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ActiveNavigator: Toward Real-Time Knowledge Capture and Feedback in Design Workspaces*

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Knowledge capture and reuse systems, such as interactive table surfaces or smart whiteboards, have long enabled designers to review and revisit the knowledge artifacts generated by their creative work. Advances in data sensing and computation now allow near real-time analysis and feedback to be added this toolbox. In this paper, we outline our exploratory application of real-time speaker identification, audio transcription, linguistic analysis, and proactive content retrieval to design team meetings. We highlight the potential benefits and limitations of tools available to collect and analyze real-time design interactions and identify areas of future exploration for engineering educators and designers. In addition, we consider the implications of these tools for design research; automatic data analysis makes it possible to instrument several design workspaces simultaneously, increasing the chance of capturing critical moments, and increasing the opportunity to draw comparisons and contrasts across teams.

Keywords: design, knowledge capture, teams, team dynamics, interactive spaces, meetings, collaboration

1. Introduction

Advances in data sensing and real-time analysis have the potential to radically change the workflow in design environments. Collaborative design teams often take notes, draw whiteboard sketches, build paper prototypes or act out use scenarios during their creative process, and these interactions are captured by many kinds of devices [1, 2]. In our experience, these knowledge artifacts are often limited in their usefulness, because they are not intended as lasting outputs, but rather are by-products generated as team members communicate with each other in-the-moment [3, 4]. The saliency of the unfolding process, which also typically includes the context, conversation, gestures and tacit understanding, is difficult to recover [5]. Knowledge capture systems that focus on retaining the products of the process, rather than its activity, can thus miss the relevance of the process itself. Hence, the advent of computational tools that enable real-time capture and feedback may be transformative in ways that predecessor knowledge capture systems were not.

Quickly advancing technology and globalization will affect the Engineer of 2020 and beyond [6]. Technology captures ever-larger amounts of data, and globalization leads to more international collaboration and more diverse teams. Technology has the potential to aid collaboration within design teams, both enhancing design processes and addressing the perennial problem of friction in design teams, which is only likely to amplify as teams become more distributed.

Modern technology has the potential to build on knowledge capture systems to enable dynamic workspaces that provide real time feedback and information to teams. These augmented workspaces can enable teams to better communicate, to more easily access resources, and to improve their design process. Given the limited resources of engineering educators to interact with teams directly, augmented workspaces could serve as surrogates for the teaching team, supplying additional resources and feedback on team process and direction. Teams could react to this feedback in real time, continuing confidently or changing course as needed.

In this paper, we briefly explore background in knowledge capture and team dynamics, present results from our needfinding efforts within the context of a year-long product development course at Stanford, ME310, and describe various technologies currently available to address identified needs. We focus on what types of feedback are both interesting to teams and technologically feasible without extensive software development and discuss the readiness and shortcomings of modern technology to address these needs.

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2. Related work

2.1 Knowledge capture and reuse

The ActiveNavigator project is a sequel to the WorkspaceNavigator project, which addressed the challenge of recalling work produced during collaborative design activity by teams in unstructured work environments [7]. WorkspaceNavigator comprised of two parts: (a) knowledge capture tools, such as cameras and digital whiteboard markers incorporated into the design workspace, and (b) an online interface for teams and researchers to track visually captured activities along a timeline. The authors highlighted the difference between the fidelity of media used by teams to discuss ideas internally versus the fidelity of media to present ideas externally. The low fidelity of internal media often meant that the design process itself was not well captured, so teams found the WorkspaceNavigator system an invaluable tool to capture and recall their design process while writing final design documentation.

Effective knowledge management has the potential to improve teamwork. However, access to and capturing knowledge are necessary but insufficient conditions for impact. In a building construction exercise involving collaboration between architects, engineers, and construction workers [8], a *knowledge-capture report* generated by team members to summarize key concepts and contributors allowed others outside of the team to quickly understand a project's evolution. However, the authors note that capturing such detailed information requires significant time; moreover, the report lacked any information about the team's interaction. In a classroom setting, researchers created an easy-to-access database of past projects for students to reference during a rapid design cycle but found that access to the database did not necessarily impact design teams. Team coaches had to prompt students to use the database to take advantage of past knowledge [9].

