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EXPERIMENTS WITH A CAMERAPHONE-AIDED DESIGN (C_PAD) SYSTEM

Farrugia Philip J., Borg Jonathan C., Camilleri Kenneth P., and Spiteri Christopher

Abstract

Paper-based freehand sketching is still widely used by practicing designers to externalise their early form design solutions. Existing Computer-Aided Design (CAD) systems are mostly used in later design stages, as their user-interface lacks the fluidity of freehand sketching. To combine the benefits of sketching with those of 3D modelling technology, various Computer-Aided Sketching (CAS) tools have been developed. However, research efforts in this field were focused on integrating *digital* sketching with 3D modelling technology, thereby replacing the natural, portable and readily available paper medium. It is frequent that designers also think of concepts outside their design office. In view of this, a sketching medium that is portable and readily available to use, is required to instantly capture the flow of design ideas. Based on these arguments, this paper reports the on-going development of a cameraphone-aided design (C_PAD) system. Such a system enables designers to remotely obtain visual representations of 3D geometric models from freehand sketches, by exploiting paper portability with that of cameraphones. Although limitations were identified from a prototype C_PAD tool implemented, evaluation results collectively justify further research on the C_PAD approach being developed.

Keywords: 'early form' design, sketching, languages, global communication

1. Problem background

Despite the availability of CAD systems, more specifically of Computer-Aided Geometric Modelling (CAGM) systems, practicing designers still resort to *paper*-based freehand sketching in conceptual design [1]. The WIMP (Window, Icon, Menu, and Pointing device) based user-interface (UI) of these systems is the major reason attributed to this. As remarked in [2], such UI is rigid for designers to use in conceptual design. The limitations of this WIMP-based UI for early form design were highlighted in results of a survey conducted by Lim et al. [3]. Respondents in this survey remarked that using CAD tools in conceptual design is too time consuming with slow feedback, too complicated for design thinking, and it has a different feeling compared to pencil-and-paper sketching [3].

Therefore, to bridge the gap between freehand sketching and CAGM systems, various Computer-Aided Sketching (CAS) tools were developed. However, in most CAS tools, paper is replaced with digital sketching media such as a digitising tablet and stylus [4], [5], [6] and Virtual Reality (VR) equipment [7]. A digital sketching medium offers real-time data capture which can be exploited for sketch recognition, and enables direct user interaction. Yet, it is not actually integrating pen-and-paper sketching with CAGM systems. Digital sketching lacks the speed, ease-of-use, immediacy, quality of response and the expressive qualities offered by paper-based sketching [8]. As a result, users typically find it more comfortable to sketch with a pencil on paper, rather than using a light pen, mouse or tablet [9]. Moreover, paper is more portable and available compared to digital sketching media. The CAS tools which retained paper (e.g. those described in [10] and [11]), do not fully exploit paper *portability* and *availability*, since the sketch is captured with a normal flat-bed scanner. Consequently such tools can be used only inside the design office. Table 1 indicates the type of sketching medium used in the CAS tools cited above. Moreover, this table shows the situation where these tools can be utilised. It must be noted that the scope of Table 1 is not to provide an exhaustive literature review, but to illustrate that digital sketching media are *mostly* used in existing CAS tools. A more detailed review about CAS tools carried out by the authors may be found in [1].

Table 1. A representative selection of CAS tools and type of situation where they can be used.

Name of tool/ Author(s)	Type of medium	Type of situation where CAS tool can be used
Quicksketch [4]	Pen-based computer	Both inside and outside the design office. (1)
Lispon [9]	Specially devised equipment	Inside the design office only.
CIGRO [5]	Digitising tablet & stylus	Both inside and outside the design office. (1)
SMARTPAPER [6]	Tablet PC*	Both inside and outside the design office. (1)
Fiorentino et al. [7]	VR-based equipment	Inside the design office only.
Marti` et al. [10]	Paper	Inside the design office only. (2)
DeCign [11]	Paper	Inside the design office only. (2)

(1) Provided that the designer is *readily* carrying the sketching medium.
(2) A normal flat-bed scanner is employed to capture a digital image of the sketch.
* A laptop computer with an integrated digitising tablet and stylus.

The portability and availability of a sketching medium are two important characteristics for 'mobile design work'. In analysing instants of a designer's activity, Hoeben and Stappers [12] observed the *"benefits of portability of sketches in a train, or any mobile situation and situations where the designer is not in his office."* In addition, since good ideas are often thought of unexpectedly, they can end up on a host of readily available sketching media including cocktail napkins and beermats [13]. This implies that ideally, a CAS tool can also be used *outside* the design office, whereby a designer can sketch on a *readily available* medium, (e.g. a simple paper napkin) and *instantly* obtain the equivalent 3D geometric model. As previously highlighted, the CAS tools which retained paper (see Table 1) are still inadequate to use for such a situation. Therefore it can be stated that presently, designers lack *mobile* computer-based design tools that effectively link *paper*-based sketching with the benefits offered by 3D modelling technology (such as 3D model visualisation).

2. Research goal and boundary

The above problem and the ever-increasing use of cameraphones (i.e. mobile phones with an integrated digital camera) motivated this research. The goal is to develop and evaluate a

Cameraphone-Aided Design (C$_P$AD) system enabling designers to obtain visual representations of 3D models from *paper*-based sketches drawn outside the design office.

To achieve this goal and to evaluate a prototype C$_P$AD tool, as boundary, research efforts are presently embarked on 'early form' design of *mechanical components*.

