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Rapid and Flexible Graphical Communication for Conceptual Design*

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Professionals who work in conceptual design spaces have very different communication needs than those who work in design spaces for detail design. In the conceptual design stage, people, ideas and technologies are typically mobile, fluid and distributed—even when relatively co-located. While our approach is exploratory, we hope that this endeavour can help organize a new family of techniques and ideas in the engineering design community. Some key concepts that we deploy are conceptual design, informal graphics, rapid graphical communication and optimal ignorance in the graphical communication process. We will illustrate what we mean by describing a few new methods such as feature-based sketching and edited/annotated photos. We will also discuss preliminary trials using new mobile technologies, such as digital ink pens since 2004, and our research plans for student design teams using Tablet PCs.

Keywords: conceptual design; informal graphics; rapid graphical communication; optimal ignorance; feature-based representations; digital link

INTRODUCTION

ENGINEERS WHO WORK in conceptual design have very different CAD and graphics needs than those who work in detail design (Table 1) [1]. We seek to enhance communication during conceptual design and will illustrate what we mean by describing methods such as feature-based sketching and edited/annotated photos and by examining digital ink technologies such as digital ink pens and Tablet PCs. We have been exploring these since 2004 in the context of a program offering an introductory engineering design course to about 1000 students a year and upper division courses in innovative and global design. Our focus is on the conceptual stage of design where people, ideas and technologies are typically mobile, fluid and distributed–even when relatively co-located. Some key concepts we deploy are conceptual design, informal graphics, rapid graphical communication and optimal ignorance in the graphical communication process.

The *2006 Horizon Report* [2] on emerging technologies in higher education identifies six areas that they consider drivers of change in higher education, including dynamic knowledge creation and social computing tools, and processes are becoming more widespread and accepted. 'Social computing is essentially the application of computer technology to facilitate collaboration and working in groups' [2, p. 10].

Mobile and personal technology are increasingly being viewed as a delivery platform for services of all kinds.

On social computing, they also note that 'The application of computer technology to facilitate interaction and collaboration, a practice known as social computing, is happening all around us. Replacing face-to-face meetings with virtual collaboration tools, working on a daily basis with colleagues a thousand miles away, or attending a conference held entirely online is no longer unusual' [2, p. 5]. We have also been running cross-national design teams for 8 years using information technology and have done so with students in five different countries [3]. Our aim has been to replicate the distributed teams of the global economy.

The idea that engineering design is a social process is arguably the most significant development in design over the last few decades [4, 5]. It is the central tenet of the new Engineering Design Program at Penn State University [6], which practices integrated engineering design: that process that integrates the disciplines and people required to address a specific design problem. We think the social, physical and symbolic (informational) features of collaborative design environments (CDEs) can shape both the processes and outcomes of design. Hence our interest in conceptual design communications (the social environment) and in the use of new communication technologies (the symbolic environment) such as digital ink.

Historically, engineering graphics has focused on the methods of communication needed in the detail design stage, which has led to the widespread adoption of mid- to high-end CAD software in education and industry. Here, we wish to move upstream in the design process and consider the conceptual stage of design, which we believe is both important, since it generates the most influ-

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Table 1. Graphical communication in conceptual and detail design stages compared

Graphical communication feature	Conceptual design	Detail design
Objective of design phase	Real-time* interactive communication to transfer ideas and information for concept generation	Sequential** communication of drawings, specifications for manufacturing/ construction
Speed	*Fast: minutes, hours, days	**Slow: days, weeks, months
Knowledge stasis	Largely fluid	Largely fixed
Completeness with details	Undesirable	Mandatory
Multi-modal format and multi-disciplinary content	Yes	No
Supports creative expression	Yes	No
Ambiguity tolerated	Yes	No
Knowledge transfer within teams or across teams	Within (Integrates knowledge)	Across (Integrates organizational units)
Team members mobility and the degree they are distributed	High	Low
Degree of formality (fixed norms, symbols, languages, methods and conventions)	Low	High

ential ideas for the design and often neglected. Conceptual design is a stage where the amount of information flowing, the diverse nature of that information and the speed at which it flows are far greater than in detail-design. It is also a stage where the information is of many different forms that are hard to capture via a single graphical mode or text format. In addition, information flows during conceptual design need to promote, rather than constrain, creativity. A comparison between communications in the conceptual and detail design stages is shown in Table 1.

