INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

CAMERAPHONES AS NEW DESIGN TOOLS

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ABSTRACT
It is well known that at the early design stage, designers still prefer the fluidity of traditional sketching as means to express their form concepts, instead of the rigid, user-interface of Computer-Aided Design (CAD) systems. The inherent characteristics of the pencil-and-paper medium, such as its portability, make it the first choice for designers to instantly express their ideas, both inside and also outside their usual workplace. Also, due to increased globalization, designers are frequently mobile, requiring instant access to engineering knowledge whenever a critical decision needs to be taken. Therefore, this paper concerns the on-going development of a mobile design tool which integrates freehand sketching with three-dimensional (3D) modelling technology. More specifically, this paper discloses a framework enabling designers to remotely obtain 3D models and related knowledge from sketches by combining the portability of paper with that of cameraphones. Three applications of an implemented prototype tool, based on this framework, are presented. Collectively, these applications demonstrate that cameraphones are useful tools which provide mobile support for designers.

Keywords: conceptual form design, mobile knowledge, collaborative design, DFX

1 PROBLEM BACKGROUND
Despite the availability of CAD technology, designers continue resorting to freehand paper-based sketches during conceptual design [1, 2]. It is only when designers have developed their ideas by sketching them on paper that they resort to the computer [3]. The sketching material generated by a practising designer found in [4] and the results of various studies [5] and surveys [6] clearly reflect such a trend. This working practice is attributed to the fact that designers, at these early stages, want to express their ideas quickly and naturally, which is effectively accomplished via freehand sketching. Compared to sketching, the user-interface (UI) of CAD systems, which is primarily based on Windows, Icons, Menus and Pointing device (WIMP), is rigid [1]. For this reason, such a UI is not suitable for the generation of early form concepts. Additionally, due to the nature of the design work, it is a common behaviour that designers think of concepts both inside and outside their office [7, 8]. The availability and portability of CAD systems outside the design office is limited, constraining designers to make use of readily available media (e.g. a paper napkin) to express spontaneous design solutions in such situations [7]. Moreover, mobile designers lack tools which provide them with engineering knowledge support [9]. Such knowledge (e.g. the consequences of an incorrect design decision on the life phases of a component, termed as *life-cycle consequences* [10]) is useful, especially, for novice designers [9].
Sketching can be integrated with CAD by either scanning the paper sketch or using directly digital sketching. Each approach has its own strengths and limitations. As argued in [11] the new generation of tablet computers could serve as the tools of choice for designers. At the same time, although digital sketching devices have their advantages, their adoption is still low, whilst adoption rates for low-cost image acquisition devices (such as scanners, digital cameras, and cameraphones) continue to increase [12]. In view of the aforementioned issues, we argue that for a sketching medium to be useful it must be portable and readily available to use. Survey results in [7] show that more than 40% of the respondents carry a piece of paper and pen on them on a regular basis to sketch spontaneous ideas. Moreover, it was evident that for mobile design work, traditional sketching media were preferred over digital media. On average, the characteristic of a portable sketching medium which respondents consider as the most important resulted to be 'readily available'.

The overall goal of this research is, therefore, to develop a computational framework which enables designers to remotely obtain 3D geometric models and relevant knowledge support directly from freehand sketches, by combining the portability of paper with that of cameraphones.
The rest of this paper is structured as follows. Section 2 discusses related work on Computer-Aided Sketching (CAS) technology and on design tools. Section 3 describes the framework architecture developed for a cameraphone-based design tool. An overview of a sketching approach required, to robustly communicate form concepts to the computer, is also provided. Based on this framework, details of an implemented prototype tool are given in Section 4. To demonstrate the potential of cameraphones as new design tools, typical application scenarios of the prototype tool are illustrated in Section 5. Based on these scenarios a discussion follows in Section 6. Future research directions are also recommended. Key conclusions are finally made in Section 7.