3. C$_P$AD approach

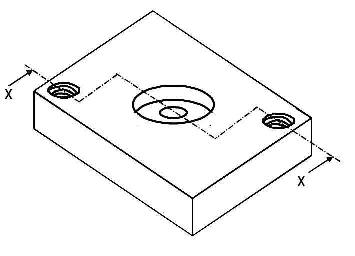
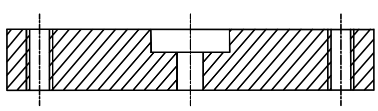
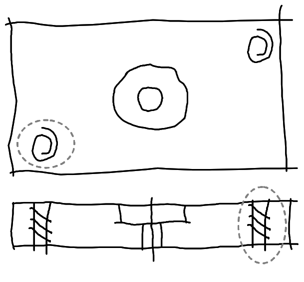
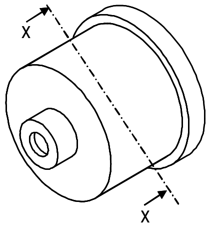
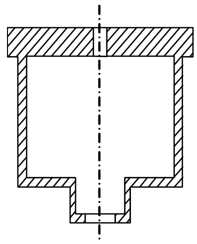
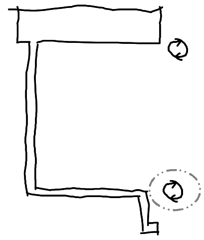
One of the underlying concepts characterising the approach taken to develop a C$_P$AD system concerns the use of a *prescribed sketching language*. As argued in Section 3.1, such a language is instrumental to *robustly* and *automatically* convert paper-based sketches into 3D geometric virtual models. Section 3.2 then outlines the framework architecture upon which a prototype C$_P$AD tool has been implemented.

3.1 Use of a prescribed sketching language

Difficulties arise to automatically separate geometric from non-geometric information, particularly in paper-based sketches, as data cannot be captured in real-time [9]. To compound the problem further, due to its inherent properties, a freehand sketch can have multiple interpretations [14]. As noted in [14], compared to Optical Character Recognition (OCR) techniques, the development of sketch recognition techniques was quite slow. Whilst OCR has a well-defined set of patterns to be matched (i.e. a set of alphabet and numeric characters), the number of patterns and their combination in sketches is infinite [14]. Despite this, although many drawing standards (such as *BS8888:2002*) were established for detail design drawings, no standards are yet available for sketches. This makes automatic sketch recognition more difficult [15].

To address these issues, a prescribed sketching language [15] is being developed. With this language, designers can represent semiformally a range of mechanical component forms in paper-based sketches such that automatic recognition is simplified (see examples in Table 2).

Table 2. Examples of mechanical component forms sketched with a prescribed sketching language.

	Designer's intent	Section 'X-X'	Sketch representation
Prismatic component			
Rotational component			

Legend: ◌ = a type of *'form_feature_symbols'* ◌ = a type of *'3D_CAGM_operator_symbols'*

The first component in Table 2 consists of a prismatic base characterised by 2.5D form features (e.g. threaded holes). A plan and sectional views passing through all the form features are utilised to represent these classes of components. A library of predefined sketching symbols is used to represent form features [15]. The second component has rotational geometry. In this case, symbols representing 3D operators (e.g. *revolve*) commonly used in CAGM systems, are employed to map 2D closed profiles (e.g. half of the cross-section of a rotational component) into the equivalent 3D virtual models (see Table 2).

3.2 Framework architecture

The framework architecture being developed for a C_PAD system is constituted of the following frames (see Figure 1):