CONCEPTUAL DESIGN COMMUNICATION

A major priority in conceptual design is to optimize the communication process. To do this we will borrow the concept of 'optimal ignorance'. This means being clear about what you do not need to know (and what you do need to know) in order to make a decision. This term was applied in political science some time ago [7] and in many places since. Much further back in time, the real origin is Occam's Razor: 'do not assume anything you do not have to', after William of Occam, a 14th century logician and Franciscan friar in England: '*Pluralitas non est ponenda sine necessitas*' (Plurality should not be posited without necessity) [8]. In information theory this idea is expressed as minimum message length [9], the communication model generating the shortest message is most likely to be correct. We think that in graphical communication theory this translates into something like the smallest amount of images and text with content still sufficient to achieve the objectives of the communication: the Rapid Graphics Principle (RGP).

The main problem with the RGP is that of parsing: excluding essential information. In general, RGP is applied during a time when the design knowledge base is growing. Therefore, exclusion has as much to do with knowledge not yet explored, as it does with parsing the existing information base. In addition, the knowledge that is included is often a 'signpost' to what has not yet been included. For example, indicating that a sensor and a feedback control loop is required takes a quick sketch and notation and not a full account of available sensors and how they work, but it is understood that many such accounts exist. Perhaps adopting the axiom that short notations should be adequately referential would help solve the parsing problem.

Ideally, graphical communication during conceptual design is a fast process. Imagine a brainstorming session, for example, where someone has a new idea and says 'I will send you the CAD drawing next week to show you what I mean'. Therefore, rapid graphical communication, which conveys only essential information, is the key for conceptual design. There are many techniques that are used for this, but we think only one, traditional sketching, is being taught and it is being usually done without considering the revolution underway in digital ink.

We continue with a functional breakdown of the communication process, some methodologies that support the RGP and an examination of some digital ink technologies with preliminary data on student use of them.

INFORMAL DESIGN GRAPHICS

Almost all texts in engineering graphics have included the words design and communication in their book and/or chapter titles [10]. In addition, Lockhart and Johnson, for example, explicitly link design process stages to particular graphics tools following the same line of thought that we do [11]. However, for conceptual design, they do not go beyond traditional graphical techniques for sketching. As a preliminary rubric, we see five functions on which we need to focus:

- discovery: idea generation and information retrieval;
- capture: record ideas and information;

