DIGITAL SKETCHING IN A MULTI-ACTOR ENVIRONMENT

ALEXANDER KOUTAMANIS
Delft University of Technology, The Netherlands

Abstract. The paper discusses digital sketching in the framework of multi-actor design processes. The discussion focuses on the registration, analysis and feedback of annotations made with digital pens on prints of CAD drawings and early stage sketching, both in synchronous and asynchronous situations. It is proposed that the main advantages of this form of digital sketching are the registration of syntagmatic information and the ability to distinguish between different actors. This makes it possible to identify meaningful entities and clarify issues of common authorship or emergence.

1. Digital Sketching and Multi-actor Design Processes

Sketching is one of the means architecture has been successfully employing for the registration and processing of design information. The success of sketching is based on the immediacy, informality and familiarity of sketching procedures and representations, as well as the flexibility and adaptability of means involved (i.e. using practically any drawing implements available on any medium). The main problems of sketching lie in the parsing and disambiguation of its typically dense and multilayered products, especially when they involve more than one sketcher or longer periods of time. The extensive use of video capture in protocol analyses of design situations is indicative of the complexity and tenacity of these tasks. It is arguably for such reasons that digital sketching has yet to come of age. Affordable digital means cannot capture the flexibility, adaptability and mechanical feedback of analogue sketching tools, while the interpretation and dissemination of information in a sketch cannot rely on the exchange structures and information standards used for drawings and models.

Sketching studies tend to focus on the generative and the representational, i.e. the processes (and products) of form generation and the depiction of real or realistic scenes. This paper concentrates on different applications where sketching plays an equally important role. We examine digital sketching in the context of multi-actor design processes. Situations where several parties are actively involved in a process, taking decisions,

J.S. Gero (ed.), Design Computing and Cognition '06, 103–121.

creating and amending forms, exploring complementary issues and frequently sharing the same media and representations put additional demands on the interpretation of sketches and their transformation into other representations. Moreover, with the proliferation of digital information in all aspects of professional and private life and the ubiquity of mobile information processing we expect that group processes and multi-actor design environments will become increasingly popular and feasible. Our exploration of digital sketching in these processes and environments also focuses on sketches as annotations of existing design representations. The main reason is that such annotations are quite common and frequently confusing, especially when several actors representing a variety of aspects or viewpoints and contributing overlapping parts of the design are involved.

The following figures present an example that illustrates the problems of group annotations. Figure 1 is a detail from a drawing used during a discussion on the refurbishment of a university building. The seven participants used several media, colors and symbols to put their ideas on paper. The registration of decisions, alternatives and variations varied from inconsistent to chaotic. When the participants met again one week later, reconstruction of the discussion and its conclusions on the basis of the drawings was expectedly biased and tainted by individual viewpoints and opinions. The participants' recollection of actual decisions and conclusions was hazy and inconsistent. One striking example of accidental emergence concerns the coffee machine niche –indicated in the initial proposal, Figure 2, by a horizontal square bracket ([)– that should be placed somewhere in the circulation/reception area. The participants had different ideas concerning the location of this facility and its relations to other areas (e.g. waiting area, information corner etc.). Many proposed alternatives involved rotations and reflections of the bracket form. The superimposition of these alternatives produced accidentally what appears to be a square form in the most popular place for the coffee-machine niche, Figure 3. When asked about this square one week after the meeting, two participants could not recollect what it signified and another two were convinced that it was a cubicle with an unknown function and an unknown originator but nevertheless a useful feature for presentation and orientation purposes.

Digital information processing should resolve such problems by identifying different elements, contributions and intentions. However, it is not always possible to record who did what and when (let alone why). Even with advanced registration systems (including versioning control), many discussions and changes are soon forgotten, reduced to their final state (no history) or even fused together in unexplainable cases of accidental emergence. In this respect digital information processing has still much in common with analogue situations, both in synchronous and asynchronous modes. As the discreteness of information items remains largely unrelated to user input, we lack the means necessary for parsing digital sketches.

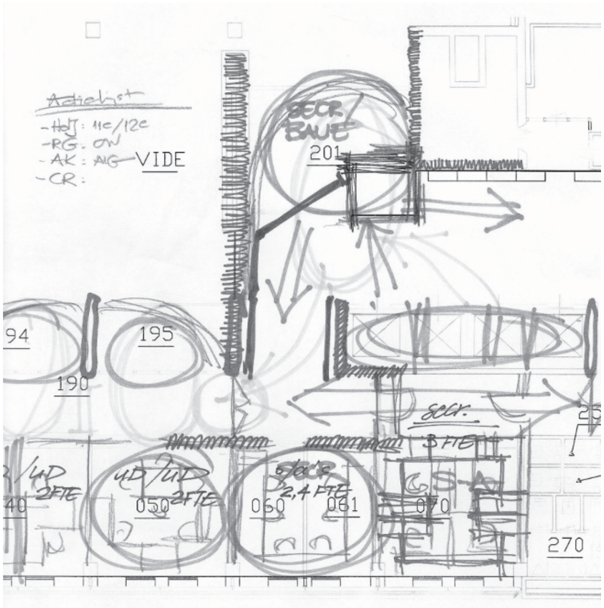


Figure 1. Annotated print of CAD drawing (detail).

