BRIDGING THE ANALOG AND DIGITAL WORLDS IN SUPPORT OF DESIGN KNOWLEDGE LIFE CYCLE

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ABSTRACT

A decision delay can translate into significant financial and business losses. One way to accelerate the decision process is through improved communication among the stakeholders engaged in the project. Capturing, transferring, managing, and reusing data, information, and knowledge in the context it is generated can lead to higher productivity, effective communication, reduced number of requests for clarification and time-to-market cycle. This paper presents TalkingPaper™ as a ubiquitous *collaborative environment* that facilitates synchronous and asynchronous communicative events. The TalkingPaper™ prototype bridges the paper and digital worlds. It transforms the dialogue and the paper & pencil sketches into indexed and synchronized digital audio-sketch content that can be streamed on-demand over the Web to all stakeholders for rapid knowledge transfer and decision-making.

KEY WORDS

Knowledge Lifecycle, collaboration, knowledge management, multimedia, analog, digital

INTRODUCTION

A decision delay can translate into significant financial and business losses. One way to accelerate the decision process is through improved communication among the stakeholders engaged in the project. Capturing, transferring, managing, and reusing data, information, and knowledge in the context it is generated can lead to higher productivity, effective communication, reduced number of requests for clarification and time-to-market cycle. However, knowledge transfer often fails, since knowledge is not captured, it is captured in an abstract format rendering it not reusable, or there are no formal mechanisms to find and retrieve it. Valuable knowledge is lost at project transition points of the building life cycle from one phase to the next, i.e, finance, design, procure/fabricate, build, manage as the handover between different stakeholder teams takes place.

We view knowledge reuse as a step in the knowledge life cycle [Fruchter and Demain, 2002, 2005]. Knowledge is created as designers collaborate on design projects using data, information, and past experience and knowledge. It is captured, indexed, and stored in human

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memory or digital archives. At a later stage, it is retrieved and reused. Finally, as knowledge is reused it is refined and becomes more valuable.

Our ethnographic studies performed over the past decade of cross-disciplinary team at work show that a primary source of information behind design decisions is embedded within the verbal conversation among designers. Capturing these conversations is difficult because the information exchange is unstructured and spontaneous. In addition, discourse is often multimodal. It is common to augment speech with sketches as an embodyment of the mental model, or launch into a problem solving discussion tirggered by a skeched solution.

One of the most striking means of knowledge creation and transfer among stakeholders in a project or from experts to novices in both education and industry settings is through informal recounting of experiences from past projects and collaborative dialogue connecting problems, ideas, and solutions. The advances in digital technology promise to assist in knowledge capture and re-use. However, the more digital content is created the more paper we print and use. Most digital content management today offer document management solutions with few answers how to capitalize on the core corporate competence, i.e., to capture, share, and re-use business critical knowledge. Digital archives store formal documents (CAD, Word, Excel, etc.) that can be easily edited, shared, searched, and archived. Knowledge reuse and externalization of tacit knowledge is not revealed by these formal documents. The knowledge creation takes place in informal concept generation and problem solving sessions in which knowledge workers gather around multiple blueprints and engage in *dialogue* and *paper & pencil sketching.* Paper has a tactile feel; it can be easily folded or rolled and carried to meetings or site visits. It affords single or multiple users to interact and jointly annotate one or multiple documents, and more importantly; it is socially and legally accepted [Sellen 2001]. However, paper is difficult to modify and expensive to distribute, archive, search, retrieve, and reuse. These limitations are very effectively supported by digital technology. Nevertheless, when inspecting for instance large CAD models on screen the current resolution techology only affords to either zoom in and see the details but loose the big picture, or zoom out and see the big picture but miss the details. Paper provides a high resolution for navigation through the content that enables users to view at a glance local details and global context.

We aregue that in order for knowledge to be captured and reused, the knowledge worker needs to be able to (1) create content using natural idioms as communication media such as dialogue and paper & pencil sketches, (2) explore and understand the context in which this knowledge was originally created, and (3) interact with the content in a rich, multimedia environment. Our objective is to leverage the advantages of both analog paper world and digital world in support of the design knowledge life cycle and in a larger sense the product knowledge life cycle.

