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Collaborative Creation of Engineering Artifacts by Geographically-Distributed Teams

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Abstract

It is common practice today for engineering development projects to be partitioned across multiple, geographically-distributed work locations, often in multiple times zones, and at times, in different countries. Underlying this practice is an implied assumption that the tools and services provided by such the electronic collaboration infrastructure (e.g., electronic mail, audio and video teleconferencing, group on-line editing, sharable file repositories, etc.) used to interconnect the people at these various sites is adequate for supporting such geographically-distributed teams, facilitating their inter-personal communications and collaboration. The goal is for collaborative work to be accomplished with little or no physical travel between these geographically-distributed work sites. In this paper, we describe research conducted to test the validity of this hypothesis, within the domain of projects intended to develop complex, software-intensive systems, of the sort used by the aerospace and energy industries.

We discovered important limitations in such electronic collaboration infrastructures, which limit their ability to support such geographically-distributed collaborative development. Specifically, we found that (for large-scale complex systems development) there is evidence that such mechanisms are effective for geographically-distributed *review* of engineering artifacts, but that they are *not* effective for geographically-distributed *creation* of such artifacts. Understanding this distinction is therefore crucial for effective project management. Such an understanding also identifies topics for future research and development: the need to create more effective mechanisms to support the geographically-distributed creation of complex engineering artifacts. To this end, we present findings from our research on how collaborative generation of engineering artifacts occurs, what are the specific challenges that arise from various modes of geographically-distributed project implementation, and why (within the considered problem domain) current electronic collaboration infrastructure tools are not effective to support this geographically-distributed engineering creation. We conclude by postulating mechanisms and methods that are beginning to contribute to the development of effective tools for geographically-distributed creation of complex engineering artifacts.

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1. Introduction

Large-scale engineering development projects are usually performed by geographically-distributed, collaborative teams. The teams at these multiple sites use electronic collaboration infrastructure (e.g., electronic mail, audio and video teleconferencing, group on-line editing, sharable file repositories, etc.) to coordinate their work across these sites. Underlying this practice is an implied assumption that the tools and services provided by such an electronic collaboration infrastructure are adequate for supporting such geographically-distributed teams, by facilitating effective inter-personal communications and collaboration. The goal is for collaborative work to be accomplished with little or no physical travel between these geographically-distributed work sites.

Since we did not find any experimental research to assess the validity of this hypothesis, we undertook a research program to assess its validity.

This paper describes our research the conducted to test the validity of this hypothesis on projects concerned with the development of complex, software-intensive systems. Examples of such large-scale systems are commercial aircraft, military weapon systems, and complex real-time process control systems.

2. Motivation

It is well-established that large-scale engineering projects often result in schedule- and cost-overruns, while also failing to meet system/product requirement specifications [1] [2] [3]. Many of these sources conclude that the *majority* of such projects fail in one or more of these ways. Therefore, a line-of-reasoning that asserts that "many engineering projects are completed, and of those that are completed, many are performed in a geographically-distributed fashion, and therefore, it is fair to conclude that whatever tools and procedures are used to execute geographically-distributed engineering projects must be adequate" is clearly flawed. The fact that engineering projects are allowed at times to complete, even at a cost many times more than their planned budget, while taking years longer than planned to complete, and that customers at times accept completed systems that fall significantly short of their specified requirements – which is what sources such as those cited above have found – is not evidence of success!

Of course, large, complex engineering development projects might fail for reasons other than the problems caused by the its geographic dispersion. Therefore, in our research, we attempted to isolate weaknesses that might derive solely from the geographic distribution of the people performing the task. We did this by: (a) identifying a small set of project activities that we deemed critical to success (such as design), and (b) comparing artifacts about those particular project activities from real projects, both some that were geographically co-located and some that were geographically distributed, and assessed the quality of those artifacts, and (c) conducted instrumented sessions for these same project activities in both geographically-co-located and geographically-distributed settings, and thereby sought to compare directly how well these activities worked when performed by a geographically-co-located team, as compared to when performed by a geographically-distributed team that makes use of the sort of electronic collaboration infrastructure described above.