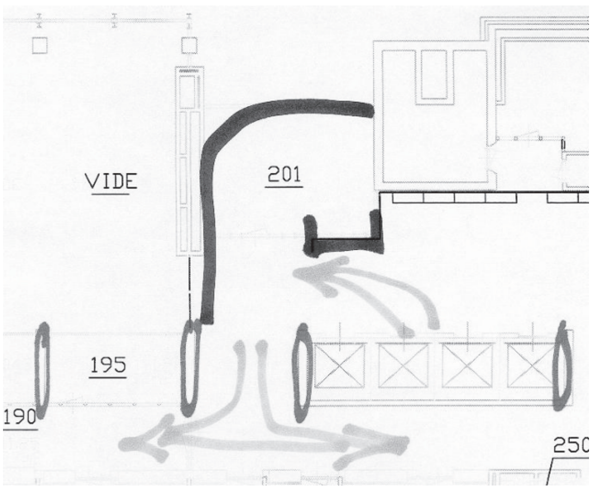


Figure 2. Initial proposal with bracket-shape coffee-machine niche in the middle.

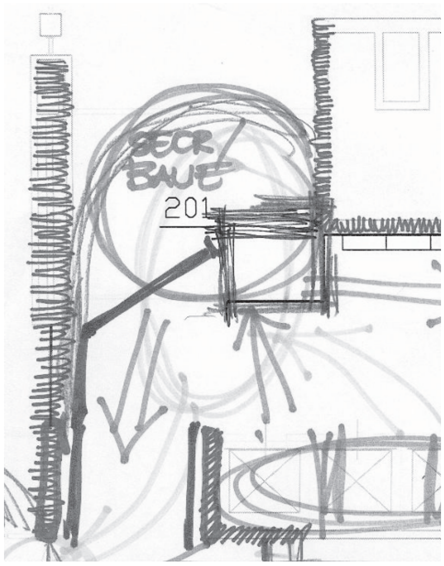


Figure 3. Detail of Figure 1 with accidental square in the middle.

2. Sketching Dimensions and Requirements

Sketching can be analyzed in several dimensions, which it shares with similar activities such as drawing and writing (Van Sommers 1984). The most important are:

1. The *mechanical* dimension: the physical interaction between the sketcher's anatomy and pen, paper, the writing surface etc.
2. The *paradigmatic* dimension: the strokes made by the sketcher and the graphic primitives or symbols they comprise
3. The *syntagmatic* dimension: the sequence by which the drawing is formed by discrete strokes and symbols

The paradigmatic dimension is a traditional focus of computational sketching studies (Achten and Jessurun 2002; Do 2002; Jozen et al. 1999; Koutamanis 2001; Sugishita et al. 1995). The mechanical dimension is largely unexplored in architectural research, with the possible exception of interfaces to 3D environments (Achten et al. 2000; Do 2001; Woessner et al. 2004). The same applies to the syntagmatic dimension, despite attempts to improve the means of protocol analysis and some interesting research in the semantic and syntactical significance of this dimension (Cheng 2004; Gross 1995). In our research the paradigmatic dimension is only a secondary point of attention. The mechanical dimension is considered in more detail, especially with respect to the comparison between digital and analogue media. The syntagmatic dimension is central to the research, as a primary means for disentangling actions, symbols and individual contributions.

A brief analysis of these dimensions in comparison to current digital technologies for architectural sketching returns several primary limitations:

1. *Viewing limitations*: One class of well-known limitations concerns the viewing distance and angle from computer monitors. Most users agree that viewing information on a standard computer monitor together with more than one other person can be uncomfortable, especially for longer periods and with information that requires attention. The common response to such complaints is to increase the size of the viewing facilities with beamers and large monitors. By comparison analogue documents fare significantly better, allowing very large sizes and multiple views at a low cost.
2. *Interaction limitations*: Even with larger viewing facilities, interaction with the information remains a bottleneck. Normally only one person can manipulate or input information with the computer's keyboard and mouse. The obvious solution is to pass the input devices around, allowing each user present to take a turn. Here again analogue documents are more flexible and adaptable, especially with respect to parallel processes and multiple actors: anyone who can get hold of a pen can interact with any of the available documents (including copies of the same document), frequently simultaneously with others. Group facilities like smartboards and large plasma or LCD touchscreen panels offer a halfway solution (large sizes and multi-actor support but no simultaneous multiple views) limited primarily by high cost.
3. *Tracing and reconstruction*: Digital information allows direct and generally effortless transformation but it is not always possible to record the actors involved and the context of their actions. Document management and versioning systems generally describe document states based on arbitrary time scales and prescriptive process models. In many respects such systems reproduce analogue practices and may even fail to connect to information standards so as to identify the evolution of different aspects in a design and their interrelationships.

