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A Cameraphone-Based Approach for the Generation of 3D Models from Paper Sketches

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ABSTRACT

Due to the advantages it offers, a sketch-based user-interface (UI) has been utilised in various domains, such as 3D modelling, 'graphical user-interface' design, 3D animation of cartoon characters, etc. However, its benefits have not yet been adequately exploited with those of a mobile phone, despite that the latter is nowadays a widely used wireless handheld device for mobile communication. Given this scenario, this paper discloses a novel approach of using a paper sketch-based UI, which combines the benefits of paper sketching and those of a cameraphone (a mobile phone with an integrated camera), in the domain of 'early form' design modelling. More specifically, the framework disclosed and evaluated in this paper, enables users to remotely obtain visual representations of 3D geometric models from freehand sketches by combining the portability of paper with that of cameraphones. Based on this framework, a prototype tool has been implemented and evaluated. Despite the limitations of the current prototype tool, the evaluation results of the framework's underlying concepts and of the prototype tool collectively indicate that the idea disclosed in this paper contributes in providing users with a mobile sketch-based interface, which can also be used in other domains, beyond 'early form' design modelling.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Interactive Techniques, Languages

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1. Introduction

Despite the application of computer technology in everyday life, many people still find it difficult to use computer applications or they are just using it for simple activities. This is mainly due to the non-natural interaction with applications that require a certain effort for understanding the philosophy behind and for learning how to interact with them. To address this issue, research into the development of *natural* user-interfaces (UIs) is maturing. One branch of this research field concerns the development of sketch-based UIs aimed at integrating an easy-to-use interaction medium, i.e. freehand sketching with computer applications. Due to the advantages it offers, a sketch-based UI has been utilised in various domains, such as 3D modelling, 'graphical user-interface' design, 3D animation of cartoon characters, design of 2D mechanical devices, electronic circuit diagrams, etc. However, its potential combined with that of a mobile phone, has not yet been adequately investigated, despite that the latter is nowadays a widely used wireless handheld device for mobile communication. Given this scenario, this paper discloses a novel approach of using a *paper* sketch-based UI, which combines the benefits of paper sketching and those of a cameraphone (a mobile phone with an integrated camera), in the domain of 'early form' design modelling.

The rest of the paper is structured as follows. Section 2 outlines the problem that this research attempts to address in the context of 'early form' design modelling. Section 3 critically reviews related work in the field of Computer-Aided Sketching (CAS) technology, in which the lack of portability of current systems is highlighted. Based on the problem identified in Section 2, the goal of this research and boundary are formulated in Section 4. Section 5 focuses on the underlying concepts of the proposed framework supporting the research goal. In Section 6 the six frames that collectively constitute the developed framework architecture are introduced. Following the proposed framework, the implementation of a prototype tool is detailed in Section 7. Section 8 presents evaluation results related to the framework's underlying concepts and an experiment carried out with the prototype tool, which are then discussed, together with future work, in Section 9. Finally, Section 10 draws conclusions from this work, particularly focusing on the contribution of using a paper sketch-based UI as proposed in this paper.

2. Problem background

Despite the recent advancements in Computer-Aided Design (CAD) systems, designers still use the natural paper-based freehand sketching for the rapid exploration of their early form design concepts [SH99]. This is mainly attributed to the fact that the UI of existing CAD systems is based on the WIMP (Window, Icon, Menu, and Pointing device) paradigm. With this type of UI, the designer is constrained to learn the syntax of actions to manipulate the evolving 3D geometric model and how to operate through the interface of menus and icons [SH99]. As argued in [PJBF00] such UI is detrimental for creative idea generation during the conceptual design stage. Furthermore the WIMP-based UI constrains designers to manually transfer paper sketches into CAD systems, which is a time-consuming process [AOD02].

To address the highlighted UI-related limitations of CAD systems for early form design, various Computer-Aided Sketching (CAS) systems have been developed. However the majority of them employ a digital sketching medium, such as a digitizing tablet and stylus. Whilst such medium emulates paper-based sketching, offers real-time data capture which can be exploited for sketch recognition, and enables direct user interaction, however it is not actually integrating traditional *pen-and-paper* sketching with CAD systems. Paper-based freehand sketching offers greater speed, greater ease-of-use, greater immediacy, better quality of response and more expressive qualities compared to *'digital'* sketching [MGR98]. As a result, typically users find it more comfortable to sketch with a real pencil on a real paper, rather than using a light pen, mouse or tablet [Lip98]. Additionally, paper is more portable and readily available compared to a digital sketching medium. As stated in [SH99] *'creative ideas often arise away from the drawing board, in a bar, a bathroom, or in bed'*. In this respect, a simple napkin allows the immediate capture of the flow of ideas [SH99].

Therefore, the above arguments collectively suggest the need to develop *mobile* computational 3D modelling tools which integrate the fluidity and portability of freehand *paper* sketching with the advantages of 3D modelling systems, such as 3D model visualisation.