2 RELATED WORK

QuickSketch [13] is an interactive sketch-based modelling system, which allows the generation of 3D solid models and B-spline surfaces from sketches, the latter refined by 2D and 3D geometric constraints. Other on-line CAS systems employ Constructive Solid Geometry (CSG) to generate 3D models. For instance, *GiDeS++* [14] supports the generation of 3D models by a symbolic set of gestures representing 3D entities and dynamic 3D model modification by CSG modelling. *SilSketch* [15] allows users to interactively modify surface meshes by sketching strokes over the 3D surface model. Other systems, such as *CIGRO* [16], resort to 3D reconstruction techniques to build a 3D model from a sketched pictorial projection (e.g. isometric) of a 3D model. Other researchers are investigating the usability of immersive 3D sketching for the conceptual design stages [17].
The systems referred to above, collectively, indicate that the trend in developing CAS support is to replace paper with a digital sketching medium. This trend was also evident from an extensive literature review on CAS systems found in [14]. In CAS systems which preserved paper, such as the system described in [18], the sketch is digitized with a flat-bed scanner, thereby impairing the portability of paper. In addition, only simple 3D polyhedral shapes are supported. Although the system described in [7] exploits cameraphones as means to remotely obtain 3D models from paper-based sketches, it does not provide designers with feedback on the form solutions being conceived. The work reported in [19] aims at developing a system which provides mobile engineering knowledge support on portable devices, such as Personal Digital Assistants (PDAs). However, the system architecture does not incorporate the generation of 3D CAD models from sketches drawn on portable devices. The provision of such models would assist mobile designers to better visualize the evolving design solution.

3 FRAMEWORK ARCHITECTURE

As illustrated in Figure 1, the framework architecture being developed for a cameraphone-based design tool is constituted of six frames:

1. *Form Sketching* (*FS*) frame: is characterized by a two-stage sketching approach. In stage (1a), the designer is allowed to sketch, in pencil, a form concept without any drawing constraints, on a paper-based medium. The first-stage sketch is then marked up, with a colour pen, with the elements of a *prescribed sketching language* (*PSL*) [4] in stage (1b). The rationale for using *PSL* is to address the inherent characteristics of sketching (e.g. idiosyncrasy, vagueness) [4], which collectively make computer-based recognition a difficult task [4]. Given the fundamental role that *PSL* plays in the framework, its underlying principle is delineated in sub-section 3.1;
2. *Sketch Digital Image Processing (SIP)* frame: the role of this frame is to extract the 3D geometric information represented by *PSL*. Stage 2a involves acquiring a digital image of the sketch by means of an optical device. Depending upon the situation where the designer is sketching, the framework supports different image acquisition devices, including flatbed scanners and cameraphones. If the image of the sketch is captured by a cameraphone it is transmitted in order to be processed in the subsequent stage. Therefore, by supporting portable optical devices, the framework aims to exploit the benefits offered by paper as much as possible, in particular its portability and availability-to-use [4]. Redundant information such as noise blobs and shadows

which may have been introduced when capturing the image with a cameraphone [7] are removed in the image pre-processing stage. Features (e.g. the bounding box enclosing a *PSL* element) are then extracted in the subsequent stage. As illustrated in Figure 1, such features are utilized either to classify the *PSL* elements in stage 2d or to derive the 3D geometric meaning in stage 3a;