Ideally, knowledge capture systems consume minimal time, and immediately create value for users. Such knowledge management can inform both *content*, in terms of identifying additional resources for teams based on their ongoing work, and *process*, identifying ways the team could more effectively collaborate. Tur et al. [10] transcribed multiparty meetings to identify topics being discussed, isolate action items, and generate a summary of the meeting with modest success, noting the technical limitations of doing so accurately. Branham et al. [11] created an automatic whiteboard capture system allowing users to search back to find captures based on time, thumbnails of images, collaborators present, and a heat map representing locations of content on the board. Junuzovic et al. [12] designed a method for video conference participants to catch up on missed moments of a meeting through *accelerated instant replay* without disturbing other meeting participants. Meeting recall was highest when meeting participants had access to audio, video, conversation transcript, and shared media such as a PowerPoint presentation. Lastly, by displaying pictures based on a team's brainstorming conversation, an augmented workspace can successfully improve a team's productivity [13].

2.2 Studying design teamwork

Many study design teams with the goal of improving team collaboration, and engineering educators continually strive to maximize team success and minimize team conflict. A few psychological dimensions of interest include emotional signals [14], the prevalence of positive or negative affect in a team's conversation [15], physical gestures as a proxy for fluency [16], personality traits and working styles [17], convergent and divergent thinking [18], and psychological safety [19]. Diversity of knowledge can also improve team productivity, but lack of shared experiences on which to form group norms can present challenges to teams [20]. Others study the output of teams and develop interventions to improve creativity and collaboration, as groups in general have mixed success in direct ideation due to factors such as social loafing and production blocking [21, 22]. However, ideas generated in groups often have more communal buy-in as more team members feel ownership for their generation [22].

While many dimensions of group dynamics and productivity are studied using in-depth human coding and analysis, real-time automated analysis would be of more use to design teams in the moment. Wearable *sociometers* can track participants' talkativeness, interactions, social networks through microphones and accelerometers [23]. A higher number of unique noun phrases extracted from end-year design documentation is strongly associated with design team performance [24], suggesting that there may be clear proxies for predicting team success. Conversation analysis [25] can potentially be automated using text-based categorization of human emotions [26] and other psychometric properties [27] to enable real-time analysis and feedback of team conversations and interactions.

3. Research context and needfinding results

Our field observations focused on design teams in Stanford University's year-long engineering product development course, ME310 [28]. Each team of 3–4 master's level students collaborates with a global university partner team on a near-future design challenge, proposed and sponsored by corporate partners. Teams work in a dedicated design loft, which includes individual tables for each team, common work and meeting spaces, and a fabrication workshop. Each week, every student team meets with the teaching team to report on their weekly progress, learning, and plans for the future. Each week, every team also meets with its global partner team to communicate their progress and discuss next steps.

We began with in-situ observation and qualitative interviews with current students and teaching staff, and then invited three teams to work in our Design Observatory, a team meeting and activity space instrumented for audiovisual data capture [29]. This needfinding, combined with testing prototype system tools with design teams, have led us to develop the following three frames, and guided our design of the current ActiveNavigator system.

3.1 Connect teams to past knowledge

Following the guidance that "all design is redesign," design teams need to discover, and reuse knowledge developed during past projects. Each project over 40 years of ME310 history has been distinct in its user's needs, sponsor's point of view and team challenges, yet their collective benchmarking and solution spaces often overlap. The teaching team often refers student teams to review past projects' design documents, but the encyclopedic extent of that knowledge is limited. Each year's project documents are electronically preserved and accessible online, but they are not easily searchable by current project teams beyond the abstracts available on the university's library website.

Search is an active behavior based on issues that are both explicit and prioritized from a design work session. As a result, problems that leave the team uncertain, or ideas that are lightly touched upon, can be dismissed in future discussions and searches. In addition, the need to gather and relate to relevant information in the moment, in real time, is undermined. A system that offers relevant information in real time has the potential to change meeting dynamics, improve understanding of the prevalent problems, and better orient project direction.

3.2 Enhance current interactions within teams

Collaboration is challenging for students, and occasionally teams will splinter before the year is done. Global collaboration presents additional challenges for teams; communication across time, separated by distance and garbled by cultural differences inhibits teamwork. From observing team meetings, we identified two areas of intervention in ongoing process: capturing action items or resources for ongoing team activities, and monitoring or intervening in team dynamics.