If we ignore the differences between digital and analog, small and large, expensive and affordable, we can compile a number of requirements for the flexible, adaptable, reliable and direct processing of design and building information that covers sketching, drawing and related activities:

- *Large viewing facilities*: size limitations are unacceptable to a profession accustomed to A0 and A1 sheets. We may be getting used to the significantly lower resolution of computer monitors but lack of overview is a common complaint.

- *Multiple copies*: using multiple copies of the same document supports the exploration and comparison of variations and alternatives, including fast backtracking and parallel development of design solutions.
- *Free interaction* with all documents including overlaying of different documents, direct modification and markup, as well as allowing many actors to work together on one document.
- *The ability to distinguish between different actors and actions:* analysis of the paradigmatic and the syntagmatic dimensions so as to register and record complex situations, untangle contributions, disambiguate forms and interpret intentions in a reliable and consistent manner.

3. Analogue to Digital, Digital to Analog

The proliferation of digital information in all aspects of daily life, from leisure and entertainment to professional activities, is already an established fact. In most situations we assume that up-to-date, interactive information is readily available through a variety of digital media, normally at a relatively low cost. Moreover, the places where we access and consume information are becoming quite diffuse due to the recent increase of (multi)media devices at home and the popularization of mobile information processing. Still, we often transfer digital information to analogue carriers and from there back to the computer. Such transitions from analogue to digital information and vice versa are commonplace in architectural computing for a number of reasons, including:

- Ergonomic limitations of digital media, especially in comparison to analogue ones
- The distributed structure of the building industry
- The relatively low level of computerization in architecture and building

These transitions constitute ultimately a cyclical process, Figure 4. Feedback to earlier stages in this process permits comparison between different states of a design and hence facilitates accurate and precise identification of changes, as well as possible causes and conflicts. In this framework the most demanding type of transition (and hence the departure for our research) is the one from an analogue image produced from a digital model back to the computer. This may sound rather convoluted but in fact it represents an everyday need in architectural computerization. For the largest part of the field's history CAAD has been trying to replace analogue design processes and products with digital ones. However, computerization of architectural and building practice has produced results that are markedly different from many of the underlying assumptions of CAAD. One clear contrast with the intentions of digital design is the increase in paper consumption in the design office. Similarly to office automation, drawing, modeling and visualization systems appear to aim at the production of paper documents. Even though digital information is exchanged and processed more than ever, prints and plots remain the basis of building specification and design communication. Attempts to replace the paper carrier with digital media (from laptops and palmtops on the building site to smartboards in design presentations and meetings) have given us glimpses of the possible future but have yet to supplant analogue documentation.

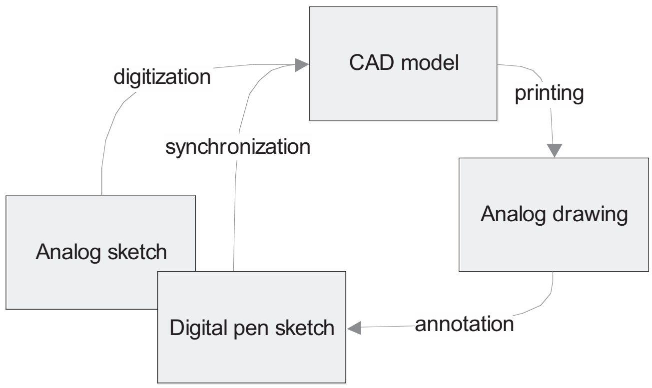


Figure 4. Analog-to-digital cycle.

The transition from original analogue image to the computer mostly takes place by means of manual and optical digitizers. Manual digitization is based on the combination of graphics tablets with pen-like pointing devices and is characterized by low user threshold, as the mechanical and ergonomic properties of such devices are similar to these of familiar analogue media: an action that would produce a stroke on paper is also captured by a manual digitizer and produces a similar result. Arguably more important for the transfer of analogue images to the computer than mechanical scanners have been optical digitizers (scanners). In terms of output the essential difference between manual and optical digitizers is that scanners produce a pixel image. This makes optical digitization less attractive for a number of applications but in terms of utility scanners provide more flexibility, tolerance and ease. They accept a wide variety of analogue documents and hence allow the user to make full use of analogue skills. In doing so, they compensate for the weaknesses of manual digitizers in mechanical aspects. Manual digitizers also exhibit limitations in terms of cognitive ergonomics. For example, sketching with most tablets involves constantly looking away from the hand and frequent interruptions in order to give commands to the computer. Admittedly experienced users may cross over to “blind drawing” but, as with blind typing, this involves weakening of significant forms of mechanical and perceptual feedback.