Other researchers [4] have identified geographic dispersion of the staff performing a task as a risk to team performance. Some researchers have even pointed to the inadequacy of the electronic collaboration infrastructure as a cause of poor team performance; while today's collaboration infrastructure enables some level of communication and information sharing, these researchers have concluded that such infrastructures are

not able to assure that all members of far-flung teams are "all on the same page" [5]. Said another way, these collaboration infrastructures are inadequate to facilitate **alignment** among the geographically-distributed engineering staff [6], where by the term *alignment* we mean that the individual team members have reached a state of a shared vision of purpose and methods, specifically:

- The team members are motivated by the purposes of the project, are willing to take actions and make efforts that allow the project to succeed, and are occasionally willing to accept less than they desire in order to reach compromises with the other stakeholders
- The team members understand and agree with the *goals* for the project, and understand and concur with project *constraints* and *limitations* (e.g., schedule, cost, capability, etc.)
- The team members understand and agree with the *approach* (methods, tools, locations, facilities, key personnel, sequencing of steps, the design, etc.)
- The team members are willing to work together to reach reasonable compromises on important issues
- The team members are committed to "keeping the project sold," and see it through to a successful conclusion

Several researchers [3] [6] have confirmed that large-scale, geographically-distributed, collaborative development projects routinely tend to be error-prone, primarily because of the inability to track what the different team members are engaged in during engineering development. Furthermore, the psychological literature clearly shows that most of the communication between two people that occurs during a face-to-face meeting is conveyed by means other than the words that each says, through factors such as facial expressions and body language [7]. Much of this non-spoken communication is lost when communications are implemented through an information-technology infrastructure.

3. Experiments

We conducted research on geographically-distributed engineering teams, using *instrumented engineering sessions* [8]. A real engineering team working on a set of real engineering problems was assembled in a single location, and their working sessions instrumented, recorded, and observed by trained observers. Conclusions were drawn about how engineering analysis was conducted, the depth and merit of those analyses, how consensus was reached, the strength of that consensus, how design decisions were made, and the eventual merit of those design decisions. The same team was then geographically distributed, and a different set of engineering problems undertaken. The same information was collected. In both the single-location and geographically-distributed instances, the problems undertaken by the team included both the *creation* of engineering artifacts and the *review* of engineering artifacts. Also, in both the single-location and geographically-distributed instances, actual company and government security / data-protection rules were applied.

These results of these experiments clearly indicated that engineering *creation* and *review* tasks placed different burdens on coordination and communication, and that the burdens imposed by the *engineering creation* tasks was far more extensive than that imposed by the *engineering review* tasks.

Other findings from this research include:

- Current methods of electronic coordination and communication (e.g., email, phone, speaker phone, video conference, sharable file repositories, etc.) were **not** adequate to achieve the *alignment described above* amongst the members of the engineering team.
- If alignment had been previously achieved over a period by co-located team members, then these current methods of electronic coordination and communication appear to be **adequate** for geographically-distributed **review** of engineering artifacts.

- Even if such alignment had been previously achieved over a period of co-location of team members, these same methods of electronic coordination and communications appear ***not to be adequate*** to support the geographically-distributed ***creation*** of those same types of engineering artifacts. The designs resulting from the geographically-distributed creation activities were critically weaker than those created by the single-site teams.

4. Findings and conclusions

Based on the above experiments, we concluded that today's electronic collaboration infrastructure products are capable of supporting geographically-distributed ***review*** of engineering artifacts, but that at the same time, these products are inadequate and ineffective when supporting geographically-distributed ***creation*** of engineering artifacts. We find that this shortcoming appears to explain some portion of the poor track record of large-scale engineering development programs and projects.

In our experiments, these findings appeared to be invariant with regard to the age of the practitioners; there is some indication that younger engineers are more enthusiastic about using the electronic collaboration infrastructure tools than their older colleagues, but there was no finding from our experiments that they in fact achieved better results. This aspect warrants additional investigation; however, it was not a primary goal of our research.

Our research also examined design artifacts from actual, large-scale, complex engineering projects that had concluded. The set of projects examined included both some that were geographically co-located and some that were geographically distributed. In each of these categories, there were projects that concluded on-budget, on-time, and met all requirements, but also projects that concluded far over budget, and far behind the promised schedule. Projects that were actually terminated by the customer prior to completion were also included. There was a material difference in the assessed quality of the examined design artifacts; in general, the design artifacts from the geographically co-located projects were deemed superior to those from the projects that were geographically distributed.