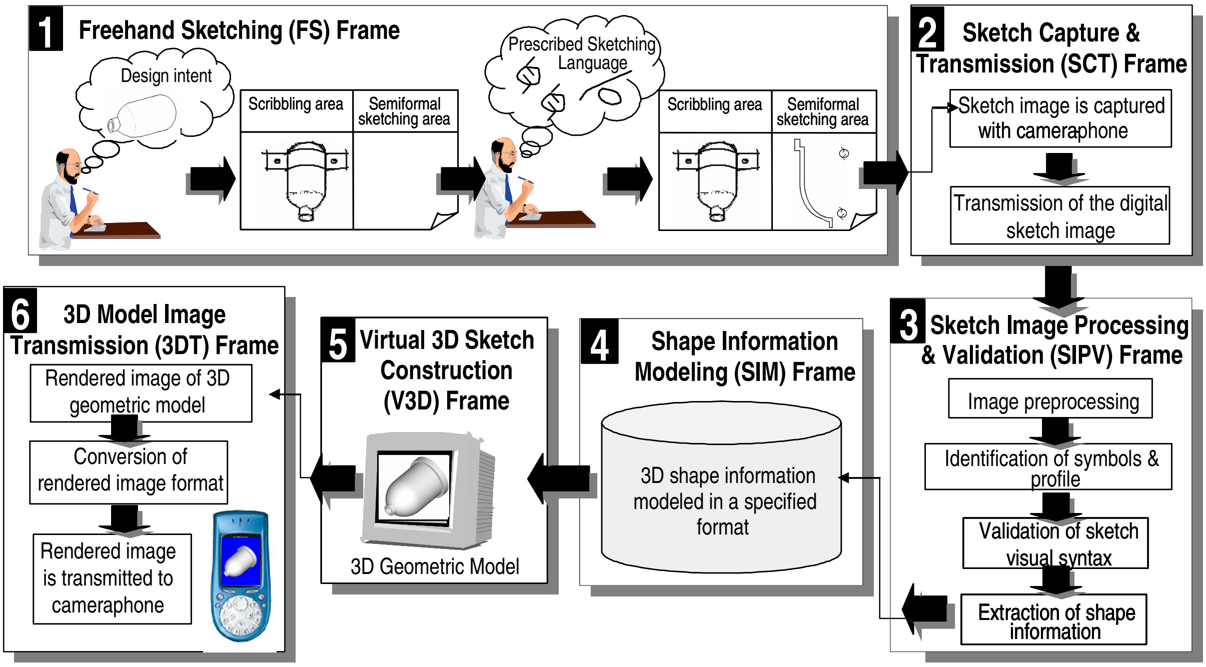


Figure 1. Framework architecture of a C_PAD system [1].

1. *Freehand Sketching (FS)* frame: the designer's form intent is first externalised in the 'scribbling area' of a devised paper-based *sketching template*, where the designer is allowed to scribble (i.e. rough sketching). The candidate form concept is then represented semiformally on the other side of the sketching template by means of the sketching language explained above. Thus, even if this approach constrains the designer to sketch in a predefined manner, it does not hinder the designer's cognitive process as scribbles can still be used [16].
2. *Sketch Capture and Transmission (SCT)* frame: an image of the form concept represented with the prescribed sketching language is first captured with a cameraphone. The digital image of the sketch is then transmitted to an e-mail address via Multimedia Messaging Service (MMS), as an attachment file.
3. *Sketch Image Processing and Validation (SIPV)* frame: several image preprocessing steps are applied to the sketch image. An example is *binarisation*, whereby the dark foreground sketch is separated from the lighter background. At this stage any unwanted information (e.g. noise and shadows) introduced in the sketch is removed. Furthermore, each image component is separated and uniquely labeled for further

processing. The next step consists of identifying each labeled component by appropriate algorithms. Details about image processing aspects go beyond the scope of this paper, however the reader may refer to [1] and [17] for further details. Image processing is followed by the validation of the sketch visual syntax. This is essential so that any invalid sketches are detected by the C_PAD system. Provided that the sketch visual syntax is correct, the 3D shape information is extracted and modelled in the subsequent frame.

4. *Shape Information Modelling (SIM)* frame: a range of possible formats can be employed in this frame to model the extracted 3D shape information. The type of format depends on what 3D CAGM package is utilised to automatically generate the 3D geometric model. For example, if AutoCAD® is used, the shape information is modelled in a *command script file* format, from which AutoCAD® can automatically execute a sequence of commands.
5. *Virtual 3D Sketch Construction (V3D)* frame*:* a 3D geometric model is generated in a commercial 3D CAGM package from the format inputted from the *SIM* frame.
6. *3D Model Image Transmission (3DT)* frame: a photorealistic rendered image of the 3D geometric model generated is first produced so that an expressive visual representation of the intended form concept is provided to the designer. This is followed by the transmission of the image to the cameraphone recipient, via MMS, from a web portal set up by a mobile communication service provider.

A computer-based prototype C_PAD tool has been implemented based on the framework described above [1]. As disclosed in the following section, through experimentation with this prototype tool, it was possible to identify factors which would affect the performance of a C_PAD system.

4. Factors affecting a C_PAD system

The aforementioned factors have been classified into *controllable* and *uncontrollable* factors. Section 4.1 provides examples of the former type, such as the factors inherent in capturing an image with a cameraphone. As outlined in Section 4.2 the factor which cannot be directly controlled concerns the MMS transmission rate.

4.1 Controllable factors

The position of the cameraphone with respect to the sketching surface is the first controllable factor which needs to be catered for. Experiments showed that three parameters affected the geometry of the captured sketch image with respect to its original counterpart. These consist of the distance $\boldsymbol{d}$ between the cameraphone and the sketching surface, and the angles $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, measuring the cameraphone orientation about two axes (see Figure 2a). Experiments were carried out to determine the optimum values for these parameters in order to preserve the geometry of the component form representation. To accurately vary the parameters, a 6-joint robot was utilised. The cameraphone (a *Nokia 3650* model) was held by the robot gripper and initially positioned parallel to the sketching surface, whereby the distance and orientation of the cameraphone were gradually incremented (see experimental set-up in Figure 2b).

To simplify the measurement of the dimensions of the original sketch with respect to those of the sketch image, a sketch having only straight edges was utilised (see sketch in Figure 2a). The distance $\boldsymbol{d}$ was incrementally increased, each time capturing the paper-based sketch.

When plotting the variation of ***d*** against ***φ*** (the latter defined as the ratio *dimension of the captured sketch: dimension of the original sketch*), it was found that when ***φ*** =1, the distance ***d*** was 16cm (i.e. the optimal distance). However, it must be remarked that this value depends on the size of the sketch and on the cameraphone's zooming capabilities.