Feedback from hand-drawn annotations on prints and plots is generally made by hand in CAD programs. There are good technical reasons for not digitizing such complex images. Distinguishing between old (i.e. printed) information and new (annotations) in the products of optical digitizers is a cumbersome and expensive task, beyond the reach of most automated recognition systems and rather inefficient to perform interactively on the basis of a rudimentary vectorization. With manual digitizers a similar interactive transfer is possible: the user distinguishes between old and new information and draw the new one in the CAD system (preferably using overlay facilities of the tablet), either as annotations or directly as changes in the existing graphic entities. This obviously duplicates the time and effort required for making the annotations. More crucially it involves human interpretation of the annotations and consequently the possibility of errors.

An alternative to redrawing is direct interaction with the digital information, ranging from direct modification to markup and whiteboarding. Most interaction facilities that go beyond the keyboard and the mouse are based on combinations of monitors with mechanical digitizers so as to recreate the mechanical and perceptual experience of analogue drawing and writing. They include facilities for individual use such as LCD tablets, tablet PCs or palmtop devices, and group facilities such as smartboards and interactive touchscreen additions to plasma and large LCD monitors. From a technical viewpoint most of the smaller systems use pressure-sensitive screens, while the larger ones employ infrared scanning to determine the position of a pointer on the projection surface. The alignment problems that used to plague such systems are no longer an issue but cost may still be an objection, especially with the larger solutions.

4. Implementation

A comparison of the viewing requirements stated above with the capabilities of analogue documents suggests that the prints and plots routinely produced from digital representations could meet our expectations, provided that the interaction with these analogue documents would return reliable analyses of user input and focused feedback to the digital representations. This interaction should be characterized by a higher degree of mobility than current design automation: information processing should be brought to the drawing and not the other way around. A new technology that could satisfy our requirements is the *digital pen*. The name refers to a number of recent devices and ideas that attempt to incorporate digital processing capabilities to the familiar processes of writing and drawing on paper. The currently most advanced / established among these is the Anoto digital pen and paper (http://www.anoto.com). This technology is actually a combination of mechanical and optical digitization. Anoto pens can write on any kind of paper form that is covered with a proprietary dot pattern with a nominal spacing of 0.3 mm. A minute portion of the total pattern uniquely defines the absolute position in the form. A number of custom symbols for specific actions (e.g. changing stroke color or thickness) can also be included on the form. The digital pen is equipped with a tiny infrared LED camera of the CMOS image-sensing type. The camera is positioned beside the ballpoint tip and takes 50-100 digital snapshots of strokes made by the pen on the dot pattern within a 7 mm range from the tip. The snapshots are stored in the pen as a series of map coordinates that correspond to the exact location of the strokes (as continuous curves) on the particular page. In fact the camera (being sensitive to infrared) does not capture the ink traces on the paper but the movement of the pen with respect to the dot pattern.

The drawings are transferred (synchronized) to a computer using Bluetooth or USB. The digital images produced by synchronization are precise and exact copies of the analogue drawings. In transferring the images the pen also reports on which form the drawing has been made. This automatic document management allows users to switch between different documents without having to keep track of the changes. Post-processing includes grouping of strokes into higher-level primitives (e.g. OCR). The digital images are dynamic and can play back the sequence of strokes made on paper. For our purposes this technology has two main advantages:

1. *Feedback from analogue to digital*: using a digital pen on a print of a CAD drawing records only the new information (annotations) and transfers it back to the computer. As such it closes the analog-to-digital cycle in an efficient and unobtrusive way, Figure 4.
2. *Recording of syntagmatic information*: the digital pen captures strokes as discrete events and transfers this information to the computer. Analysis of the syntagmatic dimension contributes to the recognition of symbols (as contiguous series of strokes), the identification of relationships between symbols (in terms of temporal clustering) and the distinction between different actions and decisions (by means of temporal distance).

4. Synchronous and Asynchronous Group Processes

Our exploration of digital sketching in the annotation and modification of CAD drawings took place in both synchronous and asynchronous multi-actor settings. The synchronous side was covered in design meetings involving three to five participants, each representing a different aspect or specialization (architectural, interior and structural design, building cost, brief satisfaction). Each participant used a separate digital pen so that we could distinguish between individuals / aspects. The drawings used in the design meetings were normal laser prints from CAD models, with the difference was that they were overlaid with the Anoto dot pattern. In the asynchronous settings each participant (again representing a particular aspect or specialization) was also issued with an own set of laser prints that formed the background to a number of parallel, overlapping tasks.

In both settings we focused on the correlation and integration of information from different aspects. In the synchronous cases a large part of this took place in the meetings on the basis of the analogue documents. The main contribution of the digital pen technology was to distinguish between actors, aspects, actions and versions of a decision. The final versions (including histories) were fed back to the computer and linked to relevant design entities. These links formed the departure for modifications in the design. Modifications were frequently guided by the history of the particular decision (e.g. as a means of adding details than may have been omitted from the final version). As the asynchronous situations missed the correlation of aspects that took place in the meetings, the input from different actors was collated in the CAD models and fed back to the actors for a short round of verification, comments and possible adaptations.