Teamwork is a complex social process, and design teams find it difficult to reason and clearly explain to a third party their process of forming ideas or collectively making decisions. Inspiration, change of directions, and sudden realization are often subtle and ephemeral, as is typical in design innovation scenarios. It is thus imperative for our system to retain relevant information of critical design episodes to make them easily accessible to teams after meetings. One team uses a Facebook page to capture key insights, tests, or photographs to share with their global team, but they mentioned that this had limited human interaction, and the value and quality of the information shared decreases compared to video conference calls. One of the most challenging tasks of the year requires the Stanford and global teams to converge to a single design vision after working in parallel for many months, and without extensive memory of teams' design process and rationale, this stage can create friction between teams.

Teams consistently express the interest to learn more about intergroup interaction and intragroup dynamics. Team dynamics are often a key predictor of team success [30], and many have worked to form new teams in a way that balances different personality strengths and weaknesses [17]. There are also times in team meetings where the tone or team dynamic becomes more negative than usual, but meeting participants are often reluctant to speak up and redirect the conversation. Or, one particular team member dominates the conversation, but no other team members speak up. It was also clear from one of our surveys following an ME310 team meeting that not all members agreed that the session was productive. On a 7 point scale from "Extremely Unproductive" to "Extremely Productive," two listed the meeting as 6 ("Moderately Productive") and one listed it as a 2 ("Moderately Unproductive"). These symptoms of larger issues could become problematic if left untreated — occasionally teams will splinter or disintegrate before the projects are completed.

3.3 Clarify teams' future actions

Teams often keep notes during meetings, but they do not always capture all explicit questions and to-do items discussed, given that many team meetings are unorganized and unintentional. Teams also find it difficult to keep track of issues brought up by third parties, such as instructors and coaches, in their weekly progress-reporting meetings. This is especially challenging when attention is given to presenting, rather than receiving, information.

We identified the need for a task list that captures

Fig. 1. We observed student teams as they conferenced with their global partners in our design observatory.

action items explicitly and implicitly discussed during meetings, as in the CALO meeting assistant [10]. Explicit action items include tasks such as interviewing users, visiting particular locations, or building prototypes. They could also include specific action items suggested by the teaching team. Implicit action items emerge when discussion implies perplexity, strong interest, or disagreement. Teams could express interest in an area or user group without dictating a specific action, which could lead to the investigation being postponed for several weeks until it emerges again. A team circling around an old issue again and again for several months is evidence that the issue has not received enough attention to be resolved. For example, a Stanford team may uncover user information in conflict with insights that their global partner team found in a field study. If the issue is properly attended to, both teams would dig deeper into their notes or make further observations or interviews, however without an explicit push to do so, conflict can arise.

4. System components and sample data

We began by using Wizard-of-Oz (WoZ) to prototype interfaces and services for how the system might deliver information in-the-moment. After we verified these needs, we moved forward toward developing tools to satisfy those needs. To connect teams with the past, we built a searchable knowledge database of past ME310 team documents and assignments. To improve teams' knowledge capture and interpersonal dynamics, we explored real-time conversation transcription, speaker identification, and sentiment analysis software. To improve teams' focus on future actions, we used transcripts and WoZ prototyping to identify key concepts and action items. A summary of meeting inputs and outputs is captured in Fig. 2.

We primarily captured data from students during global team meetings, where Stanford teams conferenced with their global partner teams via Skype. The two Stanford teams that we primarily engaged had global partner teams located in Sweden and