From the foregoing, we developed some insights about why existing electronic infrastructure and collaboration tools are ineffective for geographically-distributed engineering creation. Here are some of the principal such insights:

- Humans have evolved to see both context and detail at the same time; we can use the entire 15,000,000- to 20,000,000- pixel frame human vision to do this, and rapidly (in periods measured in fractions of a second) move our focus of attention from one location to another. No existing electronic collaboration infrastructure supports this vital capability across distributed locations. Directional hearing appears also to be a vital portion of this human capability, yet is seldom supported at all (much less supported effectively) by electronic collaboration infrastructures.
- Electronic collaboration infrastructures generally omit all of the non-verbal communications modes, even though (as cited above) these comprise the majority of human-to-human information exchange. Who is paying attention? Who seems to disagree? These appear to be vital aspects of creation and the forming of consensus.
- During creation, people are very susceptible to losing their train of thought due to distractions. We found that the need to operate computer programs, even simple typing, frequently caused such a loss of the train of thought. The electronic tools cannot operate as fast, or with as little disruption to thought, as drawing on a white board or on a piece of paper. We need tools that can "operate at the speed of thought".

In a separate and later activity, we collaborated with the USC Marshall School of Business on a separate research project (based on a survey instrument) on the topic of geographically-distributed engineering [8]. This

research project was aimed at determining the state-of-the-art across multiple industries and companies for performing geographically-distributed engineering, and the assessment of senior engineering leaders at those companies about the adequacy of engineering creation and review activities under various circumstances. The goal was to determine if there were indications that geographically-distributed engineering was taking place on a regular basis, and if so, to collect various metrics and opinions about the efficacy of that work. Approximately 1,000 responses were received [8].

The survey provided some insight into what organizations are doing today:

- They are using those tools that are commercially available, ranging from speaker phones, to shared data repositories, and group-document editing (e.g., Google docs, etc.)
- They supplement this with physical travel, but generally fail to recognize the distinction between those who are willing to travel, and those who ideally would be the ones to travel.
- They recognize that using today's tools both slows down the progress of the project, and ends up increasing the cost of the project, as compared to performing the project all at a single geographic location. They still undertake geographically-distributed projects, because business reasons require it. They use the available collaboration tools in lieu of co-location or travel because customers and their management seem to expect them to do so.
- They had firm ideas about exactly where the existing collaboration infrastructure tools and methods fell short:
  - They perceive that they are being *slowed down* by the tools
  - They perceive that they are not able to deal with *complicated ideas* using the tools
  - They perceive that they cannot tell *who is paying attention* to the discussion, and who is not
  - *They perceive that they are not able to perform consensus-building* and consensus-checking ("can't see the head-nods")

Our principal conclusions and findings from this survey were as follows:

- That geographically-distributed engineering is very common, occurring in all sampled industries, and almost all sampled companies.
- That geographically-distributed engineering is generally considered more difficult, slower, more expensive, and as having a lower success rate than single-site projects.
- That there is little variation across these companies and industries in the types of tools and methods that are used to implement collaboration infrastructures between sites; they are all using electronic mail, audio and video teleconferencing, group on-line editing, sharable file repositories, and so forth.
- That there was support for the findings of the previous research about the distinction between the efficacy of such infrastructures in supporting geographically-distributed engineering ***creation*** and geographically-distributed engineering ***review***.

The insights gained from the above allowed us to create recommendations for achieving better success in the current tool environment: recognize the distinction between geographically-distributed creation and geographically-distributed review, and, as much as possible, use co-location or extensive travel (by the right people!) for the former, and the electronic tools for the later.

5. Analysis and discussion

Clearly, geographic distribution of large-scale engineering development projects will continue, for a variety of technical, business, competitive, and political reasons. Therefore, improving our understanding of why such geographically-distributed work often fails would be a valuable contribution. So, too, would the creation of

rules, guidelines, and improved tools that would gradually increase the scope of those engineering activities which could be accomplished successfully using geographically-distributed teams.

We have found it useful to distinguish two use-cases for such geographically-distributed engineering: (a) those projects that take place entirely within a single country, or within a single cultural area; (b) those projects that encompass multiple countries &/or cultures.

Use-case 1: projects whose work is geographically distributed across more than one work site, but within a single country, or within a single cultural area. It is common practice today for engineering project development to be split across multiple geographically-distributed work locations, often in multiple times zones and/or countries. This is driven by many factors: wanting to make use of particular company facilities, needing to make use of other companies that possess specialized skills, a requirement from the customer that some of the work be performed at specific customer locations, and so forth.