Participants experienced few problems with the mechanical aspects of digital sketching. With just a few experimental sketches they became aware of the main limitations of the pen and were able to avoid their consequences. This was also facilitated by the nature of their tasks: making textual and graphic annotations on a drawing is less demanding than making an artistic sketch of a three-dimensional scene. The only persistent irritations were that (a) line thickness and color were visible only in the digital version, and more significantly that (b) strokes made on heavily printed parts of the drawing did not register because e.g. dense hatching interfered with the dot pattern.

The ability to record syntagmatic information meant that we could distinguish clearly between states, actions and actors, Figure 5. In the follow-up meetings, which normally took place one week later, the participants' recollection of events and decisions was refreshed by playing back the sequence of strokes made with each pen. This improved the accuracy of decisions taken by the whole group and facilitated concentrating on their consequences for the development of the design. It also supported continuity in the design process, including backtracking to earlier states and decisions. Syntagmatic information played an important role in the disambiguation of the paradigmatic structure of the typically messy annotated drawings produced in a design meeting. Visual fusing of adjacent or overlapping strokes from the same or different actors in a synchronous situation, as in the accidental emergence case in Figure 3, was reduced to an absolute minimum (a couple of temporally sequential strokes).

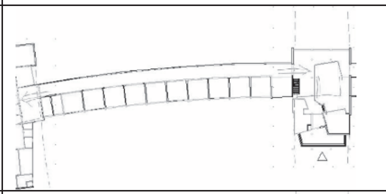
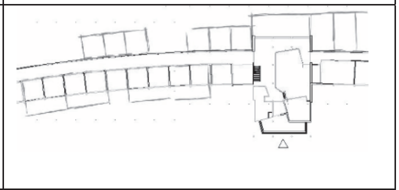
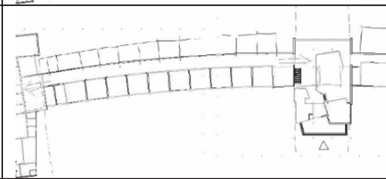
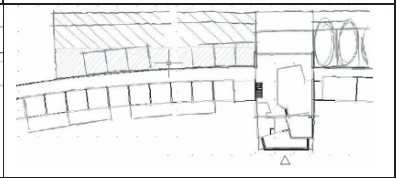
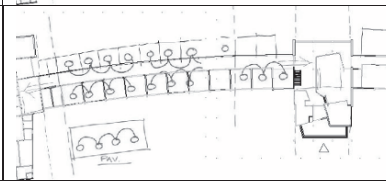
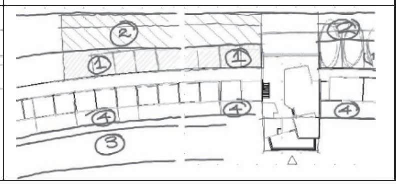
	Actor *L*	Actor *M*
State *n*		
State *n+1*		
State *n+2*		

Figure 5. Syntagmatic parsing of synchronous case.

Feedback of annotations to the CAD files used for the production of the prints was assisted by (a) the high precision of sketches, drawings and texts produced with the digital pen, and (b) the built-in document management capabilities. As a result, synchronized information could be directly linked to the appropriate views of a CAD model as an overlaid pixel image, as markup, Figure 6 and Figure 7.

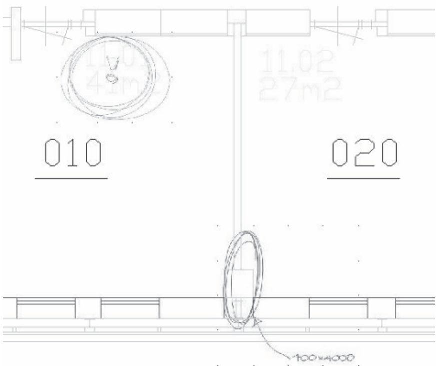


Figure 6. Annotation feedback to CAD.

OCR of verbal annotations enriched post-processing by returning e.g. numerical values for proposed metric modifications and labels that could be matched to entity properties. For example, the text “door” could be linked directly to door symbols in the vicinity of the label or to layers containing doors.

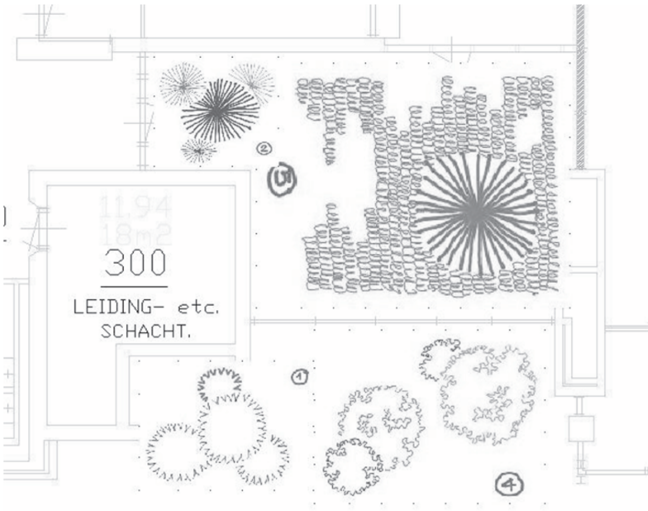


Figure 7. Composite view in CAD produced through annotation feedback.