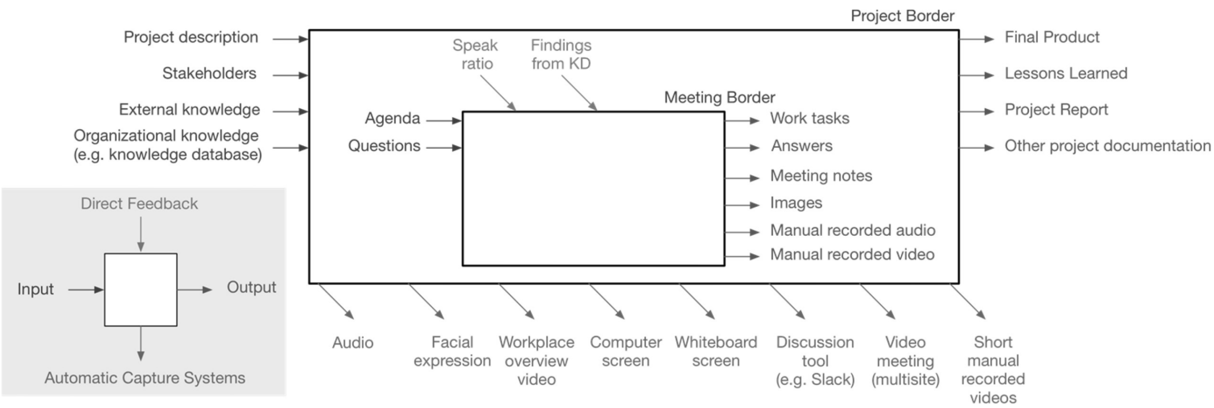

Fig. 2. Key inputs, outputs, feedback, and potential areas of analysis. Information and analysis will be modified with input from teaching team and students enrolled in course.

Table 1. We explored several technologies to address each of the identified needs in Section 3

Identified Need	Explored Technology
Connect teams to past knowledge	Video Capture Conversation Capture Knowledge Database
Enhance Current Interactions Within Teams	Video Capture Conversation Capture Psychometric Analysis
Clarify teams' future actions	Conversation Capture Action Item Identification Critical Moments Prototype

Germany. These two teams volunteered to participate in exchange for a quiet and comfortable space to hold their Skype meetings. The space included a table with chairs, large video monitor, webcam, microphone, and speakers. We recorded each session using four video cameras from different angles combined into a single stream. We also took notes, then transcribed each video, and performed our analyses.

4.1 Video capture

We replicated much of the video capture functionality of the original WorkspaceNavigator system using a simple NestCam, shown in Fig. 3. This smart home security camera captures video and posts it to the internet, making it easily reviewable by researchers and teams. The website also generates easily downloadable time lapses that can potentially summarize a team's day of work to be sent to their global partners.

4.2 Conversation capture

4.2.1 Audio Transcription

Real-time, multi-speaker speech-to-text transcription was a critical element of being able to give teams real-time, relevant feedback automatically. To explore this area, we tested many programs, APIs, and libraries to gather the current state of real-time, multi-speaker audio transcription. These offer a promising future, but presented several unexpected limitations preventing modern adoption in our context. High quality microphones helped the software provide better transcripts, but overall, we were unable to implement real-time transcription to a usable level when recording multiple speakers from multiple countries in an active and naturalistic live meeting context.

Many APIs work well enough for one person speaking slowly and clearly. These include Apple's Siri, Google Voice, and Nuance. However, clarity of transcription with multiple speakers often speaking simultaneously in fragments was very challenging. The best current available software to accomplish

Fig. 3. The NestCam replicates much of the original Workspace-Navigator video capture, with an intuitive website and app to access to video history and create video clips or time-lapses.

this was built on the Nuance recognition engine, Casette. Casette is advertised as a meeting transcription tool for multiple speakers and worked reasonably well for two native English speakers not talking over each other. However, Casette does not differentiate between speakers, and the output is a single block of text with odd punctuation. While it might work sufficiently well to identify common keywords in real time, it would not identify project or course-specific jargon (e.g., "needfinding"). In addition, many algorithms barely understood fluent non-native English speakers, presenting serious limitations for studies with international participants, as is the case for ME310.

The lack of real-time transcription was a significant limitation towards *automatic* real-time analysis and feedback, so we would often do a post hoc review of teams' meetings and Wizard-of-Oz analysis. For the required transcription accuracy, in lieu of real-time audio transcription, we used rev.com to transcribe meetings after they were completed. With nearly perfect accuracy and a turnaround time of 24 hours or less (sometimes much less), a human element was required to generate sufficiently accurate transcripts for other types of analysis. Several post-hoc transcription services are also available that provide automatic computer-generated transcription (e.g., swiftscribe.ai and trint.com). These work reasonably well and have short turnaround times (on the order of minutes).