Such geographic distribution of work creates *additional costs* and *additional risks*. Some of these additional costs result because people must travel, and at times, certain facilities need to be replicated at multiple sites. More subtly, and probably a larger contributor to these increased costs, is the fact that having the team geographically separated *always decreases the efficiency of the team*; coordination is harder and less effective; so are communications. Creating options, analyzing them, and reaching consensus are all harder, too. These same effects usually cause the schedule to require more time, too. Because of the decreased efficiency of the team, the risks that might arise from poor coordination and communication are increased; in particular, we determined that the designs created by geographically-distributed teams were generally not as good as the designs created by co-located teams. Since design is a critical element of almost every engineering project, having weaker designs is a significant risk, and a likely contributor to project failures and dissatisfied customers.

Not all approaches to geographically-distributed engineering appear equally effective; such work seems to be more feasible if you geographically separate only those tasks that require relatively weak coordination, and geographically co-locate at the same site those tasks that require extensive coordination with each other.

You must also account for the *additional schedule, cost, and risk* in your proposal and project baseline. If a company probably has performed geographically-distributed work in the past, they may have records that can be used for calibrating your schedule and cost predictions, so as to account for the decreased efficiency caused by geographic distribution.

People will tell you that you do not need to worry about this, that modern information-technology infrastructure and tools (email, speaker phones, video conferencing, shared file repositories, and so forth) are so good that the geographic distribution does not matter. Our research findings, cited above, do not support such an optimistic view. Our findings – and those of other researchers – show that *there is a significant degradation of team efficiency* with geographic distribution of the participants. As noted above, one of our own contributions is to distinguish between the case geographically-distributed *review* of project and engineering artifacts, and the geographically-distributed *creation* of these artifacts.

You will need to have significant travel budget to allow team members to meet face-to-face, and at times, to co-located for extended periods. But even this is less than perfect; research [4] has shown that many people do not like to be away from home for long periods of time on business travel, and that what you therefore get are a set of people who are *willing* to travel, but who may or may not be the people who are *best qualified* to do the work.

Geographically-distributed projects, therefore, *always* incur inefficiencies. Our recommendations for coping with these inefficiencies are to (a) partition the work in a feasible fashion, as described above, (b) get some

appropriate compensating means and resources into the proposal and the schedule / cost baseline, (c) work hard to get the right people actually to travel, (d) be aware of the distinction between engineering *creation* (which is not generally feasible for geographically-distributed teams) and engineering *review* (which may be feasible for geographically-distributed teams), and (e) must constantly monitor this as a gigantic risk to the project.

Use-case 2: projects that include teams located in multiple countries &/or cultures. Many projects are not only geographically distributed, but those geographic sites are located in multiple countries. Obviously, all of the issues that we just talked about pertain to these projects, but there are some additional factors that apply to these projects. These additional factors pertain to *law* and *culture*.

The factors of law are items such as these:

- What law and regulations are applicable under what circumstances, and in what locations?
- There are almost always restrictions about moving information, equipment, and people to and from certain countries.
- How are disputes that might involve parties in multiple countries to be resolved?
- What expenses are to be paid in what currencies? There are risks involved in the fluctuation of currency exchange rates, too.
- Are there limits or procedures that must be followed to move funds from one country to another?
- Are there risks created by the particular employment law and regulation in particular countries? For example, in some countries, your company may have an obligation to pay employees for quite a while after a project completes. Such costs must be accounted for in your proposal.

The factors of culture are items such as these:

- Work ethics and work habits vary significant from culture to culture. For example, in some countries, everyone goes home exactly at 5:00 pm; in others, if there is a vital task that needs doing, they will stay and get the task done. Do you have data that allows you to calibrate for this in your proposal? Have you trained your team to know these differences? Do you have a strategy for how you will operate in the presence of these differences?
- Skill levels vary significantly from culture to culture; people with nominally the same job title in different countries will know very different things and have far different levels of skills. Do you have data that allows you to calibrate for this in your proposal? The same thing applies to education; a bachelor's degree in computer science may mean very different things in different countries.
- Sociologists and psychologists use a term called *power distance* as a measure of the social distance between the layers of a hierarchy [9]. Power distance varies hugely from culture to culture [10]. Other factors of culture will also vary, and therefore the methods that are effective in dealing with your team members will vary from culture to culture. Do you and your management team have the requisite understanding of each culture that will participate on your team?
- Cultures vary significantly in their willingness to bring forward bad news; in some cultures, this just is not done. Do you know the culture of every country participating on your team? Do you have mechanisms in place to compensate for these cultural variations?