A further elaboration of the standard synchronization was the automatic derivation of selection areas in the CAD model on the basis of the form and size of annotations. For example, a bubble form drawn with multiple lines triggered a window-type selection with the dimensions of the bounding box of the annotation, Figure 8. These selection areas assist in identifying the relevance of annotations to specific parts of the CAD model, as in most cases the annotations overlap with the elements they refer to. Relevance identification by means of such selection areas was instrumental in the correlation of annotations from different actors in asynchronous situations, as well as for the identification of relevant actors for subsequent communication and development actions and tasks.

The parsing of an image into groups of strokes also opens up possibilities for the recognition of design entities and symbols in a manner similar to OCR (Do 2001; Koutamanis 1995). This was not attempted with the annotations that were fed back to the CAD system. The main reason was that the annotations we handled were too elliptical to present a coherent and consistent basis for identifying symbols. However, we were able to observe that such symbols tended towards the personal and idiosyncratic. This suggests further research into the use of simple strokes to compose a symbol (paradigmatic dimension), as well as into how these strokes are spread in time (syntagmatic dimension) due to e.g. mechanical issues.

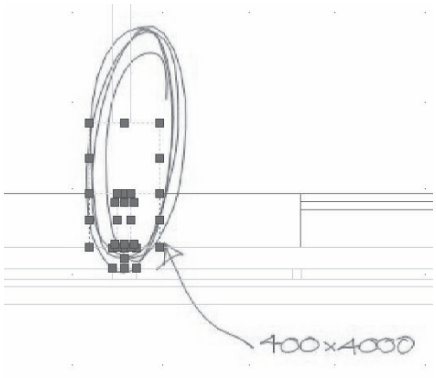


Figure 8. Automatic selection of entities on basis of annotation feedback.

It should be noted that most of the above observations refer to synchronous cases. In the asynchronous setting we were unable to observe objective advantages over other means of interactions with digital information (e.g. markup with a tablet). On the contrary, users preferred to work with a tablet PC and a LCD tablet that were also available. The only clear advantages of the digital pen in the asynchronous cases were mobility and the ability to use large drawings. These advantages were of particular interest in later design stages, when the amount and precision of design information, as well as the underlying history of decision-taking, were much higher and more binding. Tracing back previous states and relevant decisions along the syntagmatic dimension recorded in digital sketching was instrumental in clarifying the constraints of particular situations.

5. Beyond Annotations

A wider exploration of the applicability of digital sketching was performed through the progressive relaxation of the constraints used so far, starting with the feedback to computer documents. In design meetings that started from scratch (as far as visual design documentation is concerned), disambiguation of the final products also benefited from the recorded syntagmatic information, Figure 9. The allocation of a pen to each actor allowed for greater flexibility than with e.g. smartboards. Parsing the images produced in the meetings into discrete actions, decisions and relationships was technically less challenging, as there was no feedback to CAD models.

Probably the most interesting observations made in such settings concerned the use of each other's information as a reference frame or point of departure. Sketchers referred not only to their own previous input but also to that of the others, frequently in a positive sense.

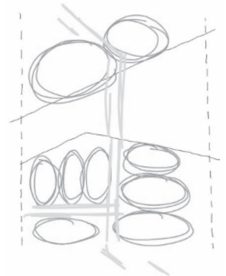
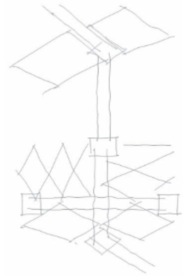
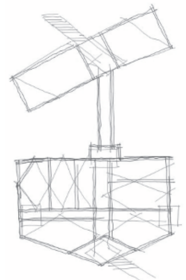
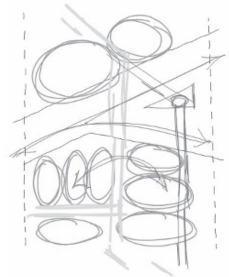
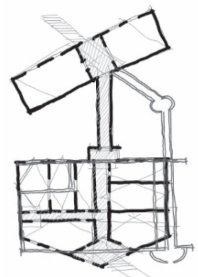
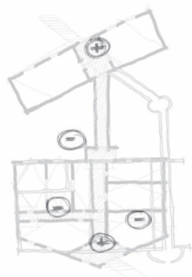
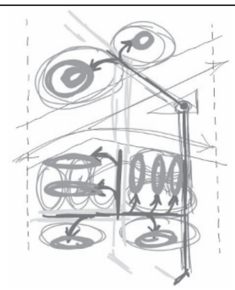
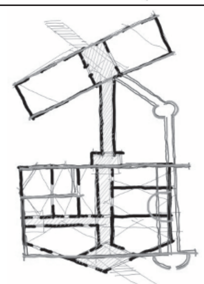
	Actor *A*	Actor *B*	Actor *C*
State *n*			
State *n+1*			
State *n+4*			
State *n+5*			

Figure 9. Syntagmatic parsing of synchronous case.

