Open Sourcing the Design of Civil Infrastructure (OSD-CI): A Paradigm Shift

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ABSTRACT

Few will argue the importance of civil infrastructure to society, yet its condition has been allowed to deteriorate to a staggering level. Meanwhile the research and design practice dedicated to it has relied only upon limited, fractured resources scattered physically across the community with little formal collaboration. As the information used in the design, analysis and even management of civil infrastructure is trapped inside proprietary systems, these essential public works projects often do not benefit from the full expertise and latest advances available in the wider engineering community. To address this problem, a new virtual organization has been launched: Open Sourcing the Design of Civil Infrastructure (OSD-CI), welcoming Citizen Engineers to engage in four dimensions of collaboration (sharing hardware, software, knowledge and manpower). This paper presents the ongoing development of this concept, specifically focusing on two recent prototypes allowing this crowd to contribute and assess engineering data.

INTRODUCTION

A few years ago, no one would have believed that a global team of volunteers could write a major operating system kernel or a comprehensive encyclopedia. But today, Linux and Wikipedia and many similar open source projects serve as evidence that loosely organized teams can create and maintain the complex technical and intellectual infrastructure upon which society increasingly depends (Raymond 2001). These projects have succeeded not by accepting participants indiscriminately, but by creating a meritocracy that rewards expertise regardless of its source. Yet interestingly, what is viewed as the best cognitive model (the crowd) has been applied to relatively non-technical societal problems (Surowiecki 2005). Why not then tap it to address one of society’s grand challenges: its aging civil infrastructure?

Interestingly, civil engineering is naturally suited towards open source concepts: complex systems like buildings, bridges and other lifelines have many different stakeholders, require many kinds of technical expertise, and have a lifetime far beyond any one contributor. As the information used in the design, analysis and even management of civil infrastructure is trapped inside proprietary systems, these essential projects often do not benefit from the full expertise and latest advances available in the wider engineering community. To address this problem, a team of civil engineers, computer scientists and social scientists at the University of Notre
Dame are engaged in the formation of a new type of virtual organization for Open Sourcing the Design of Civil Infrastructure (OSD-CI). OSD-CI will allow stakeholders – engineers, public officials, researchers, students, and even the public at-large – to review, propose, modify, evaluate, and contribute to designs, analyses, databases and other fundamental research that supports civil infrastructure and will provide these Citizen Engineers with unparalleled access to tools that will empower their individual inquiry.

The OSD-CI Concept

While it may seem bold to suggest that engineers would agree to crowdsource their problems, it is important to note that the profession presently operates within a limited crowd construct. Both scholarly research and state-of-the-art design depend on the efforts of predecessors and contemporaries, and the crowd, via peer review, citations, and standardization, decides whose work is best (Surowiecki 2005). This project now boldly extends that crowd to the public at large, with appropriate policies, governance structure, incentives, and control mechanisms to assure trustworthiness in technical tasks (Johnson 2006, O’Mahony and Ferraro 2007). As shown in Figure 1, this collaboratory would accept job submissions from end users (firms, researchers, fellow Citizen Engineers), who would specify relevant details (scope, constraints, models, etc.), deadlines, submission formats, and requisite credentials. Citizen Engineers with the proper credentials and membership status (a concept discussed in a later section) can volunteer to contribute to these job submissions, either individually or as part of teams, using the various computational resources and tools housed in the portal. The products produced by Citizen Engineers are archived in the collaboratory’s design gallery and can be retrieved and commented on by any member of the public to form a truly transparent archival system for Civil Infrastructure projects. These products are ultimately delivered back to the end user through various aggregation schemes.

Figure 1. Four dimensions of sharing and mechanisms interfacing them in OSD-CI.
One may ask: what are the incentives for end users to bring their jobs to the OSD-CI portal? Eventually, every firm is faced with projects requiring expertise outside the restricted range of their staff’s abilities and experiences. The crowd provides a flexible and informal mechanism to obtain needed expertise for specific projects at little to no cost. The OSD-CI therefore provides a mechanism through which firms of varying sizes can “crowdsource” specific projects, allowing the firms to both focus on their core competencies and obtain the expertise to solve problems requiring a more diverse group. Conversely, Citizen Engineers, whose demographics may be broad, have similarly diverse reasons to join the crowd. For members of the general public, status and ratings within a community of users and the chance to be part of a larger initiative that serves the public good has been shown to sustain involvement. However, to attract Citizen Engineers with higher level qualifications, other incentives are required. Networking, potentials for career advancement, and exposure to potential employers may be sufficiently attractive, especially for the legions of unemployed engineers. For licensed engineers, OSD-CI activities can be used to earn professional development hours (PDHs). Of course, direct monetary compensation will be warranted for those working on the most complex and challenging problems. Thus, one of the major research endeavors of this project is to determine which types of incentives work best for wide ranging tasks within OSD-CI.