6. Ideas for correcting the problem – future work

Our work has primarily been focused on characterizing the problem (which we believe has not been generally recognized to date), and to use the distinction between *engineering creation* on the one hand, and *engineering review* on the other, as a way to deal with some aspects of the problem. We tested and discussed a few other recommendations, as well, as described above.

We conclude by identifying a few concepts that might be the basis for future research and development that would lead to better mechanisms that could actually be effective in their support of geographically-distributed engineering creation. First and foremost, we need electronic collaboration tools that address the principal issues that we found during our instrumented engineering sessions:

- We need to see context and details at the same time
- We need the ability to shift our focus of attention rapidly and effortlessly from one location to another
- We need to support all human senses, including directional sound
- We need to support the non-verbal modes of human-to-human communications: head-nods, body language, indicators of paying attention (or not!). Even the most-exquisite video teleconferencing available to-date has proven grossly inadequate for this purpose. We need to do this effortlessly across all of the participants in the room.
- We need tools for notation of work-in-progress that can "operate at the speed of thought"

In general, all electronic collaboration tools in use today are too slow, and too distracting to the train of thought, to be useful for collaboration-intensive tasks, such as engineering creation.

Recent advances in collaborative distributed systems engineering hold the potential to ameliorate some of the problems identified herein regarding geographically distributed teams:
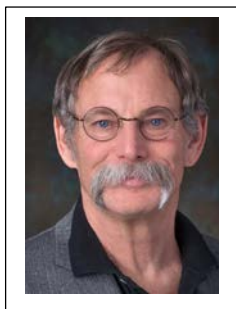
- *Context-aware Collaboration* [14] [12]. Successful collaboration among members of distributed teams depends to a large extend on maintaining shared context during artifact generation. Current tools either provide weakly-organized contexts or require far too much manual intervention to create a specific context. Working definitions of a viable context do exist [13].
- *Process-Driven Collaboration* [3] [13], This form of collaboration requires explicit representation of Process Ontology [14] [15]. Most existing electronic collaboration tools have at best weak connections to the engineering process, and to the design or organization of the specific project. Explicit representation and visualization of processes (called process-aware or process-driven or process-centered collaboration) can be a big help for problems that can be addressed by a well-defined process flow. [15] [17] [3].
- *Dynamic Context Management* [16]. The context in collaborative development of engineering artifacts by distributed teams continuously changes as the team makes progress. Consequently, the artifact (s), activities, and individuals in various roles need to be monitored and changes in context tracked. This capability is discussed in Multi-chip Module Design Process Management [13].
- *Complexity Reduction* [6] [3]. We already alluded to the value of careful selection of which tasks are geographically-separated and which are co-located. Additional ideas along this line are found in [6] and [3].
- *Multi-perspective Visualization* [18]. We already alluded to the problem of providing both context and detail at the same time. Experiential dashboards with embedded cues and alerts may offer the means to pull together geographically-distributed teams into a common world that assists at bridging some aspects of working apart [19].
- *Interactive Model-Driven Storytelling* [20] [21]. We already alluded to the difficulty at creating an effective design across multiple geographic sites. Mapping system models to system stories and having stakeholders interact with them in virtual worlds is an effective means to engage all stakeholders [22].

7. Summary

It is common practice today for large-scale, complex engineering development projects in the aerospace, defense, and energy industries to be partitioned across multiple, geographically-distributed work locations. Underlying this practice is the assumption that the mechanisms available to support such geographically-distributed teams are in fact adequate and effective for such a purpose, and therefore, the work can be accomplished with either no physical travel
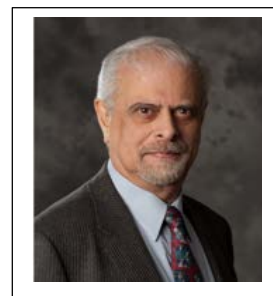
of practitioners between those geographically-distributed work sites, or that only occasional physical travel to other work sites would be required. Sadly, this appears not to be the case; we proffered evidence that these mechanisms are, in fact, ***not*** generally effective to support such geographically-distributed development; in particular, they are inadequate to support geographically-distributed *creation* of engineering artifacts, although they may be adequate to support geographically-distributed *review*. We identified a specific set of deficiencies. Understanding this distinction between creation and review is crucial to effective execution of project management responsibilities. The paper concludes with an identification of approaches, mechanisms, and methods that can potentially contribute to the development of effective tools for geographically-distributed creation of complex engineering artifacts.

8. About the authors:

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