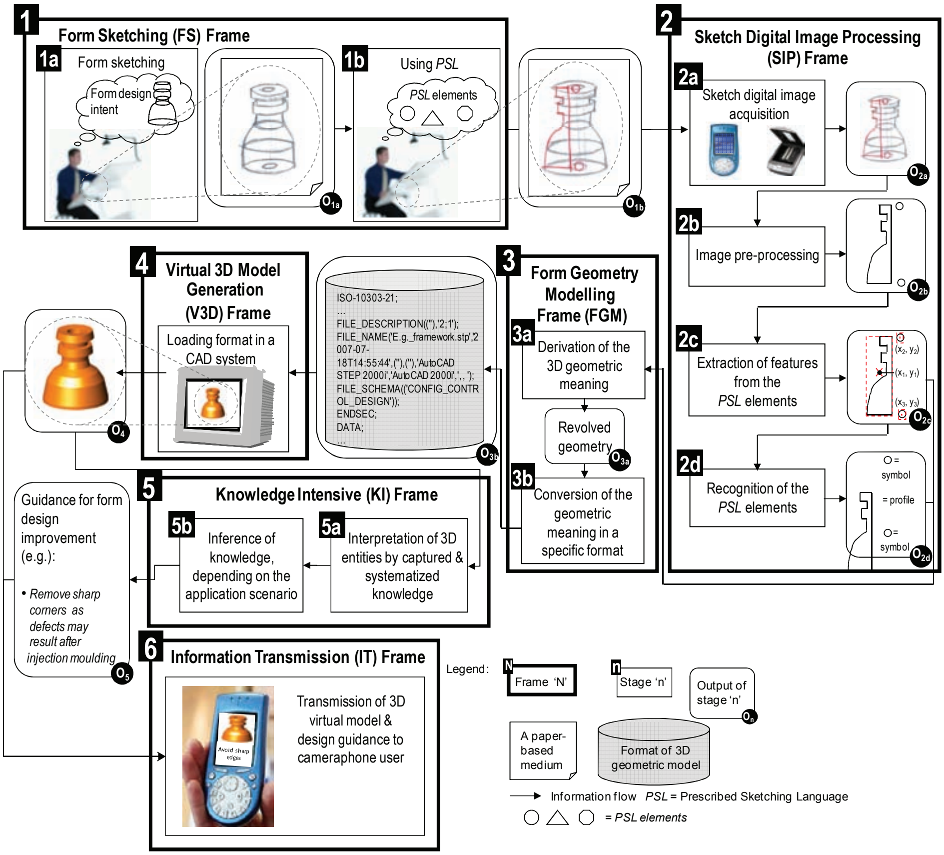


Figure 1. Framework architecture

3. *Form Geometry Modelling (FGM)* frame: whose role is to derive and model the geometric information embedded in the vector list, such that a 3D virtual model can be constructed in the subsequent frame [4]. This role is accomplished by parsing *PSL* and converting the derived geometric meaning in a specific format, which is essentially an alphanumeric representation of the ultimate 3D virtual model;
4. *Virtual 3D Model Generation (V3D)* frame: in which the alphanumeric representation outputted in the *FGM* fame is translated into the corresponding model in 3D space. Therefore, the *V3D* frame provides the designer with a 3D virtual model, whose construction has been represented with *PSL* in the *FS* frame;
5. *Knowledge Intensive (KI)* frame: the role of this frame is to provide guidance to the designer on how to improve the form solution. For this purpose, 3D features making up the CAD model are first interpreted by captured and systematized knowledge. Each feature has embedded knowledge – for instance, a sharp corner (i.e. with radius R = 0) must be avoided if plastic injection moulding is the process used in the manufacturing phase. The reason is that a sharp corner induces internal stresses in the component which may potentially lead to surface crack formation. The knowledge embedded with a particular 3D feature depends on the scenario in which the framework is applied. For example as explained in Section 5, a tool based on the framework was

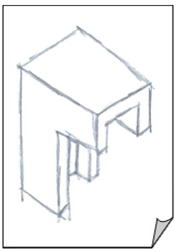
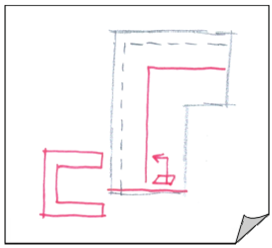
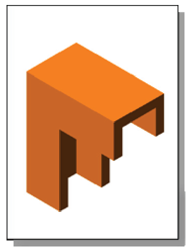
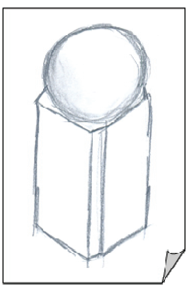
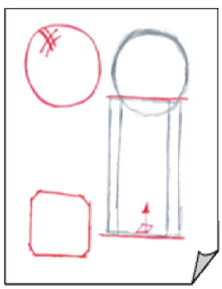
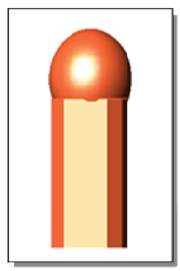
utilized to guide the designer to take a *Design for Emotions* approach in the design of a perfume bottle. In this application domain, 3D primitives (e.g. sphere, cone etc.) elicit different emotions for different user groups. Irrespective of the application scenario, as detailed in Section 5, such knowledge is then used in stage 5b as a basis to infer design guidance;

6. *Information Transmission (IT)* frame: as illustrated in Figure 1, essentially, this frame deals with the transmission of the 3D virtual model and the design guidance outputted in the previous two frames to the cameraphone user for evaluation.