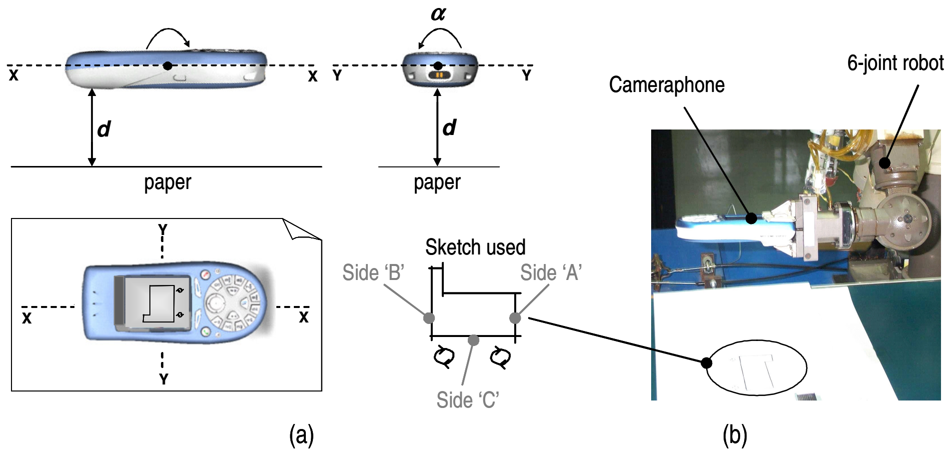


Figure 2. (a) Parameters tested (*d, α, β*) and sketch used (b) Experimental set-up

With the aim to establish the maximum allowed orientation of the cameraphone without changing the original sketch dimensions, the angles ***α*** and ***β*** were varied independently about the respective axis (see Figure 2a). A regression analysis was performed for each angle. Figure 3 shows the results obtained for ***α*** for each reference side indicated in Figure 2a. It can be observed that for angles less than 22°, ***φ*** varies from 0.94 to 1.07.

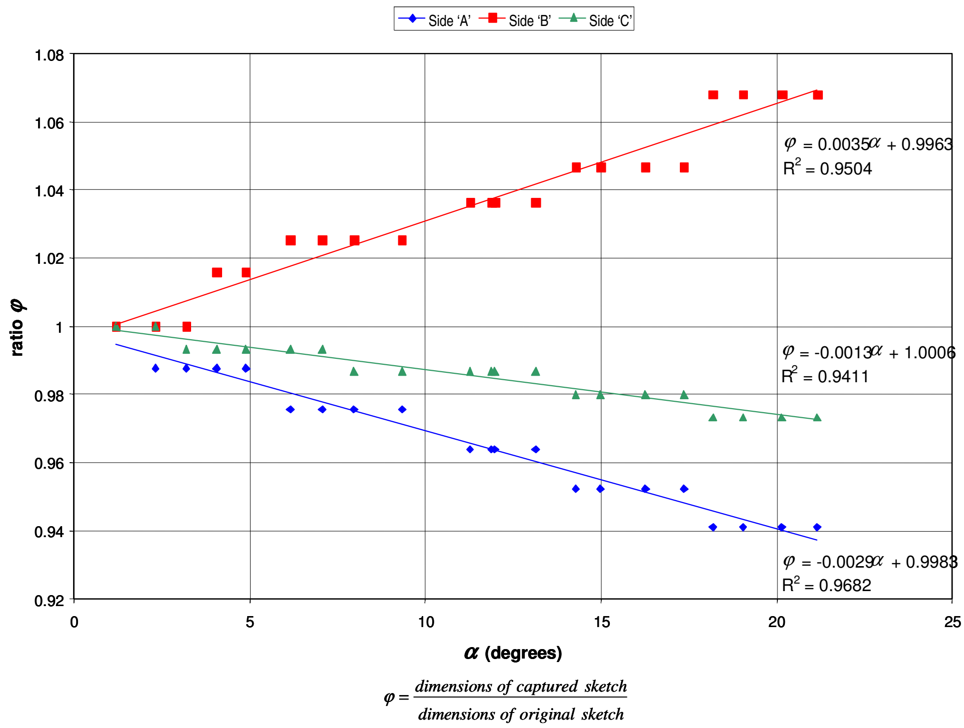
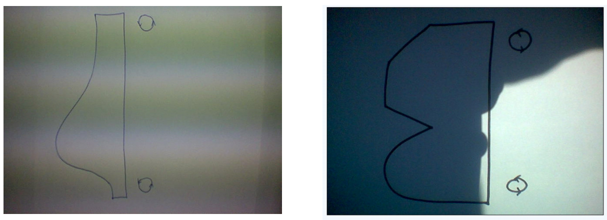


Figure 3. Graph showing the variation of φ with α

Further experiments showed that other factors had to be accounted for (see Table 3). As evident in Table 3, the most common negative effect resulting from these factors was observed during binarisation. For instance, the ambient illumination corrupts the image due to shadows. Figure 4 depicts sketch images captured in an ambient illumination of (a) fluorescent white light source and (b) sunlight. In such images, it is difficult to distinguish between the foreground sketch from the background (i.e. binarisation). To mitigate this problem, adaptive binarisation algorithms have been developed as detailed in [17].