3. Related work

This section critically reviews a representative selection of CAS systems developed specifically to support sketch-based 3D modelling. Depending on the type of sketching medium employed, CAS systems can be classified into two major categories [MGR98] - namely, those which retain the traditional pencil-and-paper and those which mimic this medium (e.g. by employing a digital sketching medium). CAS systems pertaining to the former category are referred to as *'off-line'* CAS systems in [Lip98], whereas the latter are referred to as *'on-line'* CAS systems.

Viking [Pug92] is a solid modelling system allowing its users to interactively generate 3D models using techniques normally used to create and refine two-dimensional (2D) sketches. Although the system's user-interface is based primarily on sketching, the designer can create precise dimensioned models by using geometric constraints. Similarly, *QuickSketch* [EHBE97] 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 adopted the underlying concepts employed in CAD systems, such as Constructive Solid Geometry (CSG) to generate 3D models in a sketched-based modelling environment. For instance, *GiDeS* [PJBF00] supports the generation of 3D models by a gesture set representing 3D primitives and dynamic 3D model modification by CSG modelling. The user can also utilize *gestures* to either draw in 3D or to use 2D views to describe a 3D model. Similarly, in *SKETCH* [ZHH96] gestures are used to define 3D geometric primitives and to perform CSG operations (such as 'union' and 'subtract') to build 3D models. Various other approaches for 3D model generation in a sketch-based modelling environment, have been explored. For instance, *MIST* [BMF02] has a gesture-based sketching environment which allows users to sketch directly on the desired faces of a box-like virtual 3D object. The rough strokes are then modified into geometric objects, from which the intended 3D model is reconstructed. *Digital Clay* [SG98] uses alternative reconstruction techniques to generate 3D models from freehand sketches of 3D solid polyhedral objects drawn in either isometric or perspective projection. *CIGRO* [NCJC03] exploits the pressure of pen to distinguish between construction thin lines and object thick outlines. This characteristic is combined with an axonometric inflation method to reconstruct polyhedral wireframe models. Another on-line CAS system is that developed by Lipson [Lip98], in which 3D geometric models are reconstructed from wireframe 3D drawings based on 2D-3D geometrical correlations. Other CAS systems employ Virtual Reality (VR) techniques such as the systems described in [FMRU03], oriented for styling with free-form features and that described in [MPL03] which allows users to obtain 3D virtual line-based models from the equivalent virtual sketching strokes.

Common to the above CAS systems is their digital sketching medium. Despite the advantages of paper over a digital sketching medium (as argued in Section 2), relatively few off-line CAS systems have been developed. Marti et al. [MRLV95] developed a tool, based on a multi-level structure, which automatically converts freehand paper-based 3D line drawings into the equivalent 3D geometric models. *Decign* [Rot00] converts fuzzy paper sketches into virtual sketch models made up of a series of B-Spline curves as the basis for 2D wireframe models. These models are then manually manipulated for the construction of 3D surface models. Both of these off-line CAS systems employ a normal flat-bed scanner to digitize the paper sketch. Consequently, they do not *fully* exploit the portability of paper, and of mobile image capture devices, such as cameraphones, the latter becoming increasingly popular.

Thus, although designers need to have a mobile sketch-based modelling tool for early form design (as argued in

Section 2), the state-of-the-art CAS technology does not contribute in this regard.

4. Research goal and boundary

The overall objective of this research is therefore to develop a framework to provide designers and also to other potential users, with a *mobile* computational design tool enabling them to automatically and remotely obtain visual representations of 3D geometric models from paper freehand sketches captured by a cameraphone.

In order to achieve this objective and to evaluate the strengths and limitations of a prototype tool, as boundary, this paper focuses on rotational components, characterized with a central hole along the principal axis (see Figure 1). However, it should be remarked that the underlying concepts of the developed framework are *not* restricted to this class of form concepts, but can be applied to other forms, as described in the following section.

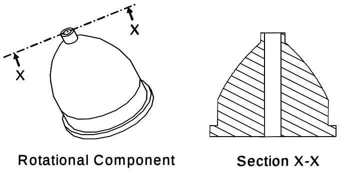


Figure 1: *Example of a component treated in this paper.*

5. Concepts of approach framework

One of the fundamental underlying concepts, upon which the developed framework is based, relates to the introduction of a *degree of formality* in a freehand paper sketch. This is necessary for various reasons. For instance, freehand sketches may contain both geometric information (e.g. lines and arcs) and non-geometric information (e.g. annotation). As argued in [Lip98] it is difficult to separate these two types of information, particularly in paper sketches. The complexity of paper-based sketch interpretation is compounded further by the inherent sketch properties, e.g. vagueness. The vagueness in a sketch can potentially lead to multiple sketch interpretations [SGP00]. Consequently, a complete automatic recognition of sketches is almost impossible to be practically achieved [Lim02]. To address these difficulties, a *Prescribed Sketching Language* (PSL) is being developed, by which the class of rotational component forms illustrated in Figure 1 can be expressed in a *semiformal* representation. Although this paper focuses on PSL, it should be noted that other sketching language solutions have been developed [BFC*03] to cater for prismatic components characterised by 2.5D form features (such as pockets, holes, threads). Details of these sketching languages go beyond the scope of this paper, however the reader may refer to [BFC*03] for further details.