4.2.2 Speaker identification

We mounted a pair of AcousticMagic Voicetracker II microphone arrays on the ceiling of our design observatory to identify the source of sound around a meeting table, enabling us to identify speakers in real time. These beamforming microphone arrays are designed to localize sound to better capture audio, for instance during a conference call. The arrays transmit a number via a serial port indicating the angle they detect sound. With the pair mounted perpendicular to one another, these two 180 degree

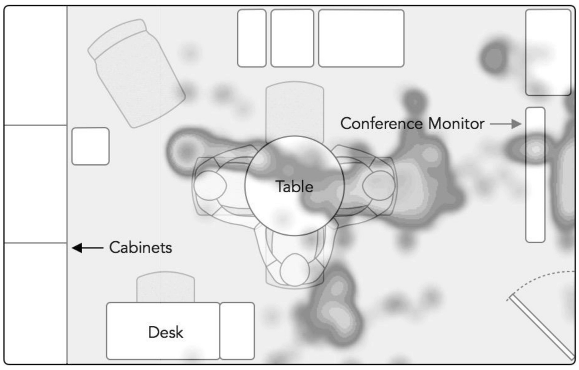

Fig. 4. Heat map of sound sources in the design observatory (approximately 13 × 19 feet). The microphones map the room to a square, so the heat map has slightly different dimensions than the room. Lighter areas within the darker areas indicate dominant locations of sound and approximate speaker locations. Some sound reflections can also be seen throughout the room.

fields of view create a two-dimensional sound localization plot. We connected the two arrays' serial ports to a Teensy 3.5 microcontroller board and sent the combined data to a Processing sketch via USB.

We generated a live heat map of the sound adapting open source code[1], as shown in Fig. 4, and logged it for future analysis. The localization was not perfect, and echoes did cause some noise in the map, but the data likely can be processed to identify speakers reliably. Cross-talk (multiple people talking simultaneously) still presented some challenges and noise within the data. In addition, if speakers stood up and moved around, this would require active monitoring to associate the sound with each speaker.

Several programs, including IBM Watson, advertise speaker identification or differentiation, but we found them to not be reliable enough. Some also require training for the software to work correctly, which presents a barrier to unobtrusively and naturalistically studying design teams.

4.3 Knowledge database and concept searching

ME310 has a large corpus of past projects available to students for their reference. The teaching team often suggests that teams review previous relevant projects during their design explorations. To better enable access to past team assignments, reports, and presentations, we copied the past 12 years of documentation (years that have the most detail available) onto a single searchable hard drive. Using the free software DocFetcher to index and quickly search through the 90 GB database, we could search for key words and offer links to resources during meetings to provoke ideation and after the meetings as resources to complete relevant action items.

Pulling out key concepts to automatically search in the database presented a challenge. The open source processing library RiTa [31] identifies nouns from a transcript that could be fed into a searchable database. However, given the quantity of text produced in a single meeting, more intelligent algorithms were required to parse concepts from nouns. IBM Watson's Natural Language Understanding advertises pulling out key words and entities from text. For example, processing one team's meeting produced the following top 10 keywords: "annotation, app, end point, annotations, Docker, function, request, database, guys, and server," and the following top ten entities: "Google, Docker, Daniella, Boston, Slack, Shawn, Alina, Facebook, US, Gabriel." While not meaningful without observing the meeting, it does reference much of the discussion that revolved around getting access to a database, so the Stanford team could add data points ("annotations") to the app they were collectively building as a team. However, analyzing another meeting's transcript produces the following top ten keywords: "people, content, story, stories, location, thing, place, kind, personal anecdote, guys," and the following top ten entities: "Dish, Stanford, YouTube, Amazon, Dad, Pat, principal, Eiffel Tower, Google, Daniella." These more generic terms allude to the user stories the team discussed in the meeting but are not specific enough to cue memories of any more detailed content of meeting. We find that a more useful annotation system should therefore differentiate unique terms from generic terms to capture the key concepts of the meeting.

By the time the knowledge database had been compiled, students were past their ideation and divergent phases, so the value could not be immediately tested with live teams. However, we believe this database to be very valuable in the early ideation and development stages and look forward to testing it early next year in ME310. Following Jung et al. [9], the database will likely require active encouragement for students to use rather than just making the information itself accessible, and we will have to balance accessibility of information with the potential to introduce design fixation [32, 33].