Table 3. Other controllable factors affecting the performance of a prototype C_PAD tool

Factor	Description	Example	Effect	Possible solution
Ambient illumination condition	Dim ambient illumination	Sketch image captured in a dark room with a cameraphone without flash capabilities	Difficulties in binarisation	Use of cameraphone equipped with a flash
	Shadows introduced in sketch image	A sketch image with shadows of cameraphone/hand of designer		Application of adaptive binarisation algorithms
Sketch image content	Extraneous information captured with the sketch	Other artefacts (e.g. a pen) introduced in the sketch image	Redundant information extracted from sketch	Designer ensures that image contains only the sketch
Sketch marker	Light, thin marker	Pencil or ballpoint pen	Difficulties in binarisation	Use of a dark felt tip pen
Sketching surface	Type and condition	Dark creased paper or textured paper napkin		Application of adaptive binarisation algorithms



(a) (b)

Figure 4. Corrupted sketch images due to (a) fluorescent white light source and (b) sunlight

4.2 Uncontrollable factor

An experiment was conducted in which a designer utilised the prototype C_PAD tool for mobile design work [1]. It was observed that a long time elapsed from the instant at which the designer captured and transmitted the sketch image until he received an image of the 3D geometric model. As remarked by the designer, this long time span impaired his flow of ideas. This was largely attributed to the slow MMS transmission rate. However, as this factor depends on the mobile communication service provider it cannot be directly controlled.

The factors mentioned in Section 4 identify limitations of the current C_PAD tool from practical aspects. The next section discloses the method adopted to evaluate issues (e.g. traditional vs. digital sketching) related to the C_PAD system being developed.

5. Evaluation method

A survey was carried out in three countries, namely, Malta, UK and Italy, with 33 evaluators having different design background, as summarised in Table 4.

Table 4. Summary of survey participants and their design background

Category	Number	Country	Type of design experience	Average years of design exp.
Students	12	UK	Various projects in *'product design engineering'*	4
	7		Various projects in *'mechanical design engineering'*	3
Engineering designers	10	Malta (4), Italy (6)	Design of metal and plastic components	12
Industrial designers	4	Italy	Design of domestic appliances	11

The survey objectives mainly consisted of investigating the following:

1. whether the evaluators also think of design concepts outside their usual design workplace, and if so, in which situation;
2. how frequent do they carry a paper and a pen to sketch any spontaneous ideas;
3. which portable sketching media is mostly preferred;
4. what characteristics of a portable sketching medium are considered as the most important;
5. whether the evaluators try to instantly externalise their spontaneous ideas on a medium by means of a sketch, even if they do not readily have a piece of paper;
6. whether a paper-based sketch is sufficient for the participants to visualise a design concept which they may think of when outside their usual design workplace;
7. whether a tool that remotely and automatically generates a 3D virtual model from a sketch is considered beneficial;
8. whether the evaluators would carry more than one colour pen instead of only one, if this would allow them to remotely obtain a coloured rendered 3D virtual model from a paper-based sketch;
9. what approach (if any) would the evaluators prefer to use to remotely obtain a 3D virtual model from a sketch.

To reduce subjectivity, the term 'sketch' was defined at the outset of the survey. It was explicitly stated that a *'sketch'* refers to a freehand drawing which is drawn in conceptual design without any drawing instruments and which is made for oneself to express his/her ideas.

The next section discloses and compares the key evaluation results obtained by students and designers. Due to the small sample sizes obtained at the time of writing, students of product design and of mechanical design engineering were grouped together. Similarly, results obtained by engineering designers and industrial designers were combined for analysis purposes.

6. Survey evaluation results

The results reveal that the majority of designers (79%) think of design concepts even when they are not in the design office (see Figure 5a). In order to have a deeper insight into this occurrence, designers were also asked how frequently they thought of design ideas during a period of two weeks from the date on which they received the questionnaire. As shown in Figure 5b, 27% replied 'almost everyday' (7 to 10 days) and 55% 'occasionally' (3 to 6 days). Results in Figure 5c show that 89% of students also think of design ideas outside their usual design workplace. Students were also asked where do they usually carry their design work. Figure 5d reveals that they practice design more at home (47%) than in the design studio (37%). It must be noted that *all* the students were carrying out a design task at the time when the survey was conducted.