This paper presents TalkingPaper^{TM} prototype as a ubiquitous collaborative environment for mobile knowledge workers. It bridges the analog and digital worlds to facilitate synchronous and asynchronous communicative events and support the knowledge lifecycle. We present the theoretical points of departure, and discuss evidence collected during ethnographic studies in the typical paper intensive environments such as project teamwork and the building permit process. Based on the ethonographic observations we introduce a formal concept of reflection-in-interaction during communicative events among stakeholders. This

concept extends Donald Schon's theory of reflection-in-action of a single practitioner. We model the observed reflection-in-interaction with the prototype system called TalkingPaper^{TM} (current status – provisional patent).
The paper provides an overview of the problem and solution space, the TalkingPaper^{TM} prototype and the spectrum of scenarios it can be used.

THEORETICAL POINTS OF DEPARTURE

The points of departure of this research are: design theory and methodology, knowledge creation and management, and human computer interaction.

Design theory and methodology. The issue of how to capture knowledge in project design teams has received extensive attention from researchers in design theory and methodology. The value of contextual design knowledge (process, evolution, rationale) has been repeatedly recognized, but so has the additional overhead required of the designer in order to capture it. Other studies of design focused on either the sketch activity, i.e., learning from sketched accounts of design [Tversky 1999, Stiedel and Henderson 1983, Olszweski 1981, Kosslyn '81, Goel '95] or verbal accounts of design [Cross 1996, Cross 1992, Dorst 1996]. Some researchers have studied the relation between sketching and talking [Eastman 1969, Goldschmidt 1991]. Recent studies of interactive workspaces [Ju et.al, 2004] explore capture and navigation issues related to technology-augmented interactions. To help guide the designer's exploration of an archive of unstructured dialogue and sketch content linked to structured document databases, it will be necessary to develop a search and retrieval mechanism. Our research builds on Donald Schon's concept of the reflective practitioner paradigm of design [Schon 1983]. Schön argues that every design task is unique, and that the basic problem for designers is to determine how to approach such a single unique task. Schön places this tackling of unique tasks at the center of design practice, a notion he terms *knowing-in-action* (Schön 1983, p. 50). To Schön, design, like tightrope walking, is an *action-oriented* activity. However, when knowing-in-action breaks down, the designer consciously transitions to acts of reflection. Schön calls this *reflection-in-action.* In a cycle which Schön refers to as a *reflective conversation with the situation*, designers reflect by *naming* the relevant factors, *framing* the problem in a certain way, making *moves* toward a solution and *evaluating* those moves. Schön argues that, whereas action-oriented knowledge is often tacit and difficult to express or convey, what *can* be captured is *reflection-in-action*.

Knowledge creation and management. The digital age holds a great promise to assist in knowledge capture, transfer, and reuse. However, the more digital content is created the more paper we print. More importantly, we need to offer clear and distinguishing definitions and instantiations for data, information, and knowledge, rather than using them interchangably. Our research uses the following working definitions for *data*, *information*, and *knowledge*. Data (e.g., printed documents or digital documents of CAD, spreadsheeds, text) represent the "raw material." This is easy to manage and store in corporate data bases or ftp sited. Nevertheless, data is not information. Information emerges during a communicative transaction between a sender and a receiver. Information is created as the sender takes data and adds meaning, relevance, purpose, value through a process of contexualization and synthesis. Neither data nor information represent knowledge. We believe and observe that

knowledge is created through dialogue within or among people as they use their past experiences and knowledge in a specific context to create alternative solutions. During these dialogues knowledge is created as connections, comparisons, combinations, and their consequences are explored. It is important to note that documents do not reveal the tacit knowledge externalized during the permit checking process. They also ignore the highly contextual and interlinked modes of communication in which people generate concepts through verbal discourse and sketching.