The concept underlying PSL is related to the mapping in a paper sketch, of the two-step method commonly used in a CAD system to generate a rotational model. In the first step, half of the model's cross-section (i.e. a 2D closed profile) along the central axis is constructed. In the second step, two axis points are defined around which this cross-section is revolved. Following this method, with PSL, a rotational form concept is represented by a 2D closed profile and two symbols indicating the axis points. Figure 2 shows a rotational form concept represented by PSL. This approach simplifies the inference and extraction of shape information from a paper sketch. Furthermore, the concept of PSL can be extended to represent other classes of form concepts by mapping the respective 3D modelling methods (e.g. extrude and sweep) in the paper sketch representation.

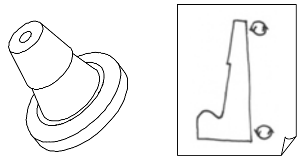


Figure 2: *Paper sketch representation of a rotational component.*

Since a degree of formality is introduced in the sketch, the designer's cognition process may be affected. To avoid this, another concept underlying the developed framework, concerns a devised paper-based sketching template which is divided into two sections (see Figure 3). In the 'scribbling area' the designer's idiosyncratic sketching style is allowed, whereby information extra to the component form being actually designed can also be used to help the conceptualisation of the solution. In the right hand side the designer then represents the candidate form concept with PSL, as described above. Therefore, even if this approach constrains the designer to sketch in a predefined manner, it preserves the designer's natural freehand sketching style.

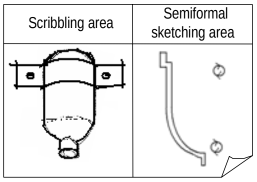


Figure 3: *Devised sketching template and sketch semiformal representation of a rotational component.*

6. Framework development

Figure 4 depicts the six frames constituting the framework being developed in this research. In the *Freehand Sketching (FS)* frame, the designer's form intent is externalized on a paper-based sketching template as previously described in Section 5. In the *Sketch Capture and Transmission (SCT)* frame, an image of the paper sketch is captured by a cameraphone and transmitted as a digitized image for processing in the *Sketch Image Processing and Validation (SIPV)* frame, where the sketch entities are first identified and the visual syntax of the sketch is then validated. In the *Shape Information Modelling (SIM)* frame, the 3D shape information extracted from the previous frame is mapped into a specified format to be inputted into the *Virtual 3D Sketch Construction (V3D)* frame, whereby a 3D geometric model is generated. In the *3D Model Image Transmission (3DT)* frame, a rendered image of the 3D geometric model obtained in the previous frame is produced, which is then transmitted to the cameraphone recipient (see Figure 4).

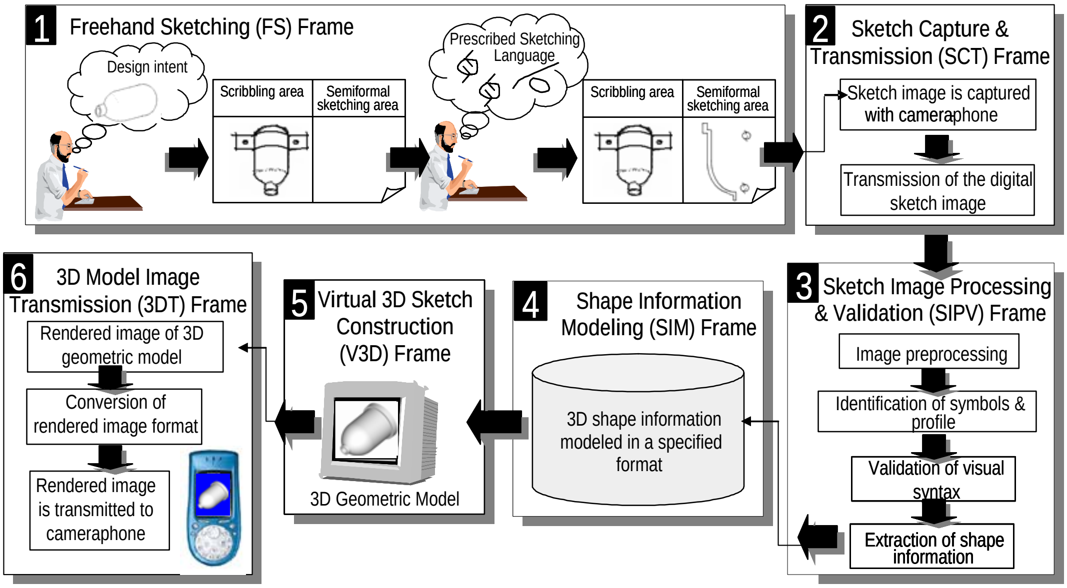


Figure 4: *Framework for a mobile paper-based sketch 3D modelling tool.*

7. Prototype tool implementation

The six frames introduced above, were collectively implemented as a prototype tool, as detailed in the following sub-sections.