3.1 Prescribed Sketching Language

PSL is based on symbols, which map 2D form descriptions on paper into 3D geometries. The symbols represent common modelling commands found in CAD systems [4]. The type of 2D-to-3D mapping depends on the particular class of symbols. For instance, a class of these symbols operates on user-defined 2D cross-sectional profiles, mapping them into 3D entities (e.g. sweep and extrude symbols in Table 1). Other symbols are directly mapped into the corresponding 3D primitives (e.g. sphere symbol in Table 1). It must be mentioned that plane lines are employed in order to locate cross-sectional profiles and 3D primitives in 3D space (refer to examples in Table 1).

Table 1. Examples of 2D-to-3D mapping accomplished by PSL symbols

Sketched form design intent	*PSL* form representation	Resulting 3D model
		
		

Legend:  *Extrude symbol*  *Sweep symbol*  *Sphere* ______*Plane line*

Similar to any language, *PSL* possesses a series of rules must be observed [4]. Primarily, the rules prescribe what *PSL* elements are required to represent the construction of a particular geometry and how they should be placed with respect to each other on paper. For example, to facilitate the classification stage, *PSL* prescribes that each element must be drawn as a separate entity, i.e. it should not touch neighbouring elements. Another important rule stipulates that in order for the computer to associate a profile or a primitive with a plane line, it must be drawn at either end of the plane line and in its projection. Furthermore, to indicate to the computer on which profile a 3D operation is to be executed, the corresponding symbol must be drawn in the vicinity of the midpoint of the plane line representing that plane on which the profile resides (refer to Table 1). Further details on *PSL* go beyond the scope of this paper, and are available in [4].

4 IMPLEMENTED CAMERAPHONE-BASED DESIGN TOOL *MX-SKETCH*

A prototype tool, *mX-SKetch* (**m***obile tool for e***X***tracting 3D form geometry information and related* ***K****nowledge from paper-based* ***Sketch****es*) was implemented based on the framework depicted in Figure 1. As implemented, the *SIP* frame is characterized by a series of image pre-processing algorithms which were applied on the sketch image to perform a number of operations including:

- separating the underlying pencil sketch from the coloured *PSL* elements;
- converting the grey level image into a binary image whose constituent pixels are either black or white, and;
- *skeletonising* the image such that the number of black pixels is reduced, whilst maintaining the structural connectivity of the main features of an image component.

A number of classification techniques were also implemented, including *artificial neural networks* in order to classify the different symbols representing 3D operators, 3D primitives and form features (e.g. threaded holes). The *Line Hough Transform* was used to distinguish between plane lines and sweep paths (e.g. the L-shaped path illustrated in Table 1). All the algorithms were implemented using *Matlab® Version 7.2 (R2006a)*, as this software has off-the-shelf algorithms in the image processing and neural network toolboxes which were directly utilized in this application.

The salient vertices of cross-sectional profiles (e.g. the four corners of a rectangular profile) are located by the *polygonal approximation* algorithm [20]. This approximation aims to capture the essence of the shape's boundary using the fewest vertices possible [21].

As detailed in [4], an *attributed grammar* based approach was taken to formalize *PSL* and subsequently to derive the 3D geometric meaning in the *FGM* frame. Since the scope of the implementation was to set up a proof-of-concept tool, the meaning derived from the *PSL* parsing was translated in *script file* format. A script file consists of a sequence of commands, which are executed automatically by *AutoDesk®* products once the file is loaded. In *mX-SKetch*, *Mechanical Desktop* has been utilized as the 3D modelling software.

With regards to the *KI* frame, *if-then* production rules, such as the ones listed hereunder, were implemented using the expert system *wxCLIPS*. The geometric information (e.g. thickness of the component) extracted from the input sketch is used as a 'facts file' on which the relevant LCC knowledge is inferred. Where appropriate, the particular life cycle consequence inferred, is explained with a diagram. The list of design improvement recommendations is then compiled and converted in *pdf* format, together with the LCC explanation.