In Figure 9, state *n*+4, actor A commented unfavorably on the positioning of the main corridor that connected the two buildings, as it was sketched by actor B in state $n+1$. He suggested that it should be transposed to the side of the main building in order to distinguish between two different types of pedestrian circulation. Actor B was actually inspired by this and transformed what he revealed to consider a disappointingly static design into a more flexible layout, which was analyzed favorably by actor A (state $n+5$). In a sense actors A and B were using each other's input in the same way annotations referred to a fixed design in the prints from a CAD representation.

Using the digital pen as a sketching tool was a logical consequence of such meetings, also in asynchronous situations: participants were encouraged to use their digital pens (including the information stored in them) also between meetings. This produced a number of elaborations of the ideas each actor had presented in the previous meeting, as well as reactions to ideas of other participants. Putting these together at the start of a meeting was a productive enrichment of approving the minutes of the previous meeting and setting up the meeting agenda.

Under these conditions the temptation to use the digital pen to sketch was irresistible. The results however were variable. Sketching with the digital pen is similar to sketching with ballpoint pen, Figure 10. The main ergonomic difference lies in the thickness of digital pen: the holding area has a circumference of approximately 60 mm compared to 30 mm for a pencil. Also the built-in LED camera has limited sensitivity: quick, short or light strokes are poorly captured, especially when the pen is held at an angle approaching 60° with respect to the paper. As a result the best digital pen sketches were fairly abstract and diagrammatic. As a sketching instrument for a single user the digital pen compares unfavorably to digital alternatives such as pressure-sensitive graphic tablets and related software in all respects but mobility and precision.

Figure 10. Digital pen sketches.

A significant limitation of sketching with the digital pen is that color and line weight are only visible in the digital version. As with mechanical digitizers the user is obliged to consult frequently the image in the computer. Unlike with mechanical digitizers this can be done only asynchronously, alternating sketching actions with synchronization and controlling the sketch in the computer. This lack of immediate visual feedback places restrictions to the use of the digital pen in artistic sketching.

A notable exception is another multi-user environment, education, where interaction between different actors (teachers and students) aims at elucidating and improving performance. In teaching activities relating to group design processes, morphological analysis or sketching, the explicitness of syntagmatic information also assists the analysis of the paradigmatic and mechanical dimensions. The ability to distinguish between strokes on the basis of the sequence in which they were made facilitates not only the recognition of accidental emergence but also the recognition of symbols composed by these strokes and the identification of drawing styles. For example, it helps analyze and structure the development of a freehand sketch, as in Figure 11 andFigure 12 (Cheng 2004; Cheng and Lane-Cumming 2003). A comparison of the two figures reveals that both sketchers used a similar syntagmatic strategy but different primitives in the basis of the drawing.

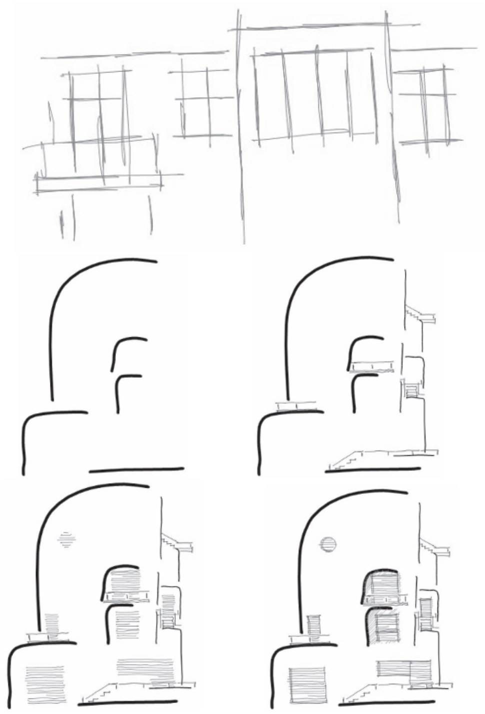


Figure 11. Drawing sequence in a freehand sketch.

Figure 12. Drawing sequence in a freehand sketch.

6. Conclusions

Our interest in digital sketching in multi-actor design environments derived from the need to identify and analyze individual input and relationships between different actors and corresponding aspects, actions and products. Even though we paid little attention to the paradigmatic dimension, the application of syntagmatic parsing returned unambiguous sequences of stokes with a clear authorship and interrelationships. This was generally sufficient for the reconstruction of group processes in a synchronous setting and led to a transparent interpretation of the content and intention of individual actions and decisions, as well as of different states of a design.

