches. *PSL* also contributes towards educating students on how to apply 3D CAD modelling principles to model their form concepts sketched on paper into a CAD system.

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