7.1 Freehand Sketching (FS) frame

This frame concerns primarily the development and implementation of the prescribed sketching language PSL. In general, a language is based on a grammar, which governs four elements, more specifically the alphabet, syntax, semantics and phonology [BLH91]. As PSL is a *formal visual* language, of relevance to this research, is how its *relational grammar* [WW96] governs the *visual syntax* between the different sketch elements. In this respect, the relational grammar, *g*, governing the visual syntax of PSL is defined by the 6-tuple $g = (V, T, \varphi, \alpha, S, p)$

where V is the infinite set of user-defined variables
T is the finite set of predefined symbols
φ is the finite set of 'invisible' relational symbols
α is the set of 'invisible' attribute symbols
S is the sketch drawn in PSL
p is a finite set of production rules of the form:

$$S \rightarrow m / \eta , \Lambda$$

where $m \subset \{V \cup T\}$

η is a set of spatial relational constraints of the format (r x y) where $r \in \varphi$ and x, y are integers each referencing a member of m. These integers in η act as references to its elements: the left-hand-side of a rule is conventionally referenced as 0; the one or more right-hand-side elements are referenced 1…n in the order in which they appear in the definition [WW96].

Λ is a set of attribute constraints of the format (a x y) where $a \in \alpha$ and x, y are integers each referencing a member of m, as above.

Legend: $A \rightarrow B$ = A replaced by B
$A / B , C$ = A is subject to B and C
$A \subset B$ = Set A is a proper subset of set B
$A \cup B$ = Set A union set B
$A \in B$ = A is an element of set B

In the above relational grammar definition, the sets V and T are non-empty and disjoint. The former set contains *all* the possible *user-defined* variables consisting of the 2D closed profiles which can be mapped into 3D geometric models by means of operators (e.g. *revolve, extrude, sweep*) used in CAD systems. These operators are represented by predefined *symbols* in T. As an illustration of the application of *g*, a sketch S representing a *rotational* form concept, consists of the following elements:

$2D\_closed\_profile \in V$
$Rev_1 \in T$
$Rev_2 \in T$

The sketch visual syntax is defined by the following production rules:

$$\begin{aligned} S \rightarrow\ & \{2D\_closed\_profile, Rev_1, Rev_2\}/ \\ & \{(outside\ 2\ 1), (outside\ 3\ 1) \\ & (right\text{-}of\ 2\ 1), (right\text{-}of\ 3\ 1), (vertical\ 3\ 2)\}, \\ & \{(smaller\ 2\ 1), (smaller\ 3\ 1)\} \end{aligned}$$

Legend: $Rev_1 =$ , $Rev_2 =$ 
1 = 2D_closed_profile, 2 = Rev_1, 3 = Rev_2

A spatial relational constraint such as *(outside 2 1)* is to be interpreted as a requirement that the object corresponding to rule element 2 (i.e. Rev_1) stands in the 'outside' relation to the object corresponding to rule element 1 (i.e. 2D_closed_profile). The spatial arrangement between the elements in *m* is determined by relational symbols such as 'outside', 'right-of' etc. Such relational symbols are 'invisible' since they are not depicted in the sketch. This applies also for the attribute symbols (i.e. *smaller*), which define the relative size between the sketch elements. Both relational and attribute symbols, which characterize the production rules have two functions. Firstly, in the context of this frame, they are required for the designer to represent properly the intended rotational form concept in the sketch. Secondly, as will be discussed later in Section 7.3, they are essential for the prototype tool to validate the sketch visual syntax.

7.2 Sketch Capture and Transmission (SCT) frame

The *Nokia* [Nok04] *3650* cameraphone model is utilised to capture and digitize (in *jpeg* format) the sketch drawn in PSL. Experiments have shown that three main factors (see Figure 5) affected the geometry of the sketch in the captured image with respect to its original counterpart. These factors consist of the distance *d* between the cameraphone and the sketching surface, and the angles θ and β which are measures of the deviation of the cameraphone from its parallel position with respect to the sketching surface (see Figure 5). From the experiments carried out, it was concluded that *d* should be approximately 160mm for a sketch of size 50x80mm, whereas θ and β should not exceed 2°.

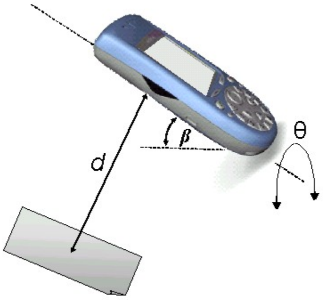


Figure 5: *Factors influencing the geometry of the sketch in the image captured with the cameraphone.*

The digitized sketch image is then transmitted by the cameraphone user from this device to the computer on which the sketch recognition system is installed. Various data transmission technologies between wireless devices and a computer are available, such as infrared, *Bluetooth*® [Blu04] and e-mail. The first two are limited in terms of the allowed transmission range, hence inadequate to attain the objective of this research. Therefore, the sketch image captured with the cameraphone is sent to an e-mail address (via a data-bearer such as the *General Packet Radio Service* - GPRS) as an attachment file which is then saved for subsequent processing in the SIPV frame.