The approach and technology used proved well suited to the needs of annotating analogue versions of digital representations, as well as of abstract, diagrammatic sketching in early design. In other applications the results were variable. This was mainly due to the mechanical limitations of the current state of the digital pen. Its (cognitive) ergonomics suffer from the pen size, the limitations of the built-in LED camera and the troublesome correlation of the advanced color images in the computer and the basic ballpoint drawings on paper. As usually in a digital environment, there is no single tool that is perfect for every task.

Our positive experiences with the technology used lie not in the replication of analogue means and procedures but in the integration of digital information processing in analogue situations. In the currently confusing interchangeability of digital and analogue versions of the same information, technologies that bridge the gap can be particularly useful. Mobility in information processing is essential to this, as it allows for more flexibility in the interaction between digital tools and analogue situations.

From a holistic viewpoint syntagmatic analysis is a prequel to the recognition of the paradigmatic structure of an image. The identification of meaningful symbols in a sketch is a prerequisite to any transformation into another representation, e.g. a measured drawing or a three-dimensional model. However, our analysis of the syntagmatic dimension reveals that such symbols may be formed by strokes that do not follow each other or may integrate strokes made by various actors (normally used by a single actor as a reference frame). Consequently the combination of discrete strokes and syntagmatic information may be insufficient for unambiguous recognition. The hypothesis that a model base of paradigmatic primitives forms the foundation of sketch recognition underlies the following stage of our research into digital sketching. The same applies to the recognition of symbols and forms produced by the combination of elliptical annotations with information already existing in the representation.

References

Achten, H, De Vries, B and Jessurun, J: 2000, DDDOOLZ, A virtual reality sketch tool for early design, *CAADRIA,* Singapore, pp. 451-460.

Achten, H and Jessurun, J: 2002, An agent framework for recognition of graphic units in drawings, *eCAADe*, Warsaw, pp. 246-253.

Cheng, NY-w: 2004, Stroke sequence in digital sketching, *eCAADe*, Copenhagen, pp. 387-393.

Cheng, NY-w: 2004, Teaching with digital sketching, *in* W Bennett and M Cabrinha (eds), *Design Communication Association - 11th Biannual Conference*, San Luis Obispo, pp. 61-67.

Cheng, NY-w and Lane-Cumming, S: 2003, Using mobile digital tools for learning about places, *CAADRIA*, Bangkok, pp. 145-156.

Do, EY-L: 2001, Graphics interpreter of design actions. The GIDA system of diagram sorting and analysis, *in* B de Vries, J van Leeuwen and H Achten (eds), *Computer Aided Architectural Design Futures*, Kluwer, Dordrecht, pp. 271-284.

Do, EY-L: 2001, VR sketchpad: Create instant 3D worlds by sketching on a transparent window, *in* B de Vries, J van Leeuwen and H Achten (eds), *Computer Aided Architectural Design Futures*, Kluwer, Dordrecht, pp. 161-172.

Do, EY-L: 2002, Drawing marks, acts, and reacts: Toward a computational sketching interface for architectural design, *AI EDAM* **16**(3): 149-171.

Gross, MD: 1995, Indexing visual databases of designs with diagrams, *in* A Koutamanis, H Timmermans and I Vermeulen (eds), *Visual Databases in Architecture. Recent Advances in Design and Decision Making*, Avebury, Aldershot, pp. 1-14.

Jozen, T, Wang, L and Sasada, T: 1999, Sketch VRML - 3D modeling of conception, *in* A Brown, M Knight and P Berridge (eds) *Architectural Computing: From Turing to 2000*, University of Liverpool, Liverpool, pp. 557-563.

Koutamanis, A: 1995, Recognition and retrieval in visual architectural databases, *in* A Koutamanis, H Timmermans and I Vermeulen (eds), *Visual Databases in Architecture. Recent Advances in Design and Decision Making*, Avebury, Aldershot, pp. 15-42.

Koutamanis, A: 2001, Prolegomena to the recognition of floor plan sketches: A typology of architectural and graphic primitives in freehand representations, *in* H Achten, B de Vries and J Hennessey (eds), *Design Research in The Netherlands 2000*, Faculteit Bouwkunde, TU Eindhoven, Eindhoven, pp. 93-103.

Sugishita, S, Kondo, K, Sato, H, Shimada, S and Kimura, F: 1995, Interactive freehand sketch interpreter for geometric modelling, *Proceedings of the Sixth International Conference on Human-Computer Interaction*, pp. 561-566.

Van Sommers, P: 1984, *Drawing and Cognition: Descriptive and Experimental Studies of Graphic Production Processes*, Cambridge University Press, Cambridge.

Woessner, U, Kieferle, J and Drosdol, J: 2004, Interaction methods for architecture in virtual environments, *eCAADe*, Copenhagen, pp. 66-73.