Rule_1:

IF [Material] is a *kind_of* Thermoplastic
AND [Realization Phase Process] is a *kind_of* Injection_Moulding
THEN Life_Cycle_Consequence (LCC) = *Possible_Surface_Crack_Formation*

Rule_2:

IF LCC = *Possible_ Surface_Crack_Formation*
THEN Determine corner radius (R)

Rule_3:

IF LCC = *Surface_Crack_Formation*
AND R = 0mm
THEN Replace the fact LCC = *Possible_Surface_Crack_Formation* with LCC = *Surface_Crack_Formation*

The stages in frame 2 onwards have been automated, such that the 3D model and the design guidance converted in *pdf* format, reach the cameraphone user *automatically*, once the tool detects an incoming sketch image sent via *Multimedia Messaging Service* (MMS). This has been accomplished by using *Microsoft Visual Studio .NET®* as a platform for the *Visual Basic .NET®* (VB.NET) programming language. Furthermore, *Visual Basic for Applications* (VBA) was employed in relation to software applications that support the use of VBA programs, such as *Mechanical Desktop* used in the *V3D* frame.

5 TYPICAL DESIGN SCENARIOS OF *MX-SKETCH*

This section illustrates three *typical* design scenarios where *mX-SKetch* was utilized by mobile designers to support them in:

1. participating in *collaborative design*;
2. applying *Design for Manufacturing* guidelines in the domain of plastic injection moulding;
3. taking a *Design for Emotions* approach.

5.1 Paper-based collaborative design

The first application scenario is depicted in Figure 2. A designer situated in Sydney, Australia, received a phone call from a client located in Genoa, Italy, requesting the design of a component. In this scenario, it was possible for the designer to sketch instantly, on a readily available piece of paper, a form concept of the component (1). An image of the *PSL* representation of the component was then captured with a cameraphone and sent via *MMS* to a server located in Malta, Europe for processing (2). The 3D model produced was then sent to the designer on the cameraphone (3) and also made available on a web-site to be viewed by the client (4). The client has then sent the designer, feedback about the concept.

Figure 2. mX-SKetch in collaborative design [4]

5.2 *Design for Manufacturing* (DFM) Guidance

As indicated previously in Section 4, the knowledge captured in the *KI* frame encapsulates *Design for Manufacturing* (DFM) guidelines for the design of plastic components. The implemented tool was utilized in this domain, as illustrated in Figure 3. Basically, the designer has first sketched a pictorial projection of simple prismatic component (1) made up of rectangular base and four form features (a pocket, two threaded through holes and a drilled through hole). The form concept has then been represented with *PSL* (2), in which each form feature is represented by a pair of plan and section symbols. Although no dimensions are provided in the input sketch, *mX-SKetch* computes the thickness *t* of the component from the two successive plane lines. The four corners of the rectangular base are used to determine the area *A* of the base. The ratio *A/t* is then calculated. Based on this ratio, the type of form features present in this component and the *if-then* rules implemented, life-cycle consequences have been inferred by *mX-SKetch* (3). Since the designer considered using threaded holes, as assembly features, the costs of manufacturing the mould is high, since a mechanism is required to unscrew the moulded parts from the mould. As shown in Figure 3, such a mechanism is illustrated by a diagram which forms part of the *pdf* file sent to the designer. Furthermore, from the ratio *A/t*, *mX-SKetch* inferred that if moulded, the component will warp. A diagram is also included for this *LCC* for explanation purposes. It must be mentioned that Figure 3 illustrates only two exemplars of *LCCs* detected – other *LCCs* such as the draft angle required on the vertical sides of the component base to facilitate ejection were not included for clarification purposes. For the same reason, the 3D CAD model generated by the tool and which was sent via *MMS* to the designer on the cameraphone is omitted. The tool provides also a list of recommendations for the designer to alter the concept, such that the detected *LCCs* are avoided. In this case study *mX-SKetch* has suggested eliminating the threaded holes and using snap fits instead. This has the added advantage that fasteners are not required, hence reducing assembly costs. Another recommendation concerns the reduction in the thickness of the component to eliminate warpage.