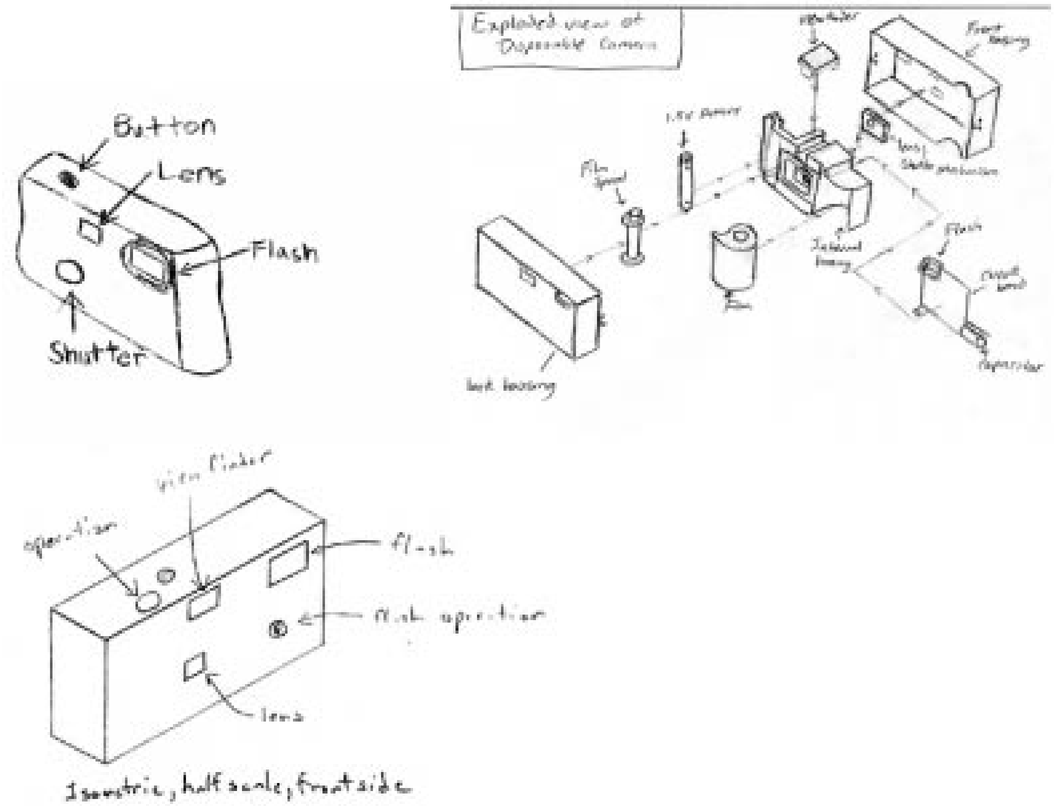

Fig. 1. Feature-based sketching (sketched by Justin Doty).

- communication: fast and flexible (multi-modal) communication of ideas and information;
- knowledge management: file management for the conceptual design database to store ideas and information;
- iteration: for each of the above the iterative nature of design must allow for changes to be made swiftly and easily and incorporated into the existing methods for recording communications and file management processes.

If we apply the RGP to sketching using traditional methods, the first thing we can find is that sketching done well (artistically) is time consuming. A decade ago, following the work of Betty Edwards for teaching recalcitrant beginners [12], we experimented with making artists out of engineering students in order to promote sketching in engineering. While this worked well, the drawings took too long to do. Our new approaches include new tools: specifically digital ink technologies such as pens and Tablet PCs and new methods, including a widely used, if unnamed, technique that we call feature-based representation (FBR).

FEATURE-BASED REPRESENTATIONS (FBRS)

This method comprises traditional sketches where the designer stops after blocking out the main features and adds additional description by writing a text description of the feature. The RGP principle is: do not transmit information that the recipient does not need in order to act (e.g., make a decision). The first corollary is: always include everything that is necessary to make the decision either graphically or in text. The second corollary and the purpose of a feature-based representation is to communicate well in the shortest possible time; hence, less is more. The use of FBR, then, is a natural expression of this (Fig. 1).

EDITED PHOTOS AND VIDEOS

This traditional method is also widely used but unnamed because of its obvious nature. It usually requires only elementary skills in such software as Adobe Photoshop, but it is so effective that it should be taught no matter how briefly. For example, during product dissection, an edited photo with captions for the parts may be the best guarantee that the product will be successfully reassembled (Fig. 2). There are many variations to the two methods displayed. For the same process, a few key photos during disassembly or even a video or two would also be valuable. Manual sketches or CAD would be slow and undesirable modes of communication for the example shown below. Moreover, edited photos go directly into the digital record.

Fig. 2. Keeping track of product dissection of a camera using edited photographs. 1. Inner Housing and Aperture; 2. Flash and Printed Circuit Board; 3. Battery (1.5V AA); 4. Viewfinder; 5. Exposure Remaining Advance; 6. Film Advance Bracket; 7. Thumb Wheel; 8. Spring; 9. Ring Adapter; 10. Front Housing; 11. Lens Housing; 12. Exposure Remaining Wheel; 13. Shutter Button and Support; 14. Shutter Spring; 15. Interposer; 16. Shutter Activator; 17. Shutter; 18. Lens; 19. Rear Housing; 20. Film (35 mm Film 27 Exposures); 21. 120 MicroFarad Capacitor.

DIGITAL INK TECHNOLOGIES

Digital ink refers to the process of sketching or writing text digitally so there is no need to convert manual sketches to the digital domain by scanning or the use of digital photography. The means of doing this varies from using a stylus on an active surface of a Tablet PC or graphics tablet to digital pens that use a paper tablet with an optical grid to create digital files. Digital ink is attractive because the conversion process from paper to digital can be tedious, requires additional time and technology and the quality can be disappointing. Moreover, it is mobile and this means no waiting until there is access to a digital medium for recording. Hence, digital ink supports the rapid graphics communication principle and some digital ink technologies can incorporate color, text, line value and other features that help to match some traditional skills.