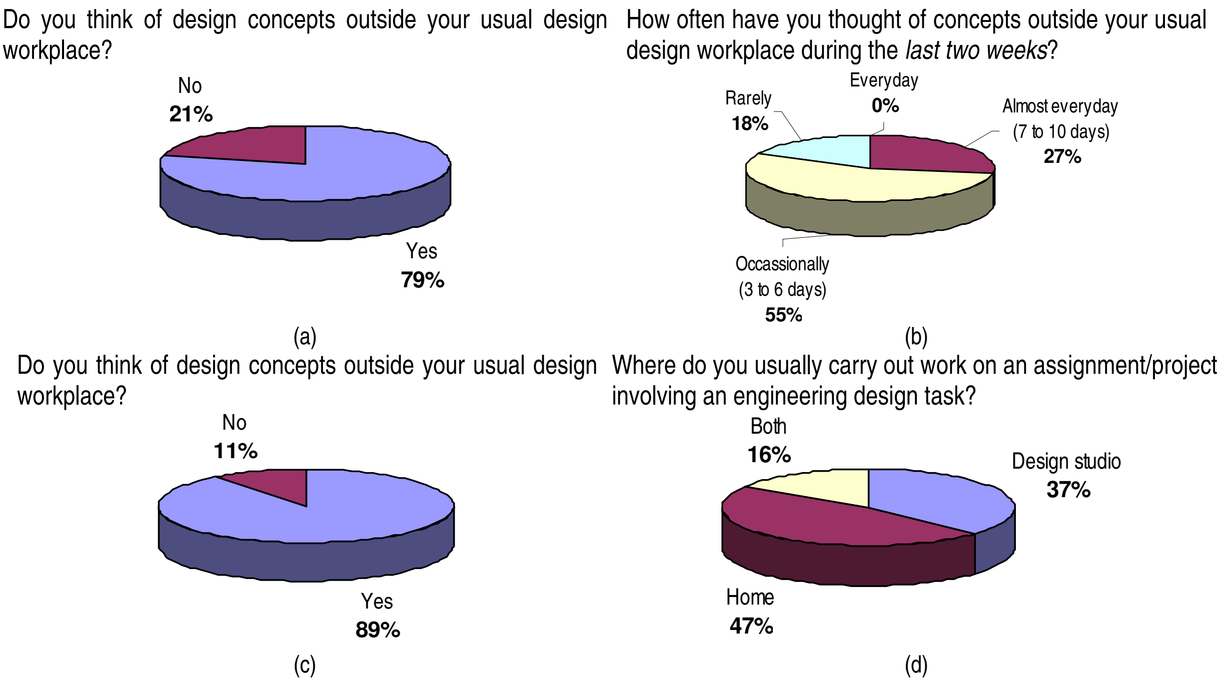


Figure 5. Results of designers (a), (b) & students (c), (d) on design activity practiced outside design workplace.

Evaluators who replied 'yes' above were asked to rank typical situations in which they usually think of design concepts. A rank of '1' had to be assigned to the *most* common situation (see Figure 6) - for designers it resulted to be 'at home after work', (average rank, r = 2.45) whereas for students it was 'when travelling in car, train, etc.' (r = 1.76).

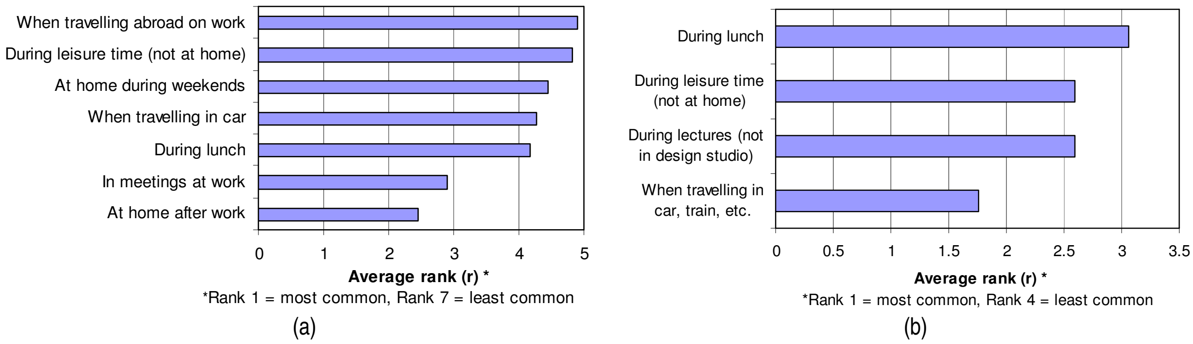
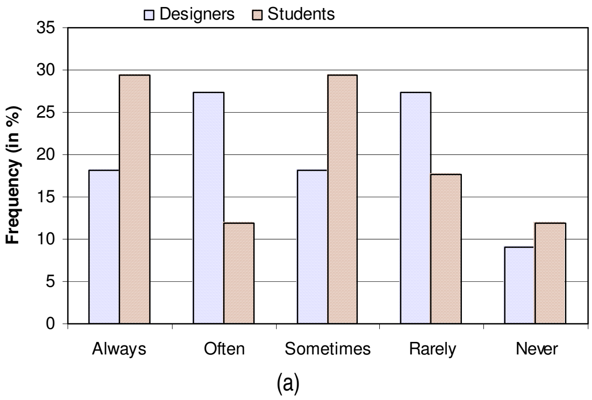


Figure 6. Situations in which (a) designers (b) students think most of concepts outside their design workplace.

Furthermore, these evaluators were asked to indicate how often they carry a paper and a pen to sketch any spontaneous ideas. Figure 7a shows that 18% and 27% of designers replied that they do so 'always' and 'often' respectively. The respective percentages for students were 29% and 12%. This implies that more than 40% of both designers and students carry these traditional sketching media on a regular basis.

Evaluators who replied in the affirmative to the question shown in Figures 5a and 5c, were asked to rank in order of preference, four portable sketching media, namely 'a sheet of paper', 'sketchbook', 'Tablet PC' and a 'Personal Digital Assistant' (PDA). Rank '1' refers to the medium which is preferred *most* for mobile design work. Figure 7b compares the average rank for each medium obtained by designers and students. It can be observed that 'a sheet of paper' (r = 1.55), followed by a 'sketchbook' (r = 1.73) were the most two preferred sketching media by designers. Students preferred most 'a sketchbook' (r = 1.53), followed by 'a sheet of paper' (r = 2.12).