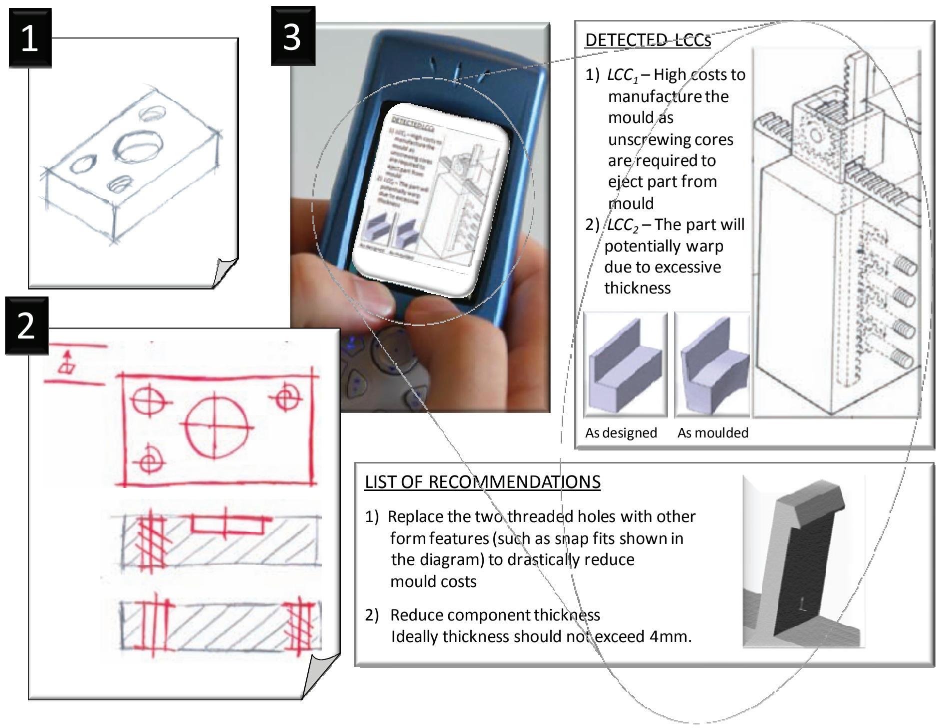


Figure 3. Application of mX-SKetch for DFM guidance

5.3 *Design for Emotions* (DFe) Guidance

When designing for emotion, it is of paramount importance that the designer first understands the potential consumers for whom the product is to be designed. Based on the customers' subjective requirements, user groups are realized for a specific product. As a starting point, three user groups were considered [22], namely:

- *Nostalgics*: relate product emotions with their past experiences and memories. Costumers in this group fancy rectangular forms and soft curves which transmit reliability, security and pleasure at the same time;
- *Funseekers*: correlate product emotions with the enjoyment provided by the product. Funseekers are attracted to products which exhibit circular shapes, soft curves, and are free from sharp edges.

This blend should psychologically be perceived as playful for funseekers;

- *Usability-minders*: are more concerned with the ease-of-use of the product setting aside product emotions. Usability-minders prefer high concentration of angular profiles in their products.

Emotional product stimuli are mostly related to these product characteristics namely, structure, form, material, dimensions, and surface. Manipulating such product characteristics can in turn help create an emotionally engaging product and provide unique experiences to the clients buying the product. As research boundary, efforts were embarked upon form only. More specifically, as mentioned earlier, the emotional knowledge captured in the *KI* frame was associated with a set of 3D primitives (e.g. a sphere) [22].

Different combinations of 3D primitives building up a geometric shape are prioritized according to the user groups' emotional needs which build up correlation matrices. This means that every geometric shape has a *pleasure-arousal* mapping onto the emotional space map for different user-groups. As depicted in Figure 4, the emotional space map consists of two bipolar, independent dimensions that describe subjective emotions, based on the dimensions of *pleasure* and *arousal* [23]. The former refers to the condition of consciousness or sensation from the enjoyment or anticipation of what is felt or viewed as good or desirable; enjoyment, delight, gratification. On the other hand, 'arousal' is defined as bringing about a feeling or response in someone, leading to increased heart rate and blood pressure and a condition of sensory alertness, mobility and readiness to respond.

For this application scenario, a perfume bottle was considered (1), whose form was first represented with *PSL* (2) as a lofted body with a series of circular cross-sections and three 3D primitives – two spheres and a cone. As illustrated in Figure 4, *mX-SKetch* provides the designer with a 3D virtual model, an emotional space map and the list of recommendations (3).