We view the act of reflection-in-action as a step in the knowledge creation and capture phase of what we call the "knowledge life cycle" [Fruchter and Demian, 2002, 2005]. Knowledge represents an instance of what Nonaka's knowledge creation cycle calls "socialization, and externalization of tacit knowledge." [Nonaka and Takeuchi 1995]. We build on these constructs of the knowledge lifecycle and the "socialization, externalization, combination, and internalization" cycle of knowledge transfer.

Human Computer Interaction. We use the scenario-based design approach [Rosson and Carroll 2001] that offers a methodology to study the current state-of-practice, describe how people use technology and analyze how technology can support and improve their activities. The scenario-based design process begins with an analysis of current practice using *problem scenarios*. These are transformed into *activity scenarios*, *information scenarios* and *interaction scenarios*. The final stage is *prototyping* and *evaluation* based on the interaction scenarios. The process as a whole from problem scenarios to prototype development is iterative. This proposal seeks funding for a pilot evaluation effort.

ETHNOGRAPHIC EVIDENCE

Project teamwork and building permit approval are still paper intensive communication processes. Numerous cycles of requests for changes and clarifications lead to high hidden work [Levitt and Kunz, 2002]. For instance, a typical building permit approval cycle can take up to 18 days. A permit approval delay can translate into significant financial and business losses. One way to accelerate the permit process is through improved communication among the permitting agency and stakeholders engaged in the design, and construction of facilities. Capturing, transferring, managing, and reusing data, information, and knowledge in the context it is generated can lead to higher productivity, effective communication, and reduced number of requests for clarification and RFI cycles. However knowledge transfer often fails, since knowledge is not captured, it is captured in an abstract format rendering it not reusable, or there are no formal mechanisms to find and retrieve it. Our objective is to reduce the number of cycles to and to one cycle aiming to (1) reduce hidden work (i.e., less coordination and rework), (2) improve communication and knowledge transfer among the stakeholders, and (3) decrease response time and decision delays.

One of the extensive ethnographic studies we performed in the last two years was at the San Jose Redevelopment Agency (SJ RDA). [Fruchter and Swaminathan, 2004]. This provided a better understanding of the work environment and overall permitting process, i.e., activities, actors, interactions, and specific media through which these interactions occur. Ethnographic evidence and our field observations show that:

- the typical workspace of a professional expert at the SJ RDA (e.g., architect, engineers) comprises a large desk mainly used to spread out drawings, tons of tracing paper and sketches, a rack with all the drawings and tracing paper sketches of on-going projects
- SJ RDA experts constantly trace over the blueprints sent by the client several times using tracing paper to understand all the intricacies of the drawings – a process representing reflection-in-action.
- if a SJ RDA expert had an issue he/she wanted to think about or a new idea it was quicker to capture it by sketching on tracing paper than to make a computer model.
- blueprints are checked, annotated, and traced over to understand how they correlate.
- during meetings SJ RDA experts from different disciplines gather around a large meeting desk with multiple blueprints and other sets of documents (calculations, spreadsheets, docs) that they annotate, sketch on, correlate to identify problems, discuss key issues, make recommendations, request changes.
- sketches and tracing paper drawings are archived for future reference during meetings and re-use of good ideas. Nevertheless, it is very hard to search and find relevant material through the paper archive.
- the final decisions, recommendations, and requests for changes are summarized in a text document and sent to the client. Nevertheless, all the discourse, arguments, and rationale behind these items are not provided. This leads to (1) multiple requests for clarifications sent to the agency by the client and the project team members and (2) delays in the permit process and project progress triggered by coordination and rework efforts.

REFLECTION-IN-INTERACTION

This research adopts a scenario-based approach [Rosson and Carroll 2001] to the design of human-computer interaction. The premise behind scenario-based methods is that descriptions of people using technology are essential in analyzing how technology can support and improve their activities. We address the following research questions:

- What are governing principles for *reflection-in-interaction of multiple practitioners* that expand Schon's concept of the *reflection-in-action of a practitioner*?
- How can we map the natural paper environment with its dynamic and complex interactions and concept generation among multiple users, documents, and input devices into a digital interactive environment?