4.4 Action item identification

Generating a list of tasks in the form of a Kanban Board (like Trello, see Fig. 5) received positive feedback from students. However, with similar problems to concept identification, automating this process proved to be challenging, and was instead performed by a human coder reviewing the meeting video for approximately three hours per hour of meeting. After one of the team's meetings,

[1] http://philippseifried.com/blog/2011/09/30/generating-heatmaps-from-code/

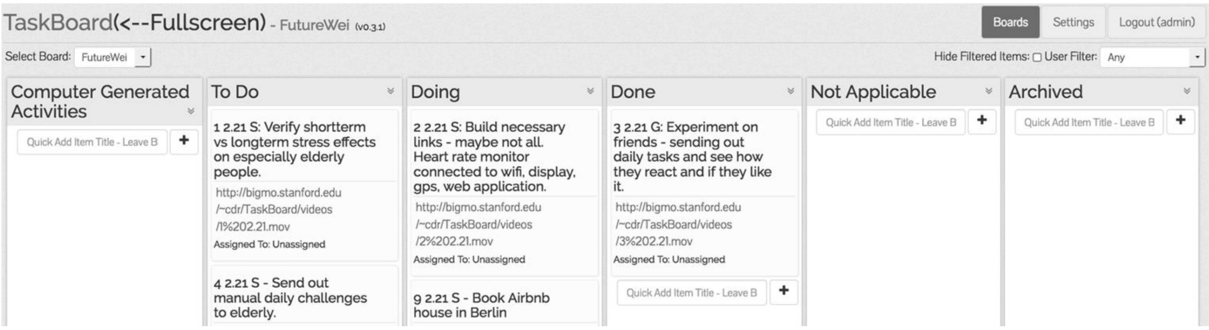

Fig. 5. Sample action item list generated for students. We correctly identified action items reviewing the videos after the meeting, including some the students admitted they missed during the meeting.

we provided a student from the team a list of tasks with links to short videos of the moment the task was discussed in the meeting. We then asked the student to vocalize her observations as she dragged and dropped each "Computer Generated Activity" into one of the following five columns: To Do, Doing, Done, Not Applicable, and Archived. One reaction was the scope of the tasks varying widely, "I think the activities are on different level. Some of them are very short tasks like booking an Airbnb house which is not really connected to the project work. Then there is this overall thing [*converge to the same goal and the same user*] that stretches over the full project." While placing another task, the student mentioned "I don't remember that we spoke about this thing during the meeting." The student expressed interest in using the board to handle smaller/shorter tasks, especially those that she had missed, while those that were larger in scope could be manually broken down by the team.

4.5 Conversation analysis for psychometric information

Assuming we can eventually acquire real-time audio transcription and speaker identification, we explored various ways to inform design process and team dynamics by performing semantic and psychometric analyses. Linguistic Inquiry and Word Count 2015 (LIWC) can process a text transcript for over 70 psychometric dimensions—either looking at an entire text or dividing it into segments of specified length. LIWC looks for instances of words pulled from its large pre-coded dictionary to analyze text along dimensions of interest. Summary dimensions are scaled from 0 to 100 and include:

1. Analytical thinking: higher value represents abstract, logical thinking, while lower value represents personal, narrative thinking.
2. Clout: higher value indicates conversation contains more expertise and confidence.
3. Authentic: higher value represents more honest, personal discourse, as opposed to closed, guarded discourse.
4. Emotional Tone: higher value represents positive tone, while lower value represents negative tone.