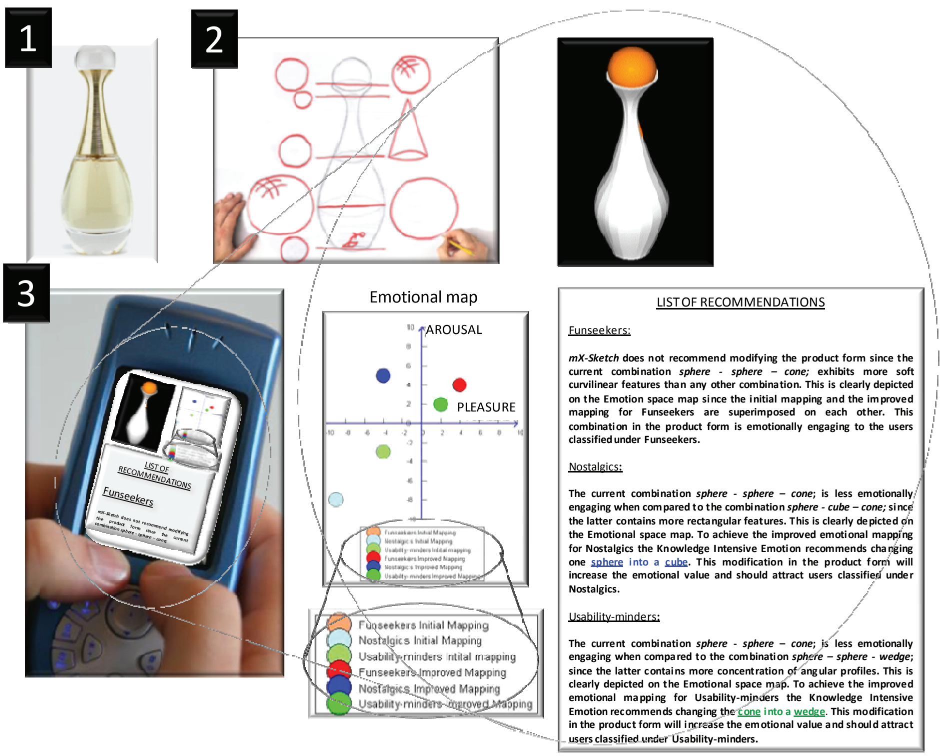
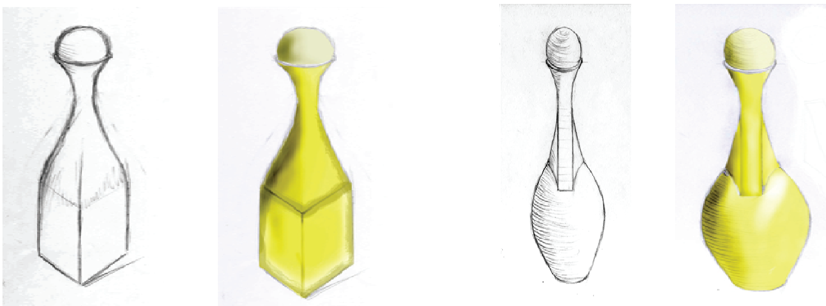


Figure 4. Application of mX-SKetch for DFe guidance – adopted from [22]

From the list of recommendations and emotional map, it resulted that *mX-SKetch* considered the product form as adequate for the funseekers group since collectively, the three 3D primitives, provide curvilinear features. However, *mX-SKetch* is guiding the designer that for the other two user groups, the form needs to be altered to be more emotionally engaging. Based on the list of recommendations in Figure 4, the original perfume bottle design can be modified to produce different form concepts in order to match the respective user groups' emotional needs (see sketched solutions in Figure 5).



(a) (b)

Figure 5. Possible form concepts for (a) nostalgics (b) usability minders – adopted from [22]