Based on our ethnographic studies focused on the interactions among stakeholders engaged in building projects we identified and modeled the activities during reflection-in-action of individuals and reflection-in-interaction of teams.

We introduce the concept of *reflection-in-interaction* during communicative events among stakeholders. *Reflection-in-interaction* extends Donald Schon's theory of *reflection-in-action* of a single practitioner and builds on our ethnographic observations. As the practitioners review concurrently multiple documents, they have a constant *reflective conversation with the situation* and the *stakeholders*. They reflect by:

1. Identifying the relevant factors through exploratory sketching and discussion.
2. Correlating these factors across disciplines and documents.

3. Discussing and exploring alternatives across disciplines.
4. Assessing alternatives and their implications.

We argue that, whereas action-oriented knowledge is tacit and difficult to transfer, what can be captured and transferred is the reflection-in-interaction that reveals the rationale and correlation across disciplines and documents, as well as the new knowledge that is created through discourse among the stakeholders.

Creating, capturing, sharing, and reusing knowledge in cross-disciplinary, collaborative, teams is critical to increase the quality of the product, reduce time-to-market and cost. Concept generation and development occur most frequently in informal media where design capture tools are the weakest. This statement has strong implications for the capture and reuse of design knowledge because conceptual design generates the majority of initial ideas and directions that guide the course of the project. Sketching is a natural mode for designers to communicate in highly informal activities such as brainstorming sessions, project reviews. Often, the sketch itself is merely the vehicle that spawns discussion about a particular design issue. Thus, from a design perspective, capture of both the sketch itself and the discussion that provides the context behind the sketch are important. It is interesting to note that today's state-of-practice or best practices are not captured and knowledge is lost when the whiteboard is erased or the paper napkin sketch is tossed away. With all the advances in computing today people still prefer to have a conversation and use paper & pencil sketches to communicate and capture ideas. Our observations show that during communicative events there is a continuum between discourse and sketching as ideas are explored and shared. We assert that a primary source of knowledge behind design decisions is embedded within the verbal conversation among designers. The link between dialogue and sketch provides a rich context to express and exchange knowledge. This link becomes critical in the process of knowledge sharing, retrieval and reuse to support the user's understanding of the shared information and assessment of the relevance of the retrieved content with respect to the task at hand. Nevertheless, paper is a media hard to share, exchanged, and re-use, and does not capture the discourse among users. The moment you lost the paper sketch the ideas are lost.

This research address the communication, coordination, and cognition needs defined by (1) the need to bridge the analog paper and discourse world with the digital world. Such a bridge will improve the knowledge transfer and reuse over the life cycle of the building. (2) the increasing complexity defined by the three dimensional problem space – multiple stakeholder, multiple documents, multiple pens (as input devices) – posed by the paper-intensive *reflection-in-interaction* process in which the stakeholders engage in dialogue and sketching activities. Note that this three dimensional problem space is applicable to both the paper and digital worlds.

TALKINGPAPER™

TalkingPaper™ is a true horizontal technology that can have a huge impact on the work practice and process in all phases of the life cycle of a building, e.g., design, construction, facility management, as well as in education. TalkingPaper™ facilitates capture, sharing, and reuse of content created during reflection-in-action and reflection-in-interaction sessions, e,g., *dialogue* and *paper & pencil sketching* or *joint annotation of one* or *multiple shared paper documents* (e.g., blueprints), through *digital processing* and *indexing* of the content.

These *digital audio-sketches* are *synchronized with corresponding documents stored in a corporate database.* We model the reflection-in-interaction *collaborative, multi-participants*, and *multi-document paper-digital* scenario that represents a dynamic and complex environment. This interactive environment provides methods for unique identification of participants and documents synchronized and indexed with the *digital audio-sketches.* This allows future contextual search, retrieval and replay, and re-use based on sketch, annotation of document, keyword, and/or participant who represents a specific domain expertise or perspective.