7.3 Sketch Image Processing and Validation (SIPV) frame

This frame has two principal roles, namely the processing of the sketch image and the validation of the sketch visual syntax. With regards to the former role, the first image preprocessing step concerns *binarization* of the image, in which the dark foreground sketch is separated from the lighter background. Since a sketch is captured with a colour cameraphone in a natural environment, 'illumination artefacts' (e.g. shadows) are introduced in the sketch image (see example in Figure 6), thereby resulting in the corruption of the image. This will in turn cause a problem in binarization, when the colour sketch image is converted to a monochrome grey-level image, as it is difficult to distinguish between the foreground sketch from the background.

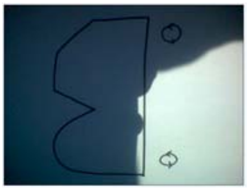


Figure 6: *Shadows in a captured sketch image.*

To overcome this problem, the binarization algorithm based on *Kamel and Zhao's Logical Adaptive Technique* [KZ93] is employed. This algorithm processes every pixel by simultaneously comparing its grey level with eight local averages in the $(2SW+1) \times (2SW+1)$ sized neighbourhood of each pixel. The algorithm originally required two user-defined parameters namely, *SW,* the stroke width of the line drawing and an initial threshold *T*. These were evaluated adaptively by using the *Yang and Yan's method* [YY00], thereby making the algorithm free from user defined parameters. Binarization may result in undesirable noise blobs in the image - these are removed at a later stage in the processing.

The 'image components' (i.e. the separate elements constituted of black pixels in the binarized image) are then thinned using a classical *'skeletonization'* algorithm [GW02] to obtain one-pixel wide image components. Each separate image component is then uniquely labeled by a 'region growing' technique [GW02]. At this stage, labeled image components having less pixels than a pre-set threshold value are removed, thus eliminating the undesirable noise blobs mentioned previously.

The next processing steps make use of the *Hough Transform* [GW02]. The generalized form of the Hough Transform maps an image into some parameter space defined in terms of relevant shape parameters. For example, a straight line can be parameterized by its gradient and intercept. Each boundary pixel of a specific shape is mapped to all those Hough space cells that satisfy the shape parameters at that pixel. Whenever, a pixel is mapped to a cell, that cell is incremented to keep count of the number of pixels being mapped to that cell. Although pixels belonging to the boundary of a shape contribute to several cells, they will all contribute to that particular cell that represents the parameters of that shape. Therefore, the parameters of the shape can be identified by finding the co-ordinates of the peak cell in the Hough space.

Each labeled image component is first processed by the *Line Hough Transform* [GW02] which parameterizes straight lines. In order to be able to compare the Hough Transform peaks of different image components of different size, the peak is normalised by the number of pixels in the image component. Empirical tests have shown that a 2D closed profile can be distinguished from the 'axis' symbols by employing this technique [Seg03].

The 2D closed profile is then represented by a *chain code* [GW02] which is used to identify its corners. This makes it possible to finally represent a 2D closed profile by means of an ordered list of Cartesian coordinates of the identified corners. It should be noted that with the chain coding technique any arc segments on a 2D closed profile are *approximated* to line segments, this being one of the current limitations of the developed prototype tool.

Non-polygonal sketching symbols such as the 'axis' symbols currently used in PSL may not generally have a simple shape. Therefore, a Hough Transform capable of representing a general boundary shape is required. In this respect, the *Randomized Generalized Hough Transform* (RGHT) [FLK96] is employed. The RGHT makes use of symbol templates that have to be matched. A symbol that is mapped into the RGHT space through the template of the same symbol will result in a large Hough space peak, whereas if it is mapped through the template of another symbol, the Hough space peak will be lower. The RGHT normalized peak value is thus used to properly classify 'axis' symbols. The Cartesian coordinates of the identified symbols are then determined.

Given the readily available image processing toolbox in *MatLab*® [Mat04], all the algorithms referred to above, have been implemented using this package.

The second role of this frame is to validate the visual syntax of the sketch, S, with respect to the sets of spatial relational and attribute constraints. This is necessary so that any invalid spatial arrangements between the sketch elements (see examples in Figure 7a and 7b), are detected. The invalid spatial relational constraints in Figure 7a and 7b are respectively *(outside 2 1)* and *(vertical 3 2)*. Similarly, the set of attribute constraints ensures that sketches such as that depicted in Figure 7c are not validated. In this case the attribute constraint *(smaller 2 1)*, is not valid.

At the time of writing, the sketch visual syntax is *assumed* to be correct since alternative approaches to be implemented in this step are still being investigated. One of these approaches concerns *Fuzzy Relational Grammars* which combine fuzzy logic and spatial relation syntax in a single unified formalism [CGFJ02]. As argued in [CGFJ02], this allows variations in a sketch input to be flexibly modelled. For instance, with fuzzy sets, the spatial relation *(vertical 3 2)* could be modelled in such a way so that a variation in the horizontal direction between the two 'axis' symbols is allowed.

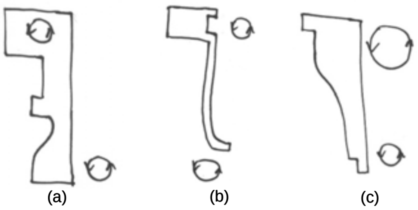


Figure 7: *Examples of invalid sketches due to incorrect spatial arrangement (a), (b) and incorrect size attribute (c).*

Provided that the sketch visual syntax is valid, the shape information extracted from the image processing algorithms is modelled in a specified format as explained in the following section.