6 DISCUSSION

We argue that the framework presented in this paper gives more freedom to designers in mobile situations, in the sense that a range of sketching media can be utilized. Experiments that we have conducted show that *mX-SKetch* is capable of supporting blank paper, whiteboards, *post-it*® notes and napkins. In contrast, on-line CAS systems are only confined to digital media, as also argued in [24]. Moreover, the first application scenario suggests that a cameraphone provides a convenient means for its users to globally communicate their ideas in a collaborative design context. The first scenario suggests that technology based on the framework helps reduce time in synchronous collaborative design, as design ideas can be quickly communicated between different product development stakeholders who are geographically dispersed [4]. In addition, customers can very quickly visualize the ideas developed by the designer, as the 3D geometric models are made available on a web-site. Further, suppose that the designer situated in Australia wants to change the original design of the component, after having evaluated the concept from the 3D model sent on the cameraphone. The changes can be instantly communicated to a CAD operator so that the final 3D model is completed. If something is not clear, the CAD operator can get back to the designer by sending questions on the cameraphone. We also argue that the framework promotes customer-driven design. Given the ever-increasing use of cameraphones and the fact that *PSL* makes 3D CAD packages more accessible to laymen, the framework facilitates the involvement of the customers in the design of a product. Yet, despite these envisaged benefits in collaborative design, tests are required to evaluate, in practice, the framework's effectiveness in this respect [4]. In relation to this, the slow *MMS* transmission rate may strongly impair the time required for the tool to receive/send the 3D geometry information. In addition, it must be pointed out that *PSL* poses considerable limitations as regards to the type of forms supported. As it is, *PSL* is capable of supporting forms of *linear topological ordering* [25]. Topological ordering refers to the distribution of the elements in a product with respect to each other in 3D space [25]. Forms with a linear topological ordering are characterized by a planar linear axis.

The second and third application scenarios demonstrate how mobile technology can be exploited to convey relevant knowledge to mobile designers directly from simple handmade sketches. It must be underlined that although the sketch used in the second scenario is dimensionless, the ratio of the component thickness to the base area, together with the type of form features, were used to avoid undesired LCCs later in the manufacturing phase and to guide designers accordingly. This type of feedback is particularly beneficial to novice engineering designers. Related to this, survey results in [9] indicate firstly that novice designers are more mobile than experts and secondly that knowledge support is more required by novices.

The third application of *mX-SKetch* was evaluated with six professional engineering designers working in different sectors, including that of cosmetic cases. It turned out that *all* designers would

consider using it in practice. The positive attitude exhibited by these evaluators highlights the usefulness of the tool from the *DFe* perspective. Particularly, one designer noted that the emotion knowledge captured in the *KI* frame would work very well if linked with agencies that foresee market trends. Another key finding was that the majority (83%) of the designers commented that *mX-SKetch* would closer reach the customer's emotional needs if *all* product characteristics, (i.e. not just form), are taken into account when developing the emotion knowledge in the *KI* frame. These results also indicate that more work is required to enhance the potential of the tool, before it can be utilized.
Despite the promising results achieved so far, it is recommended that the following research directions are taken:

- extending the range of forms that *PSL* can represent, beyond those having a linear topological ordering;
- expanding the DFM guidelines captured in the *KI* frame to other domains, e.g. sheet metal;
- enhancing the *KI* frame such that the designer is provided with a *Design for Multi-X* support [10], rather than a narrow DFX support;
- introducing another frame such that the 3D model can be verified and modified if necessary;
- evaluating the tool by:
    - considering other case studies, especially in collaborative design scenarios;
    - conducting experiments in order to assess the proposed paper and cameraphone-based approach with alternative, portable sketching means (e.g. PDA and Tablet PCs);
    - assessing the tool's usefulness or otherwise with novice and expert engineering designers.

In addition, our research team is currently investigating means how to extend the use of the framework to support paper-based *remote physical prototyping*. By such technology, it would be possible that a 3D physical model is produced remotely and automatically on a Rapid Prototyping machine, directly from its *PSL* sketch representation, captured by means a cameraphone.

7 CONCLUSIONS

The results of the experiments reported in this paper reveal that cameraphones can indeed be considered as a new type of design support tool. In particular, it is concluded that two key characteristics, *collectively*, make the framework contributed in this paper unique compared to previous work. The first characteristic lies in the provision of 3D virtual models on cameraphones directly from paper-based sketches. The second characteristic regards the provision of support to *mobile* designers, guiding them to adopt either a DFM or a DF*e* approach when conceptualizing their form solutions by traditional sketching.

ACKNOWLEDGEMENTS

The authors would like to thank Alexandra Bartolo for her input in the *SIP* frame, and Oliver Fenech, Giovanni Piscopo and Charlon Grima for their input in the *KI* frame. The financial support provided by the University of Malta through the research grant 'Innovative 'Early Stage' Design Product Prototyping' (31-330) is also greatly appreciated.

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