TalkingPaper™ is a ubiquitous *collaborative environment*. It provides an analog-to-digital content processor that:

- enables seamless transformation of the informal analog content, such as *dialogue* and *paper & pencil sketches* into *indexed digital audio-sketches* objects. The knowledge capturing, indexing, and sharing process takes place in real-time, with high-fidelity, and least overhead to the participants.
- supports knowledge reuse through contextual content understanding, i.e., an *interactive replay* of *indexed digital audio-sketch* rich multimedia content that captures the creative human activities of concept generation and development through *dialogue* and *paper & pencil sketching.* The TalkingPaper™ sessions are automatically uploaded to a TalkingPaper™ Web server that was developed to archive, share, and stream these sessions

Related digital pen pilot efforts and trial phase projects focus on text document mark-up [Guimbretiere, 2003] and forms automation for different sectors such as healthcare, service and support companies, government organizations, education testing agencies, pharmaceutical research companies, e.g., forms for clinical studies, forms for customer data and signature, weekly report forms for service engineers, etc.

We view knowledge capture, sharing and reuse as key steps in the knowledge life cycle. Knowledge is created as stakeholders collaborate on building projects. The knowledge is captured, indexed, and stored in an archive. At a later time, it is retrieved from the archive and reused. Finally, as knowledge is reused it is refined and becomes more valuable. In this sense, the archive system acts as a knowledge refinery. Previous empirical observations [Fruchter and Demian, 2002][Fruchter and Swaminathan 2004] of cross-disciplinary teams at work show that knowledge reuse is effective since designers can:

- quickly *sketch* and *explain* their ideas using paper & pencil,
- quickly *find* (mentally) reusable items, and
- remember the context of each item, and therefore *understand* it and reuse it effectively.

Highly structured representations of design knowledge can be used for *reasoning*. However, these approaches usually require manual pre or post processing, structuring and indexing of design knowledge. In order to capture, share and reuse relevant content (i.e., knowledge in context) from media such as paper & pencil sketches and verbal discourse it is critical to convert such externalized tacit knowledge into digital symbolic representations by converting the unstructured, informal content capturing the dialogue into digital audio and sketch objects. This facilitates future sharing, searching, replay, and reuse of the tacit knowledge. TalkingPaper™ aims to empower the project stakeholders and engage them in productive collaborative synchronous and asynchronous teamwork by leveraging the best of

the all worlds – paper, digital multimedia, and networked communication. TalkingPaper™ is building on innovative technologies – RECALL™ technology [Fruchter and Yen, 2000][3], Anoto™ paper technology, and cutting edge hardware technology such as digital pen (e.g., by Nokia, Logitech), Bluetooth and cellular phones and GSM/GPRS network services. In the reflection-in-interaction collaborative scenario each participant has a digital pen and can be uniquely identified as he/she sketches and annotates documents during the meeting. The TalkingPaper™ interactive replay retrieves and synchronizes formal digital documents with the digital audio-sketch if the user(s) printed the specific document on the Anoto™ paper, e.g., CAD drawings, spreadsheets, or other documents, that are stored in a digital database. This enables the user to explore, understand and assess the content. (Figure 1) It is important to note that the analog-to-digital transformation can be iterative as the stakeholders replay the digital multimedia contenct on screen and understand the proposed idea or solution, they can decide to print the sketch or annotated document displayed on screen, and further annote it or sketch on it using TalkingPaper™ therefore creating a new cycle. TalkingPaper™ affords any number of analog-to-digital and digital-to-analog cycles necessary.

Based on our observations, we formalize key activities in the knowledge life cycle: *create* and *capture* sharable and reusable items, *find* reusable items, and *understand* these items in context. TalkingPaper™ supports the *create* and *capture* activity through a high-fidelity, interactive, integrated multi-user paper-to-digital multimedia conversion. The *sharing* process is supported by an interactive Web service that automatically synchronizes digital audio-sketch episodes with any additional document that was printed on the Anoto™ paper. The *find* activity is supported by an integrated *digital audio-sketch* search engine, and the *understand* activity is supported by a real-time indexing mechanism that takes place during knowledge capture, and contextual synchronization during knowledge retrieval.