7.4 Shape Information Modelling (SIM) frame

In this frame, the shape information inputted from the SIPV frame is mapped into a specified format so that a 3D geometric model is automatically generated in the V3D frame. Since *AutoCAD*® [Aut04] is the 3D modelling application used for preliminary evaluation purposes, the shape information is modelled in a *command script file* format (see Figure 8), from which AutoCAD® executes a sequence of commands.

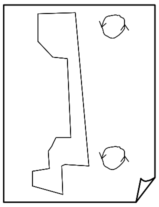
Paper-based sketch	Script file	Meaning of command
	pline	*Polyline*
	71,7 70,30 94,30 82,154 49,153 49,131 62,118 75,117 78,53 65,53 61,46 58,42 59,28 44,26 44,14 71,7	Coordinates of corners of the 2D_closed_profile
	revolve	The 3D operator, *revolve*
	last	Polyline generated
	100,144 108,39	Coordinates of *centre* of axis symbols
	360	360º, i.e. full revolution

Figure 8: *Typical script file format used for modelling shape information.*

7.5 Virtual 3D Sketch Construction (V3D) frame

Basically the main purpose of this frame is to generate a 3D geometric model from the script file format inputted from the SIM frame. To this end, as previously indicated, AutoCAD® is employed. It should be noted that when loaded in AutoCAD®, the type of script file shown in Figure 8, produces a 3D *wireframe* model. Since a wireframe model consists of a skeletal representation of the equivalent real-world 3D object, it usually lacks visual coherence.

7.6 3D Model Image Transmission (3DT) Frame

Therefore, to provide the cameraphone user with a more expressive visual representation of the intended form concept, in this frame, the 3D wireframe model is photorealistically rendered to a file, using AutoCAD®. The rendered 3D geometric model is first saved in bitmap (*bmp*) format and then converted to another format (e.g. *gif* or *jpeg*) so that the image significantly takes up less memory space compared to a bitmap image. This conversion is required for two main reasons. Firstly, the size of an image which can be sent as a multimedia message to a cameraphone via a web portal is presently very limited. Secondly, neither the *gif* nor the *jpeg* formats is readily available in AutoCAD® when rendering a view to a file.

The last step in this frame concerns the transmission of the image in either *jpeg* or *gif* format to the cameraphone user. This is accomplished by sending the image via *Multimedia Messaging Service* (MMS) available in a web portal set up by a mobile communication service provider.

7.7 Prototype tool automation

To enable a designer to *automatically* and remotely obtain a rendered image on the screen of the cameraphone directly from an image of the paper-based sketch, the steps in frames 3 to 6 (see Figure 4) have been automated. *Microsoft Visual Studio .NET®* [Mic04] is used as a platform for the *Visual Basic .NET®* (VB.NET) programming language. Furthermore, *Visual Basic for Applications* (VBA) is employed in relation to software applications that support the use of VBA programs, such as AutoCAD® used in the V3D frame.

8. Evaluation

The evaluation was aimed firstly to assess the underlying concepts upon which the developed framework is based and secondly to evaluate the strengths and weaknesses of the implemented prototype tool. With regards to the former evaluation objective, a survey was carried out with 22 practicing designers in industry and 26 mechanical engineering students, to have a preliminary indication on whether the subjects:

1. use freehand sketches to externalize their early design solution concepts;
2. think of conceptual form design concepts *outside* their usual design workplace so that to assess whether mobile sketch-based computational tools will be useful;
3. prefer to use either (i) a normal A4 paper, pencil and a cameraphone or (ii) a *tablet PC*, (i.e. a type of notebook computer with an integrated digitizing tablet and stylus), to obtain 3D geometric models from freehand sketches;
4. consider the use of a cameraphone as a means to remotely obtain an image of a rendered 3D geometric model directly from a paper sketch, as beneficial.

With regards to the prototype tool evaluation, an experiment was carried out in order to assess the tool effectiveness for *remotely* generating images of 3D geometric models from paper sketches.

8.1 Survey key evaluation results

The survey key results relevant to the concepts underlying the framework adopted, are depicted in Figure 9. From the sample proportion ($\overline{p}$), the actual proportions (p) of the population were also inferred with 95% degree of confidence (see Figure 9).