Digital ink technology is being pursued aggressively in medical and insurance fields where patient and customer information can be entered directly into a computer while leaving a hard copy in the hands of the agent and or customer or patient [13, 14]. Both pens and Tablet PCs are used. The impetus is a big savings per coding transaction and an expectation of better quality and more accessible data [15, 16]. We think it has similar value for design teams during conceptual design.

We first evaluated a 6 inch $\times$ 8 inch WACOM Graphire Tablet [17]. It is slightly more expensive than the digital pens described below. It worked well and would allow decent original sketches and tracing of existing images. However, it did not leave a hard copy on the Tablet and we were disappointed in the way it mapped onto the computer display. We had no control and it was not an efficient use of the display. Since the high-end Tablets are expensive and designed for artists and graphic designers who are not typically using the RGP, we decided to try digital pens that work without Tablets.

The variations in digital pens are characterized by some key parameters:

- whether or not they need to be connected to the computer when they are used;
- whether or not they simultaneously display on screen;
- whether or not they also create a physical copy of the sketch (real and digital ink);
- how they performed coordinate referencing (use a base station or a digitized paper pad);
- whether or not they store images in the pen;
- the quality of the file management software.

We tried several models such as Ink Link and i-pen pro and then purchased 40 Logitech io pens [18] that use digitized paper away from the computer and can store up to 40 images for download through a USB connection to a computer with the software loaded. We thought this model would maximize the opportunities for student use and let them use them as they wished. The pens were primarily distributed to lower division students. Other pen models have appeal such as those that display the sketch synchronously on-screen (the Logitech io pen does not), which could be very valuable for group work and class discussion where a computer is available.

The students loaded the software on their per-

Table 2. Digital pen and sketchbook use compared

	Recording ideas with sketchbook	Conceptual design communication with sketchbook	Recording ideas with digital pen	Conceptual design with digital pen	Would like to own digital pen
# say Yes	21	27	10	42	43
Number of students	22	29	11	48	76
Probability	95.45%	93.10%	90.91%	87.50%	56.58%

sonal computers and were encouraged to use their pens a lot, which most did since they viewed the pen as a free loan of a neat toy. The pens were found to be very useful for homework assignments and design concept sketches. In other words, it is a technology that may be integrated into their lives. The students liked the easy software setup and file management capabilities such as editing previous sketches, converting to jpg, scalable vector graphics, cutting and pasting into documents and emails, or posting to the web. The pens were frequently used for class notes and preparing emails for sending later when they were back at their computers. The hard copy was appreciated. A small drawing assignment in obliques turned out very well. The digital pen is an asynchronous device that allows any time anywhere rapid note taking and idea recording. It is easier to carry than laptop, while lacking the functionality of a laptop. In another trial still underway, we installed them at fixed computer stations in a laboratory environment and found that the convenience appealed to the students. This suggests a non-mobile use of the pens whereby they could be compared with the sketch and scan method and with computer sketching software such as SketchUp [19].

Most students reacted positively and some were very enthusiastic. Many felt the cost of ~US$100–200 was prohibitive. Since this pen comes with special paper that is ~US$10/pad, one might expect that if the pen became popular, the price would come down and the revenue streams for the paper pad would be the marketing focus. However, we might soon see pens based on inertial technology that are 'pad free' and work on any paper and this would make existing technology obsolete [20]. Even students who were deterred by the cost of the pen and the paper described frequent use and an appreciation of the convenience. Other negative comments were that it is too large (the newest model is smaller), that it only used the color blue (this may be changed by editing in the new version) that it did not have effective character recognition (some thought it was OK and the new version is better), and it did not work well with a straight edge.

STUDENT USE OF DIGITAL PENS

We have data from 54 students collected from the Fall of 2004 until the Spring of 2006. Of these students, over half said they would like to own such a pen if at a reasonable price. What they thought was reasonable usually fell in the range of US$15–40, well below the US$100–200 range for new pens (old pens can be found sometimes on the web for much less). At present, very few students seem likely to buy one, but most of these problems with the pen are probably tractable and if the pens were redesigned and the price dropped to under US$40, we think that a market would appear among engineering students. Our data imply a very large consumer market that will not be realized unless someone takes a risk on greater volume at much lower prices very soon before the next generation devices appear.