We used LIWC to find minima in the participants' tone to verify if the algorithm's lower tone represents problematic team dynamics, as in Fig. 6. A minimum segment length from the LIWC manual is 50 words, whereas an increased number of words will give more correct results. Through iterative testing, we found that a 2 minute segment length (around 150 words) balanced accuracy with data noisiness. However, even so we were unable to correlate LIWC's indication of a negative tone with negative team dynamics. For instance, LIWC could not discriminate sarcasm. At the end of a meeting, one of the German students expressed "we need to end this meeting or I'll be mad," which seems to be a very negative tone when reading the transcript. However, in the video, it is clear that the tone is sarcastic, and the student's body language and humorous vocal cadence conveys a comfortable team dynamic. In another instance of decreased

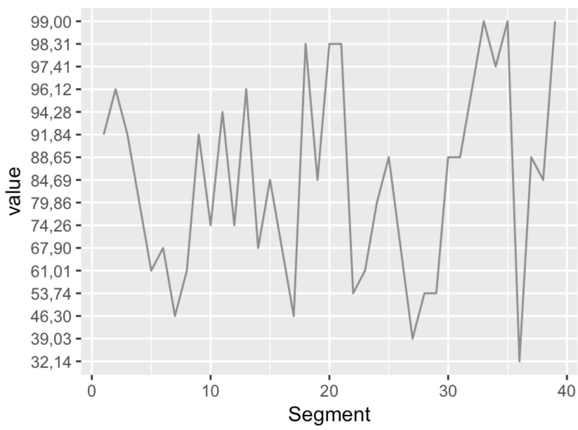

Fig. 6. Plotting 2 minute segments of meeting transcript tone from LIWC shows how conversation sentiment evolves over the course of the meeting. Above 50 represents a more positive tone, and below 50 represents a more negative tone.

Fig. 7. A critical moments prototype tested during a large group. Note the male in the lower left corner with outstretched arm indicating an important moment.

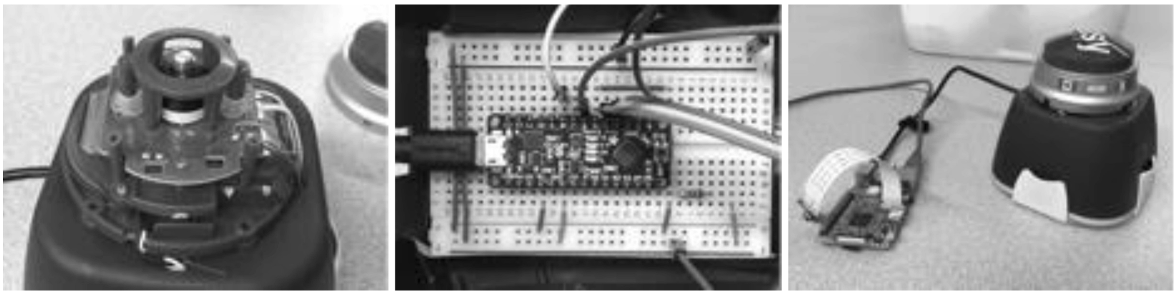

Fig. 8. The current critical moments interface is a large pushbutton connected through an Arduino to a Raspberry Pi. The Raspberry Pi records video using a webcam. When someone presses the button, it runs a Python script that annotates and appends clips of the video recording for later review.

tone, the team members were explaining a situation where they tried to find users but were unsuccessful at talking to them and getting their stories, "Yes, so we went there, but it was very hard to find our user, the older adults. And we approached them and they were very defensive. They did not want to talk to us." It was not that the team dynamic had deteriorated, but rather the students were describing something that they tried that did not work.

4.6 Annotating and reviewing critical moments

We realized that meeting participants would likely be more accurate at identifying important concepts resulting from a session than an automated system might be. We therefore set out to create an interface for them to do so. Allowing participants to note critical moments at the time that they occur, in a visible or audible way, signals to others that someone believes that the immediate discussion is important. It also allows other participants to signal their agreement, by marking the moment as well.

An interface that records, concatenates, and presents these moments can also be used by latecomers to quickly catch up on the current meeting's progress [12], as well as by the team, their colleagues, or superiors to summarize the session's main content at a later time, without having to review the full transcript (see Fig. 7).

Our current embodiment is a pushbutton with several modes (shown in Fig. 8), although we envision other potential implementations as well, such as dropping marbles in a bowl, clapping hands, or tapping the table [34].

5. Discussion

We explored several potential technologies with the expectation that we could combine them into a coherent, live, autonomous intelligent meeting room system. Many of the components express promise, however the lack of truly accurate, live transcription presents the largest challenge to fully autonomous implementation and study. For now, the individual components do still offer potential for design research in and of themselves.