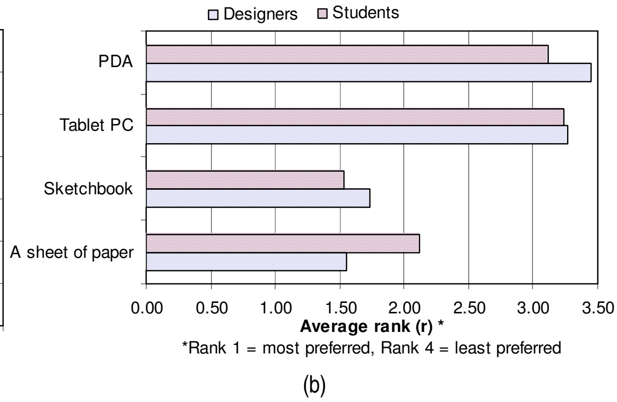
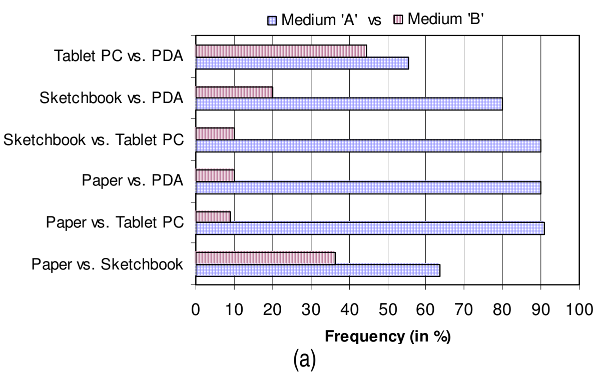


Figure 7. Comparison of results on (a) frequency of carrying paper & pen (b) different sketching media.

In order to investigate further why one type of portable sketching medium is preferred over another, the above four media were also compared between each other as indicated in Figure 8. For each comparison, (e.g. paper vs. PDA) the evaluators had to select the most preferred medium and also provide reasons for their selection. Clearly from Figure 8, the majority of both designers and students preferred conventional sketching media over digital media. The most common reported reasons reflected the advantages associated with traditional sketching media, in particular portability and availability.



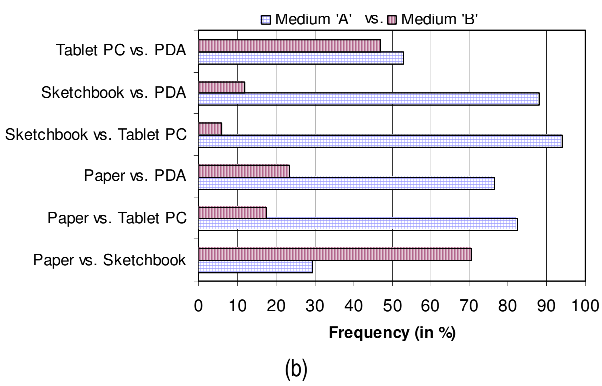


Figure 8. Preference of (a) designers (b) students between comparisons of sketching media of Figure 7b.

These evaluators were also asked to rank in order of importance four characteristics of a portable sketching medium (see Figure 9). The characteristic with a rank of '1' refers to the *most* important. Results in Figure 9 show that a sketching medium with no power requirements (r = 2.18) and which is readily available (r = 2.27) is mostly preferred by designers (see Figure 9). 'Availability' (r = 2.06) followed by 'lightweight' (r = 2.29) are considered as the two most important characteristics by students (see Figure 9).

All the survey respondents had to indicate the extent to which they agree or disagree with a set of four statements relevant to survey objectives (5) to (8) listed in Section 5 (see Figure 10). A 5-level rating was employed, whereby a score of '1' implies that the evaluator *strongly agreed* with a particular statement. Results in Figure 10 reveal that compared to designers, students are more likely to instantly externalise their spontaneous ideas on a medium, even if they do not readily have a piece of paper (i.e. s = 2.37 vs. s = 2.71 of Statement 1). Both designers and students tend to agree that a paper-based sketch is sufficient for them to visualise a design concept which they may think of outside their usual design workplace (see results for Statement 2). It can be also noted that students, more than designers, consider as beneficial having a tool which provides them with 3D virtual models generated automatically from sketches (i.e. s = 1.74 vs. s = 2.71 of Statement 3). Results relevant to Statement 4 show that designers tend to disagree (s = 3.5) to carrying more than one colour pen instead of only one, albeit this would allow them to remotely obtain rendered 3D virtual models from paper-based sketches. Students showed less opposition to this suggestion (s = 2.74).

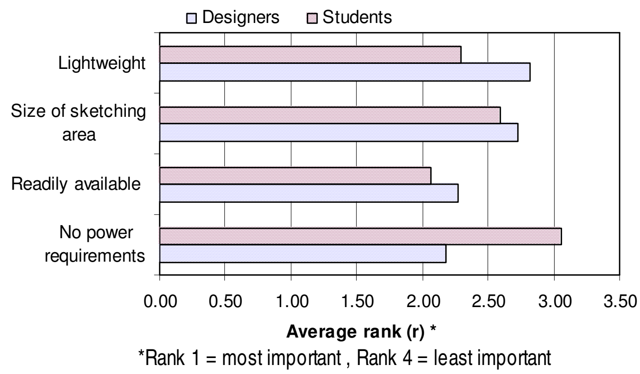


Figure 9. Results on sketching medium characteristics

No.	Statement
(1)	*If I spontaneously think of a concept outside the design office, I will try to instantly externalise it on a medium, even if I do not readily have a piece of paper with me.*
(2)	*A paper-based sketch will be sufficient to visualise a design concept which I may think of, outside my usual design workplace.*
(3)	*It would be beneficial to have a tool which provides me with a 3D virtual model generated automatically from a sketch drawn outside the design office.*
(4)	*I do not mind if I had to carry with me more than one colour pen instead of only one, if this allows me to obtain colour rendered 3D virtual models from paper-based sketches drawn outside my design office.*