The 83 students who participated in the exploratory study across five semesters did so largely on a volunteer basis, so we will not use a statistical analysis although we have rigorous studies under development. Among these, 54 students evaluated the digital pen and, in one semester, 29 students evaluated the use of a traditional sketchbook as a comparison.

Table 2 contains results from the students to evaluate either a digital pen or a sketchbook. For students who evaluated sketchbooks, more than 90% of students think sketchbook is a good tool for recording ideas as well as for conceptual design communication. For students who evaluated digital pens, slightly more than 90% of students think the digital pen is good for recording ideas; 87.5% of students think the digital pen is good for conceptual design communication. There were more students evaluating the digital pen than students evaluating the sketchbook since the latter was only evaluated in one semester. These data confirm the student qualitative observations that the pens were acceptable but unnecessary. The new inertial pens will be much more mobile and convenient and may change this assessment.

The cumulative data over five semesters revealed the following student assessments of the digital pen with regard to usage and its strengths and weaknesses.

Five most used digital pen features in order of the most used to the least used:

- recording notes and drawings;
- loading notes and drawings to computer;
- post-it feature;
- exporting notes and drawings to MS Word;
- note feature.

Five digital pen best characteristics in the order of most mentioned to least mentioned:

- the capability to upload notes and drawings to computer for storage, editing and distribution;
- the digital pen is user friendly and simple to use;
- a variety of different functions (such as email, post-it, calendar) makes things more convenient;
- portability;
- the digital pen has easy setup and installation.

Five digital pen worst characteristics in the order of most mentioned to least mentioned:

- the digital pen is bulky;
- it operates on a special and expensive paper;
- handwriting recognition is not reliable;
- it comes with different equipment;
- the digital pen is expensive.

In terms of our five categories of conceptual design communication: discover/generate, capture/record, communication, knowledge management and iteration, we see no difference in the first two functions used by the students for sketchbooks and digital pens. Most students think that both the sketchpad and the digital pens are good tools for recording ideas and for conceptual design communication. However, after that some differences emerge. The sketchbook seems to be preferred for immediate (synchronous) communications and iterative editing and the digital pen for deferred (asynchronous) communications. In addition, the sketchbook is preferred for a drawing and sketching medium. The ancillary objective of capturing thoughts any time anywhere can be met by either the digital pen or the sketchbook and probably needs a change in behavior more than it needs a particular medium.

A PILOT STUDY OF PEN USE WITH GRAPHICS

However, pens may also provide beneficial affordances within a group producing sketches synchronously, as indicated by a recent pilot study that we did. This study was implemented to investigate the effects of Logitech io pen use on student performance in assessing the qualities of conceptual sketches. All subjects were first-year engineering undergraduates taking the same introductory course and each received instructional material on preparing and assessing conceptual sketches, which material varied depending upon the treatment to which the subject was randomly assigned. In addition to the control group which did not receive instruction, there was a treatment group that received only the instructional content, another that received the content accompanied by an opportunity for practice of an exercise related to the content and the last, the most social in nature, that received the content and the practice and also feedback in the form of a comparison to an expert's performance of the exercise. Presented as print-based text for subjects to read outside of class time, these variations in treatment correspond to learning conditions in instructional design theory and furthermore represent increasingly social representations [21] of instructional delivery, approaching or suggesting aspects of face-to-face instruction to learners without them actually having that contact [22, 23].

Following the treatment, some subjects used the Logitech pen in preparing sketches for both self-assessment and peer assessment, while the rest employed conventional pens or pencils. Subjects' assessment performances were scored as their agreement with independent scores of the sketches on a rubric that had been successfully tested for reliability. Two findings are reported here (alpha level of 0.05 was used for all tests). The first is that the most social treatment had a large and statistically significant effect as measured by assessment performance in comparison to the control group. But of possibly greater interest, although not statistically significant for the overall sample size ($n = 39$), was the consistent trend across all treatments, including the control, for groups using the Logitech io pen to have a higher mean score by about half a standard deviation more than those that did not use the pen. Thus, comprehension and assessment of the information conveyed through conceptual sketching improved with pen use. Why this happens is a matter for further study.