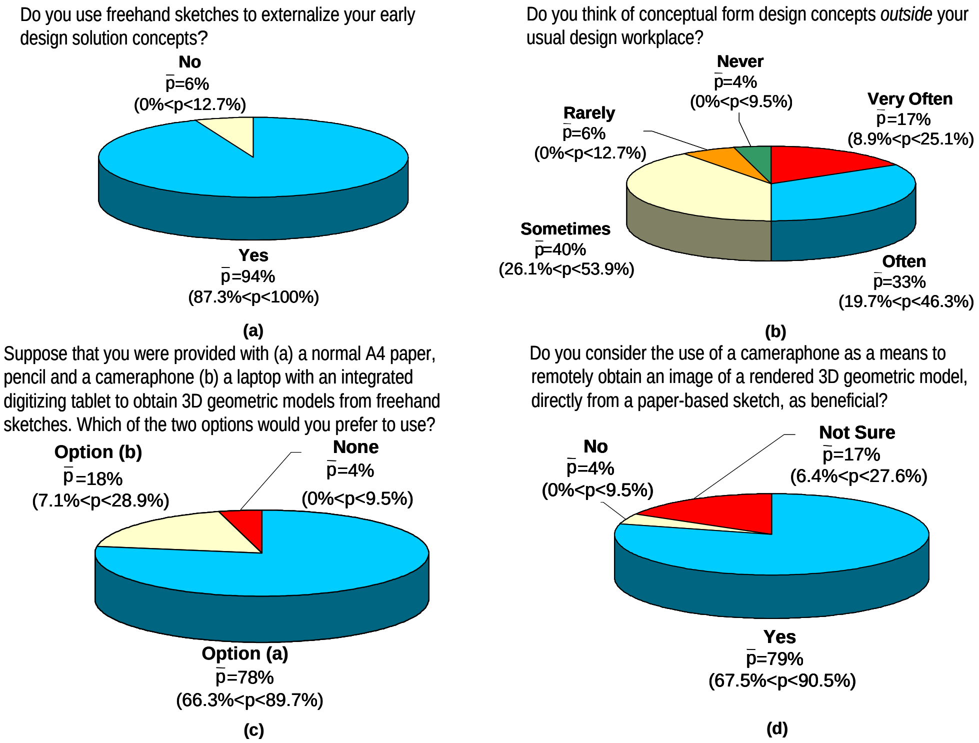
From Figure 9a, it is evident that the majority of the subjects (i.e. 94%) still use freehand sketches to express their early design solutions. Figure 9b demonstrates that 50% of the subjects think of form concepts outside their usual design workplace on a regular basis (i.e. 'Very Often' and 'Often'), whilst 40% declared that they do so less frequently (i.e. 'Sometimes'). Few of the subjects replied that they 'rarely' (6%) or 'never' (4%) think of design concepts outside their usual design workplace.

Regarding the subjects' preference of using the cameraphone-based approach disclosed in this paper, as opposed to a tablet PC, 78% favoured the former approach (see Figure 9c). Various evaluators remarked that the cameraphone-based approach allows greater portability and at the same time it retains the fluidity of the traditional paper-based freehand sketching. Relatively few of the subjects replied that they would use a tablet PC (i.e. 18%), whereas only 4% had a negative reply. However, it should be noted that the results in Figure 9c are based on the subjects' perceptions of the two mobile design input approaches and not actually on their impressions based on hands-on experience in using them.

Referring to Figure 9d, 79% of the subjects considered the use of a cameraphone as a means to remotely obtain an image of a rendered 3D geometric model directly from a paper sketch, as beneficial. 17% were not sure mainly because they still have to evaluate its utility in practice. Only 4% replied negatively.

8.2 Prototype tool evaluation

As a preliminary tool evaluation, a designer participated in an experiment, in which he was assigned the task of designing form concepts of four main rotational components of a fuel filter, at different remote locations (see Figure 10). Prior to the actual experiment, the designer was given sufficient time to familiarise himself with the cameraphone and to practice in adequately capturing a sketch so that the optimum values of d, θ and β mentioned in Section 7.2 are maintained. Since different components of the *same* fuel filter had to be designed, a graph paper was utilized as the semiformal sketching area. This enabled the designer to easily establish the relative sizes between the filter components.



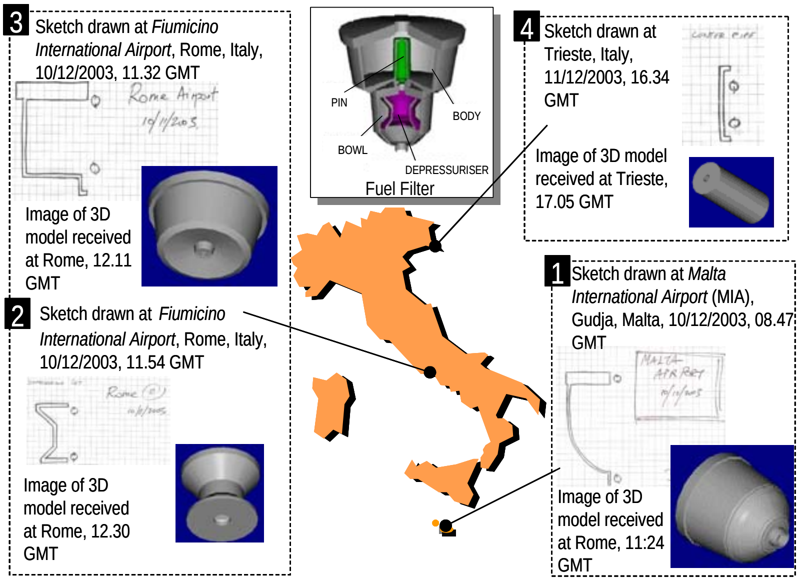
Do you use freehand sketches to externalize your early design solution concepts?