We are currently exploring the use of NestCams, placed at team tables towards the end of each project to capture the process that may be missed in the crunch to meet a deadline. This type of data collection was very helpful for teams in the original WorkspaceNavigator project when they wrote their final documentation for the course. We expect the video to help Stanford and global partner teams better stay in touch and observe what the other team is working on. Global team meetings could then focus more on discussing explicit and implicit action items rather than project work updates.

Given the limitations of real-time transcription, we are also exploring the location and amplitude of sound sources within a workspace as an indicator of team process. Teams that are more vocal and active may be more engaged in their process than teams that are less vocal, or perhaps do not spend a lot of time in the ME310 loft. ActiveNavigator could log activity levels of a team's workspace over long periods of time. It could even be expanded to capture the activity of the entire ME310 loft capturing evolution of the interactions in the space from the beginning of the year to the end of the year.

Linguistic analysis quickly converts raw meeting transcripts or design documents into quantitative data. Positive or negative tone is a good starting point, but other dimensions such as clout, authority, and analytical thinking are also intriguing. For instance, teams that score lower in analytical thinking, or have more personal, narrative discussions, may work better than those who score higher in analytical thinking or more formal discussions. However, it is important to keep in mind the limitation of LIWC and other textual analysis software. The larger sample size the better (with a minimum of 50 words), and LIWC authors also note that it was designed for written communication more than oral communication.

We had originally intended to introduce more elements of our system within the loft that Stanford teams work in, however the technological limitations of audio capture and transcription made this currently infeasible. The ME310 loft has too many disparate sources of sound that would impede audio clarity. Instead, we captured teams mostly within our design observatory, which is a quiet and controlled environment. While students expressed some initial discomfort with being video recorded during their meetings, they quickly got used to it. We made it clear that the video was only being used for research purposes and would not be shared with others. Any kind of system designed to capture information and provide feedback will have to address privacy concerns.

While a fully autonomous knowledge capture and reuse system that aids team dynamics remains many years in the future, an augmented workspace that enables teams to quickly capture important moments, such as the critical moments prototype, is very promising. This does not require sophisticated technology, rather just an interface that enables teams to quickly provide input. Synthesizing critical moments of meetings can be used to catch up other team members who missed the meeting or communicate with collaborators around the world what work needs to be done.

This exploration has identified many avenues of future work to gauge team performance and offer feedback. The largest untapped area is potentially physiological measurement. Stevens et al. [35] suggest that teams enter a form of synchrony as measured by EEG, and there may be other measures such as heart rate and galvanic skin response that indicate constructive or destructive team dynamics or individual states. There is also potential for analyzing body language, as we observed team members not involved or engaged in conversation to have more closed body language (i.e., crossed arms, slumped posture). Pose mirroring is also an indicator that conversation partners associate with one another's positions. As shown with LIWC being unable to discriminate sarcasm, other indicators of meaning such as tone or prosody could map vocal expressions to meaning and team process. Lastly, we need to design methods to give teams feedback on their process in a way that does not make any individual uncomfortable; this is particularly important if the system identifies a problematic team member.

As envisioned by this exploration, a fully functioning ActiveNavigator system would include the following functional requirements: provide students with helpful resources based on conversation content; capture students' design process and track development of physical prototypes for later documentation; identify team dynamics issues in real time; suggest ways for students to improve team dynamics; and capture critical action items for later review and sharing with collaborators.

6. Conclusion

The needs for design teams to better communicate, address unspoken problems, and make decisions may soon be enhanced by commercially available and affordable tools. We have identified several needs that students expressed around knowledge capture and team dynamics and explored ways to potentially address them. We identified needs for teams to better connect to past knowledge, enhance current interactions within their teams, and clarify their future actions. Each of the areas of technology we have explored show promise to address these needs. The largest barrier for now is accurate, live, multi-speaker audio transcription. With accurate transcription, analysis of the teams' conversations could uncover key concepts to synthesize meetings, capture action items, and link teams to resources. We hope researchers studying design activity in-situ will be able to use these tools, methods, and resultant knowledge corpus to develop new tools and feedback for students and educators alike. Longitudinal studies of teamwork with augmented workspaces offer unparalleled access to researchers to uncover processes that contribute or hinder team success.

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