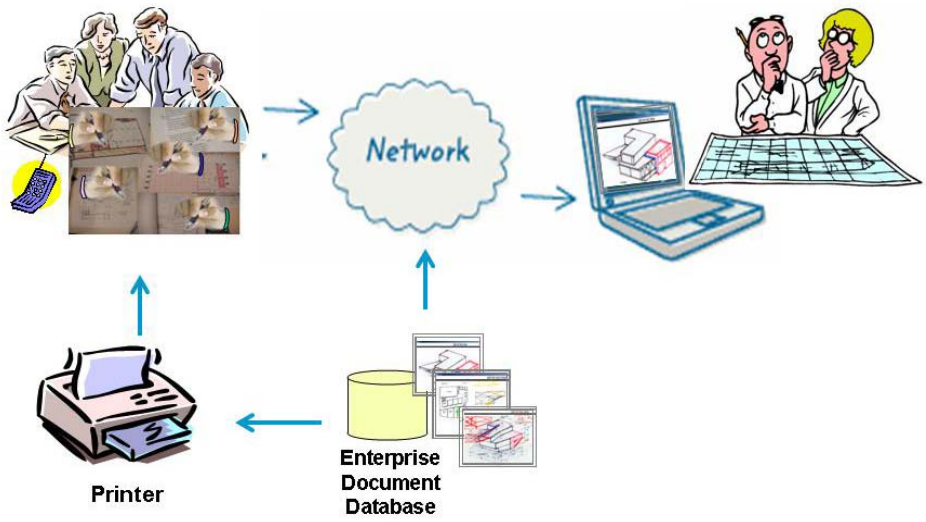

Figure 1: Knowledge Life Cycle suppored by TalkingPaper™ Analog-to-Digital Bridge

[3] Patented by Stanford University.

CONCLUSIONS

We model the observed *reflection-in-interactions* during teamwork and the permit approval process with the prototype system called TalkingPaper™. It transforms the dialogue and the paper & pencil sketches into indexed digital audio-sketch content that can be streamed on-demand over the Web to all project stakeholders for rapid knowledge transfer and decision-making. The scientific and technology contributions of this research effort present:

- an extension Schon's concept of the *reflection-in-action of a practitioner* to a *multi-practitioner reflection-in- interaction paradigm,*
- a formalization of the complex interactions in a multiple user, multiple documents, multiple pens interactive, multimedia workspace that bridges paper and digital worlds, and
- TalkingPaper™ prototype as an analog-to-digital rich communication content processor in support of the knowledge life cycle i.e. "create, capture, index, store, search, find, retrieve, share and reuse."

Six rapid prototyping generations of TalkingPaper™ have been already developed and preliminary testing and evaluation is on-going. This evaluation focuses on assessing our understanding of the *reflection-in-interaction* model, and the extent to which the TalkingPaper™ user interactions supports this process. The evaluation is *formative* [Rosson and Carroll 2001), i.e. the evaluation results are used iteratively to guide the process of developing and refining the reflection-in-interaction model and TalkingPaper™ prototype. Tests focus in particular on the usability of TalkingPaper™ and how it can reduce hidden work, i.e., coordination and rework, improve communication and knowledge transfer, and decrease response time and decision delays. Specific metrics we consider are efficiency, effectiveness, and satisfaction of both quality and process. Usability tests of TalkingPaper™ prototype are performed along the spectrum of scenarios defined by the three dimensional space in increasing order of complexity, from reflection-in-action of a *single user- document-pen* scenario to a reflection-in-interaction *multiple users-documents-pen*. Results of prliminary usability evaluation during interactions between e.g., architects and strucutral engineers, or engineers and detailers, or design teams and permiting agency, indicate that decision cycles are significantly decreased from two weeks to half a day on average. Further usability studies in large testbeds are currently under way.

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