TABLET PCS

A series of experiments over the last 20 years that were mostly failures has led to a proliferation of slates, Tablet (convertible) PCs and similar devices [24]. These are mostly successful and there is a clear trend towards mobile computing technology that is smaller, lighter, more interactive and with a longer battery life. Tablet PCs are now actively studied and deployed in higher education [24]. A trial with 400 students using Tablet PCs at the University of Virginia found that Tablet PC use led to better understanding, memorizing and filing and organizing [25]. Students in all three fields tested: biochemistry, statistics and psychology, all preferred the Tablet PC to a laptop and the biochemistry students did so by a margin of 4:1. The students also preferred One Note on the Tablet PC to other software for recording notes, organizing them and sharing them with others. These functions represent three of our five categories and the other two, idea generation and information gathering and iterative editing facility were not measured explicitly.

At Penn State, we have begun using the Tablet PC for instruction including a wireless connection to the LCD display. We have received support to deploy the Tablet PCs with our students. Wireless communications mean ubiquitous access. Tablet PCs mean a portable and dynamic learning and communication environment. We believe that pervasive mobile computing is promising for conceptual design. For example, students can use the Tablet PC to interview customers and users to identify needs and can sketch and communicate ideas spontaneously. Concepts can be developed quickly with digital ink and marked up and annotated by team members in a group process. These are processes that are currently largely paper based or simply oral. We will report results of our Tablet PC studies (outlined below) in the future.

The technological infrastructure of design is critical to the social dynamics of the design process. Designers need an environment that supports virtual communities of practice [26], facilitates multiple forms of rapid communication and promotes creativity. As team member mobility persists into the design embodiment stage we note the availability of mobile peer-to-peer CAD software such as *Alibre Design* [27].

NEW RESEARCH PROGRAM

In May 2006, we were funded by Hewlett Packard to explore student use of their Tablet PC in design teams in the honors section of the introduction to engineering design course. This class has 24 students in six teams of four, with two design projects that run sequentially for most of the 15-week semester. All the 12 students in three teams will take a Tablet PC for their own use for 6 weeks in the first design project. The tablet deployment will be reversed for the second 8-week design project. In two regular sections of the introductory design course, we will use the same model but with one Tablet PC per team for presentation modes of communication among team members and to the whole class. We plan later studies using the Tablet PC in capstone design teams.

With this experimental design to study the effect of Tablet PPC use, our metrics include:

- Student Productivity—how many ideas are generated in a given amount of time? This will be measured using a screen-capture utility (such as Camtasia Studio), through self-reports and through observation.
- Student Efficiency—related to productivity, we expect that Tablet PCs will allow students to use their time more efficiently. This will be measured through the analysis of student design-journals and team minutes.
- Student Motivation—motivation is instrumental in any learning situation. We will measure the effect of Tablet PC use on motivation based on Keller's ARCS model ('Attention, Relevance, Confidence and Satisfaction'). Each of these aspects will be measured through an online survey at various points in the semester.
- Student Performance—performance in our context is defined as project quality, team communication quality and team function. Project quality will be determined through use of an external group of raters who will be unaware of Tablet PC use as a variable. Team performance will be provided via traditional team measures.
- Student Satisfaction with Tablet—general uses, assessment of software, design uses, comparative advantage and 'likelihood to buy' will be assessed via student survey and a focus group.

IN CONCLUSION: THE ACTIVE RESEARCH QUESTIONS

We are convinced of the high level of compatibility between what digital ink technologies offer and what conceptual design communications needs. Some of the research questions that are guiding us are:

- Do any digital ink technologies (DITs) aid in idea generation (or information retrieval)?
- Do any DITs aid in idea expression?
- Do any DITs aid in the communication of I&I (ideas and information): (a) rapid; (b) flexible; (c) expressive; (d) iterative notes—and hence idea and project development; (e) successful—does the receiver correctly understand what was conveyed and does the receiver correctly perceive the importance to the sender of what was conveyed?
- Do DITs facilitate I & I recording?
- Which DITs are best at iteration?
- Do students have positive attitudes towards DITs?
- Do DITs raise productivity in idea generation, information retrieval, inter-group communications, and project quality (grades and other assessments of the projects)?

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