Do you think of conceptual form design concepts *outside* your usual design workplace?

Suppose that you were provided with (a) a normal A4 paper, pencil and a cameraphone (b) a laptop with an integrated digitizing tablet to obtain 3D geometric models from freehand sketches. Which of the two options would you prefer to use?

Do you consider the use of a cameraphone as a means to remotely obtain an image of a rendered 3D geometric model, directly from a paper-based sketch, as beneficial?

Figure 9: *Survey's key evaluation results.*



3 Sketch drawn at *Fiumicino International Airport*, Rome, Italy, 10/12/2003, 11.32 GMT

Image of 3D model received at Rome, 12.11 GMT

2 Sketch drawn at *Fiumicino International Airport*, Rome, Italy, 10/12/2003, 11.54 GMT

Image of 3D model received at Rome, 12.30 GMT

4 Sketch drawn at Trieste, Italy, 11/12/2003, 16.34 GMT

Image of 3D model received at Trieste, 17.05 GMT

1 Sketch drawn at *Malta International Airport* (MIA), Gudja, Malta, 10/12/2003, 08.47 GMT

Image of 3D model received at Rome, 11:24 GMT

Figure 10: *Preliminary prototype tool evaluation.*

As can be observed in Figure 10, the time at which the designer received the multimedia message containing the rendered 3D geometric model differed significantly from the time at which the sketch was captured and transmitted via e-mail. This was mainly attributed to the time taken by (i) the image processing algorithms to extract the shape information from the sketch and (ii) the data-bearer to transmit the sketch/3D model image from/to the cameraphone. At the end of the experiment the designer was asked to give his comments regarding the effectiveness of the prototype tool in remotely generating images of 3D geometric models from paper sketches. He remarked that he found the prototype tool very portable and useful in that the images of 3D rendered models assisted him in visualising and evaluating better the intended form concepts. However he also remarked that the long time span which elapsed between the drawing of the sketch and the instant the image of the 3D model was received, greatly hindered his flow of design ideas.

9. Discussion and future work

This paper argued that designers need a mobile computational tool enabling them to remotely obtain visual representations of 3D geometric models from freehand sketches. This need is reflected in the survey results which reveal that the majority of the subjects frequently think of concepts *outside* their usual design workplace. Additionally it is also evident that the subjects showed a positive attitude towards the cameraphone-based approach disclosed in this paper. Nevertheless, deeper investigation is required to achieve a better insight into whether designers prefer to use the proposed approach or an alternative mobile design input device such as a tablet PC. However, independent of this, it can be argued that a digital equipment constrains users to use a CAS system with only *dynamic* sketching surfaces, such as the active area of a digitizing tablet. By contrast, the framework proposed in this paper allows designers to sketch on a much wider choice of readily available *static* sketching surfaces, including for instance, whiteboards - virtually any physical surface on which freehand sketching is possible.

The preliminary prototype tool evaluation indicates that for the tool to be more effective, the designer should *instantly* receive the image of the 3D model generated from the paper sketch. As indicated in Section 8, this aspect is influenced by *tool-dependent* factors (e.g. the time taken by the image processing algorithms) and *tool-independent* factors (e.g. the transmission speed of the data-bearer). While the former type of factors can be controlled to some extent, tool-independent factors are rather difficult to control and to anticipate, thereby making the tool effectiveness unpredictable.

Since this research is in its infancy, it is acknowledged that the *current* prototype tool poses several constraints on the user, such as the limited range of components that can be sketched, how the sketch should be captured (in terms of the factors referred to in Section 7.2 and the conditions of ambient illumination), and how the 3D model is viewed. Thus, much more future work is needed, in particular:

1. the scaling up of PSL such that a wider range of geometric models can be supported;
2. experimental tests aimed at assessing whether the use of a cameraphone with ‘zoom’ and ‘flash’ features simplifies the sketch image capture process;
3. the modelling of shape information in a suitable format (e.g. *MPEG-4*) such that the cameraphone user can obtain a 3D animation of the 3D CAD model generated, for better visualisation purposes.

10. Conclusions

To conclude it can be stated that the mobility offered by combining paper portability with that of a cameraphone, distinguishes the approach described in this paper from the others adopted in the state-of-the-art CAS technology.

As discussed, future work is required in extending the practical applicability of both the overall framework and of the implemented prototype tool. Nevertheless, from the evaluation results, it seems that the developed framework contributes a step towards providing designers and other users not experienced in computational 3D modelling, with a *mobile* tool enabling them to remotely obtain visual representations of their early form design concepts from sketches drawn on the natural, portable and readily available paper medium. Furthermore, although this paper focused on ‘early form’ design modelling, the idea of a paper sketch-based UI combined with a cameraphone, can be extended to other applications. For instance, designers of cartoon characters and potentially other layusers would be able to *remotely* obtain a 3D animation of a cartoon character on the screen of their cameraphone, generated from a series of paper sketches captured with the same device.

Note

Parts of the research work disclosed in this paper are subject to a pending patent application number 2130.

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