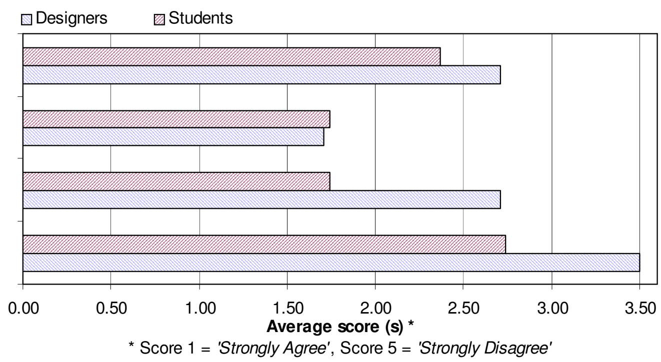


Figure 10. Results on statements relevant to survey objectives (5) to (8) listed in Section 5

Two approaches for obtaining remotely and automatically 3D geometric models from freehand sketches were proposed to the evaluators (see Figure 11). The C_PAD approach described in this paper was contrasted with that of using a portable, lightweight electronic device, i.e. approach (ii). As illustrated in Figure 11, a high proportion of designers (57%) and of students (63%) would prefer the second approach. Various evaluators, who opted for approach (ii), commented that the proposed device would have more functionalities and would be more precise and easier to use than the cameraphone-based approach. On the other hand, reasons reported by evaluators favouring approach (i), explicitly reflect the inherent advantages of the paper medium.

Suppose that you were provided with:

(i) a paper-based medium and a cameraphone or a;
(ii) portable, lightweight electronic device

to obtain 3D geometric models from freehand sketches, drawn outside your usual design workplace. Which approach would you prefer to use?

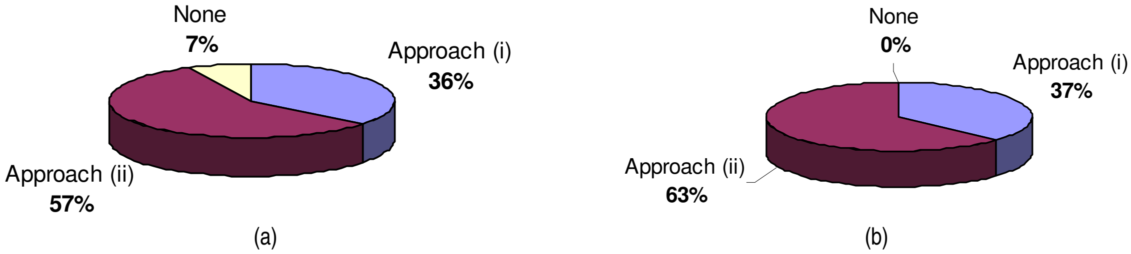


Figure 11. Preference of (a) designers (b) students between two approaches proposed for a mobile CAS tool

7. Discussion

Evaluation results demonstrate that *independent* of their design background, the majority of the survey respondents also think of design concepts away from their usual design workplace. Additionally, a high percentage of both designers and students frequently carry a paper and a pen to sketch their spontaneous design ideas. Despite the advent of digital devices which can be utilised to emulate a paper-based medium, survey results showed that independently of their background, the majority of the evaluators would still prefer paper for mobile design work. Collectively these results justify the emphasis made earlier in Section 1 on the importance of *paper*-based sketching vis-à-vis digital sketching, and hence the C_PAD approach taken. The fact that only 7% of designers stated that they would not use any of the two proposed approaches (see Figure 11) suggests that a mobile CAS tool would be useful.

On the other hand, the results in Figure 11 also advocates that further investigation is required to assess the practicability or otherwise of using a C_PAD system, instead of using a portable and lightweight electronic sketching devices. In addition, as future work, further investigation is needed to assess the benefits that a mobile CAS tool offers in practice to designers and to other potential users. This can be deduced from the results illustrated in Figures 10. For instance, results obtained for Statement 2 have indicated that evaluators are likely to agree that a paper-based sketch is sufficient for them to visualise a design concept outside their usual design workplace. From the experimentation with a preliminary prototype C_PAD tool, it is evident that further work is required to overcome its present limitations. While the factors mentioned in Section 4.1 can be controlled to some extent, MMS transmission rate is uncontrollable and difficult to anticipate, thereby making the tool effectiveness unpredictable [1]. However with further advancements in mobile communication technology this limitation may be resolved.

8. Conclusions

This paper contributes a novel approach of how designers can obtain, away from their design office, 3D virtual models directly from paper-based sketches. The evaluation results obtained collectively support the C_PAD approach being developed. Future work is however needed, in particular to evaluate this approach with others for developing mobile CAS tools.

Nevertheless, given the ever-increasing use of cameraphones, the proposed C_PAD system provides a step towards making 3D modelling applications easily accessible to a wider range of users. This would improve education in 3D modelling, increasing awareness and appreciation of 3D modelling with the general public, and enabling different people to realise their talent for 'form design'. Moreover, due to its simple sketch-based UI, the C_PAD system proposed in this paper provides a user-friendly means for its users to globally communicate their early form design concepts. This can potentially accelerate the emerging trend of 'customer-driven' design as design ideas can be quickly exchanged by customers with other stakeholders involved in the product development process.

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Corresponding author:
Mr. Philip J. Farrugia
Concurrent Engineering Research Unit,
Department of Manufacturing Engineering, Faculty of Engineering
University of Malta
Msida, MSD06
Malta
Tel:+356 2340-2045
Fax: +356 21 343577
E-mail: pjfarr@eng.um.edu.mt