Cyberinfrastructure Requirements

There are many successful examples of open sharing of computational resources (SETI@Home), source code (Linux), knowledge (Wikipedia), and even manpower (Amazon's Mechanical Turk); however, the unique feature of OSD-CI is that it will enable collaboration in all four of these dimensions as part of an integrated design chain shown in Figure 1. While this in and of itself is challenging, it is further compounded by the fact that these social computing principles have never been applied in high risk application domains where failure has serious implications. However before the issue of how to assure trustworthy work can be tackled, a robust cyber-platform must be developed to support these four dimensions of collaboration and their three distinct repositories of interacting data: (1) a design gallery consisting of all the active job submissions, (2) the social network representing the properties, qualifications, and actions of all the Citizen Engineers participating in the system, and (3) the tool repository -- a collection of open source and contributed tools from members of the collaboratory. Figure 2 provides examples of these tools such as data archives, real-time data, tele-experiments, simulation/analysis tools, and e-design aids (Kareem et al. 2008, Kwon et al. 2008). A key feature of the tool repository is the provision for both open source tools to be embedded in the system and the capacity to upload/download information and results to/from proprietary software whose analyses have been executed locally by a Citizen Engineer outside the portal. As such, Citizen Engineers will retain ongoing access to the analyses they trust and have access to new collective resources that all can be seamlessly integrated in the design chain. Further, since computational demands of various actions in the portal will vary widely, at times surpassing the local computational resources of the Citizen Engineer, there is the capability to farm computations out, e.g., to Condor or Amazon’s Elastic Computing Cloud.
Balancing Trustworthiness and Openness

Many open source systems began with no controls in order to foster maximum openness, e.g., Wikipedia. Interestingly, its founders later regretted that structure and the lack of *a priori* roles for experts (Lih 2009). Considering the high levels of risk involved in the proposed effort, the competing requirements of trustworthiness and openness are best optimized through a tiered collaboratory. This concept, shown in Figure 3, acknowledges that there is a wide spectrum of tasks with diverse requirements that not all members of the crowd would be qualified to address. At the highest tiers, projects would be increasingly complex, may require sophisticated analysis tools and substantial computational resources, and in turn offer higher levels
of compensation, but as a result, greater selectivity within the crowd. This produces a spectrum of participation from crowdsourced to sole sourced.

One of the major advantages of the tiered system is that it provides a mechanism for building trust through transparent credentials and rating systems for all its Citizen Engineers, based on the accumulated reviews received from past contributions (similar to ratings on e-Bay and Amazon). These ratings will not only create incentives, but they will also provide end users with information that they can use to pre-qualify Citizen Engineers for their projects and a mechanism to evaluate and even aggregate their submissions. The result would be a form of tournament mobility as shown in Figure 3, where Citizen Engineers would start off “competing” at lower tiers and as their efforts are positively evaluated they would become qualified to “compete” at higher levels.

EXAMPLE CROWDSOURCED PORTALS FOR CIVIL INFRASTRUCTURE

Having summarized the basic concept behind Open-Sourcing the Design of Civil Infrastructure, two case studies will be presented to demonstrate the cyberinfrastructure that can support various activities executed by Citizen Engineers.

Case Study 1: Applying a Participatory Sensing Paradigm to National Infrastructure Monitoring

There has been considerable attention paid to the concept of ubiquitous sensing for evaluation of aging infrastructure. As visual inspections are generally executed every 1-2 years, potentially significant damage can be present for sometime before the next inspection cycle. Therefore the first prototype developed in OSD-CI portal seeks to leverage the multi-sensor array with the highest on board computational and decision making power: humans. The prototype, launched late in the summer of 2010, asked Citizen Engineers, in this case Notre Dame engineering students and any family and friends they referred to the portal, to collect visual evidence of degrading infrastructure. By mobilizing citizens to collect images of troubled infrastructure in their communities, the capability for identifying potential troubled structures in the period between their regular inspections is greatly enhanced. Further, by these simple engagements of the general public, overall attitudes and awareness surrounding civil infrastructure can be heightened, creating more stewards of our national infrastructure and allies in reversing our infrastructure crisis.

To facilitate this crowdsourced project, the development of a robust and reliable portal was first necessary. The portal includes a welcome page (Fig. 4) with relatively standard features that permit users to create a secure account and manage their profile. The more significant objective was to create a seamless approach to receive geotagged photos acquired in the field. It was important to remove technological barriers from this process to maximize participation by citizens as they are going about their daily routines. As a result, users, after establishing an account tied to a specific email address, were provided with a detailed tutorial that demonstrated how to enable geotagging on their smart phones and a means to directly submit the images from their phones or upload them directly through the web portal (Fig. 5). In the event the participant did not have geotagging capabilities, i.e., phone does not permit geotagging or participant was using a standalone digital camera, users
can either input the street address or use a movable marker to pinpoint the site locations in Google Maps during the image upload process (see Fig. 5). However, the experiment found that the overwhelming majority (99%) of photos submitted were geotagged, proving that this is a seamless way to collect data on distributed infrastructure systems.

At the server side, submissions are tied to a database for indexing. This database allows all submissions to be visually represented using colored balloons/pins as shown in Figure 6, so that the details of any submission of the crowd can be easily viewed by administrators by clicking on any of these balloons/pins. Further, the use of Google Maps creates an easy to navigate interface familiar to most users.

It should be noted that the portal was opened one week before the start of classes in the Fall 2010, leaving a limited time for participation by most students.
Even so, the portal received documentation of a wide range of infrastructure degradation from cracks and holes in pavements to significantly deteriorated bridges and piers. However, only about a third (32%) of Citizen Engineers creating accounts actually uploaded one or more images – a common issue in virtual organizations – however the active users submitted on average 21 photos each.

**Case Study 2: Applying a Crowdsourcing to Infrastructure Assessment**

While the previous case study provides a demonstration of how Citizen Engineers can be harnessed to collect data, this data needs to be effectively analyzed to make meaningful decisions. This begs the question of what would be the most effective motivator for Citizen Engineers to conduct such analyses, providing their time, knowledge and effort with little or no promise of pay or recognition? The issue of motivation is central to the entire spectrum of crowdsourced activities, but specific to engineering, where the tasks are highly technical and thought intensive, the question is even more relevant. To answer this question, an experiment was developed in the Fall 2010 to evaluate the types of extrinsic motivators that are most effective in enhancing not only the quantity but also the quality of Citizen Engineer’s contributions. In order to simulate a meaningful and authentic crowdsourced civil engineering task likely to resonate with citizens’ volunteer spirit, the case study utilized a database of 400 photos of damaged reinforced concrete and masonry buildings collected by the author during field reconnaissance in Léogâne, Haiti in March 2010, two months after the catastrophic earthquake. The objective of the crowdsourced task was to ask Citizen Engineers to identify the type and severity of damage in each photo. Considering the large repositories of photos from reconnaissance following disasters, often not completely categorized or databased by their curators, if the crowd could be leveraged to accurately execute such a task, then an automated repository could be created and easily mobilized for future disasters.

The primary challenge was first to develop a schema that can break the classification of a damaged structure into a series of simple, progressive steps that could easily be replicated by citizens without an engineering background and could be implemented readily in the portal. The final classification schema used in the experiment is shown in Figure 7, customized for the construction style in Haiti. The schema asks which elements are visible, if they are damaged, and if so the type of damage and its severity. The first three classifications are largely objective, while the fourth is quite subjective. A detailed web tutorial was created to familiarize the Citizen Engineers with the schema. Figure 8a shows a screen shot of part of this tutorial focused on element identification. Later stages of the tutorial introduce various damage patterns and, as shown in Figures 8b-c, allow Citizen Engineers to take self-quizzes to gauge their understanding of each step of the schema.

After Citizen Engineers create an account, complete a brief entrance questionnaire collecting various demographic and attitudinal data, and conclude the tutorial, they are unknowingly and randomly assigned to one of four groupings depicted in Table 1. An equal distribution of participants (~50) is assigned to each of these groupings, assuming a total of 200 participants. The groupings explore the effect of monetary vs. moral incentives, as well as the impact of information fed back to the participants. Specific to the latter point, all participants receive information on the number of photos they have classified or “tagged” in the database, however, 50%
of the participants will also receive feedback on their ranking (in terms of number of photos classified) relative to others in the portal. This is expressed as a second status bar, shown at the top of each screen shot in Figure 9.

Table 1. Four possible groupings for participants in the Haiti photo classification experiment.

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<tr>
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<th>Utilitarian</th>
<th>Moral</th>
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<td><strong>Incentives</strong></td>
<td><strong>Information:</strong></td>
<td><strong>Incentives:</strong></td>
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<tr>
<td>Individual</td>
<td>cash prize based on performance</td>
<td>watches short movie about earthquake in Haiti and need for help in assessing damage.</td>
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<td></td>
<td>sees only personal progress</td>
<td>sees only personal progress</td>
</tr>
<tr>
<td>Collective</td>
<td>cash prize based on performance</td>
<td>watches short movie about earthquake in Haiti and need for help in assessing damage.</td>
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<td>sees progress relative to all other participants.</td>
<td>sees progress relative to all other participants.</td>
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Figure 8. Screenshots of Haiti photo classification tutorial: (a) definition of structural elements, (b) self quiz, (c) self quiz with solution.
Figure 9. Screenshots of Haiti photo classification process: (a) identification of structural elements, (b) determination of damage, (c) classification of damage type. Status bars shown at top of each screen shot indicative of what a Citizen Engineer in the collective information grouping would see. Individual information assignees would see the same interface but with only the first status bar.
The classification process uses a set of web pages that adapt to the previous responses at each step of the schema. An example of this sequence of pages is shown in Figure 9. Each participant is asked to classify a minimum of 25 randomly assigned photos of buildings in Haiti; however it is hoped, by virtue of the incentives and information they receive, that they will classify more and possibly all 400 photos within seven days of joining the study. At the close of the seven day period, all participants complete an exit questionnaire to gauge their attitudes and identify any functional issues with the portal or classification schema.

As both quantity and quality of classification is of interest in this application, three expert taggers (structural engineers) have independently classified all 400 photos in the database to create a “key” against which each Citizen Engineer can be graded. The analysis of the data collected from the study that evaluates performance of the crowd as a function of their assigned groupings, wide ranging variables associated with their survey responses, as well as their monitored actions within the portal (time spent on each photo, etc.) is beyond the scope of this paper; however, space does permit a brief discussion on the participation within the portal.

The portal was opened in November 2010 to Notre Dame students. In total 242 students created accounts, hailing from the Colleges of Science, Engineering, Business, Architecture, and Arts & Letters. These users executed 9445 photo classifications over a two week period or approximately 30 classifications per user. In fact, a handful of users classified all 400 photos in the database. More importantly, this resulted in an average of 23.6 classifications for each photo in the database. This would allow the “wisdom of the crowd” to be effectively gauged for each photo with sufficient statistical significance. Again not only will this allow various incentives and motivational constructs to be evaluated, but also will determine if the crowd is capable of achieving consensus or if refinements to crowdsourced engineering tasks are required. This could, for example, include grouping Citizen Engineers based on their expertise or past performance within the portal and assigning their work units accordingly.

CONCLUSIONS

This paper introduces the formation of a new virtual organization to enable Open Sourcing the Design of Civil Infrastructure (OSD-CI), allowing all stakeholders – engineers, public officials, researchers, students, and even the public at-large – to engage as Citizen Engineers in four dimensions of collaboration: harnessing human effort, tapping collective knowledge, pooling communal software and leveraging distributed computational hardware, to rehabilitate our nation’s deteriorating civil infrastructure. It should be noted that this project is particularly challenging as most social computing applications have only been attempted on projects with relatively modest technical demands, while structural design faces significant policy and technical challenges. However, this project demonstrates how the collaboration between civil engineers, computer scientists and social scientists can develop cyberinfrastructure and the appropriate policies and governance to extend one of the most powerful cognitive models – the crowd – to one of the most pressing societal problems – the design and maintenance of civil infrastructure – by leveraging an army of Citizen Engineers.
The two case studies presented in this paper demonstrate how cyberinfrastructure can be developed to facilitate a participatory sensing paradigm to monitor civil infrastructure using geotagged photo submissions and how extensions of these portals can be used to harness the wisdom of the crowd to assess and ultimately curate archives of reconnaissance photos of damaged infrastructure. This latter portal, using actual field data from the 2010 Haiti earthquake, has provided the opportunity to further study the incentives (moral vs. monetary) and motivators (feedback regarding Citizen Engineer’s status relative to others in the portal) required to maximize both the quantity and quality of voluntary work units within crowdsourced civil engineering projects. The outcomes of this research and the data collected through this latter case study will be critical to determine how best to incorporate distributed Citizen Engineers into a faithful design process that ensures extreme trustworthiness in technical tasks, while promoting participation as a first step in realizing the grander vision that is OSD-CI.

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REFERENCES


Raymond, E.S. (2001). The cathedral and the bazaar : Musings on Linux and open source by an accidental revolutionary; O'Reilly; Cambridge, MA.
