The hard hat and the hand-held:

Communication with Hand-Held Computing in the Construction Process

by

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Submitted to the Department of Architecture on June 20, 2010 in Partial Fulfilment of the Requirements for the Degree of Masters of Science in Architecture Studies

Abstract

Computer hand-held devices have the potential to revolutionize the methods of communication in the construction process. The compelling feature of hand-held computers is their ability to integrate GPS, video cameras, magnetometers and other sensors with an array of construction-relevant data layers in a highly portable form factor. This technology has the capacity to locate people in space, give them information relevant to who they are and where they are as well as allow them to input information into the system on the go. Through extensive research and interviews conducted with architects, construction managers and foremen, this thesis will assess problems inherent in the construction process and propose a new vision for methods of communication. This vision will be expressed through the design of a new hand-held application prototype.

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Introduction

Communication in the construction process needs to be simplified.
Computer hand-held devices have the potential to revolutionize the way we build and maintain buildings. The compelling feature of hand-held computers is their ability to integrate video cameras, magnetometers, GPS and other sensors with an array of construction-relevant data layers in a highly portable form factor. This thesis will assess problems inherent in the construction process, outline the evolution of construction hand-held computing technologies, identify opportunities for further improvements and propose a new hand-held application prototype.

For many years, paper drawings have been the main form of information exchange between architects and construction workers. Traditional paper-based approaches have been limited due to problems of delayed communication between team members, outdated information and inability to contextualize problems. In the past decade, architects have started to use 3D Building Information Modeling (BIM) to design, communicate and coordinate information with consulting teams, all the while sending traditional paper drawings to the construction site. Hand-held computer devices have become increasingly widespread at the construction field creating the potential for information to be made available to construction teams in novel ways. Yet 3D BIM models are heavy and complex files that contain an overabundance of information about the overall project often far beyond the needs of construction teams. Giving access to these files to front-line construction workers would needlessly confound and complicate their tasks.

Other industries have applied hand-held computing to great effect. Examples include 1) healthcare, 2) manufacturing, and 3) navigation. The effective use of hand-holds, however, also requires innovations in user interface. Google Earth and Layar are examples of software that illustrate how layers of information can be revealed through an intuitive zooming process.
In Google Earth, the viewer can query for information based on a location and interest. As one zooms into the model, the visual information transforms to become more context-specific and detailed. In Layar, an augmented reality applet, the viewer does not even need to know where she is located. Through an embedded GPS sensor in the phone, the position of the viewer is identified and information relevant to her interest is revealed on the screen superimposed on a video of the scene facing them.

A similar solution can be envisioned for the construction industry. As users walk through a hectic construction site, they should not need to know their exact location in the project. Through a combination of GPS and other sensors that are becoming standard, devices can assume the viewpoint of their users and visually guide them through the project. As users move through the site, up-to-date information relevant to their location, perspective and area of interest (e.g. plumbing, electrical, millwork etc.) can be exhibited on the screen. At the same time, visual information on problems arising at the construction site, as well as their impact on the overall schedule and people involved, can help create additional layers of information that can be exchanged among diverse teams.

A next-generation hand-held solution for the construction industry would have to address issues of intuitive navigation of information on site, mediate between real and virtual environments and facilitate dynamic communication and project management among various teams engaged in the construction process. This thesis will investigate a new hand-held application prototype to address these issues.

Chapter 1 will briefly examine the history of the relationship between architects and construction teams as well as the evolution of technologies and organizational principles used in the construction process. Chapter 2 will outline the current
technologies available for visualization and navigation of geographic and 3D information using portable and hand-held computing.

Chapter 3 will feature interviews with diverse participants in the construction process with each identifying unmet needs and opportunities for better software. The subsequent chapter and main body of this thesis is concerned with proposing a software prototype that can address the shortcomings of current applications by integrating advances in visualization and navigation in the latest hand-held computing form factors.

In chapter 5, this thesis will propose methods to evaluate and analyze the effectiveness of the proposed software. And finally, it will identify opportunities for further research and improvement upon the proposed prototype.
1. Background: methods of communication at the construction site and current state of technology

“it is not necessary to change. Survival is not mandatory.”

William Edwards Deming

http://www.cartoonstock.com/
Conventional methods of communication between architects and construction workers

Construction projects are complex undertakings, which require the cooperation of many people with different skills and expertise. In the majority of construction projects architects are responsible for understanding and formalizing the client’s vision and relaying that information to other team members. As generators of physical representations of the project, architects can be thought of as input to the construction process. Construction workers, on the other hand, specialize in different trades and are responsible for the physical execution of the project. As implementors of the architect’s plans, they can be considered to be the output to the process. Clear communication between architects and construction workers, effectively bridging input and output, becomes crucial to the success of the project.

In the Stone Age, people designed and built their own dwellings. The first buildings were simple huts, tents and shelters meant to suit the basic needs of protection from the elements, built by their inhabitants. In such a relatively closed-loop system, architects and construction workers were one and the same. People were able to learn to translate ideas into physical form as well as how to use materials and tools at their disposal. Questions were originated and answered by the same person.

In the Middle Ages in Western Europe, the development of cities led to the division of labor and the emergence of professional crafts. This created a need for a mediator between the client and the craftsmen, namely the master-builder. Master-builders served two simultaneous functions. On the one hand, they worked closely with the client to develop the design intent and, on the other hand, they instructed craftsmen on the execution of the project. (Fig 1) “The advantage of this method, however, was that
there was one person to solve problems and address the issues right there on the job, one person who had all the information." (Kymmell 2008, 5)

As projects grew in size and complexity, the master-builder required more time to resolve and address design issues. Two-dimensional drawings became the norm for communicating design intent. During this period, Leone Battista Alberti wrote on the role of the architect as a scholar and artist. Alberti advocated that there should be a clear separation between the architect and workers on the construction site responsible for the physical production of the building. “Following the Renaissance period (around the year 1400CE), more and more construction projects were planned and drawn in an office that was generally removed from the construction site.” (Kymmell 2008, 5)

The absence of the architect from the construction site created the need for an additional person to facilitate the communication between the architect and the construction workers. (Fig 2) This was an important period in the evolution of the construction industry as the architect was placed in the position of having to explain his design intent to a third party who, in turn, would convey that message back to builders on site. “The traditional single owner master-builder relationship became a
more complex threefold relationship among the owner, the architect, and the building contractor.” (Kymmell 2008, 5)

![Diagram of construction work-flows](image)

**Fig 2.** Construction work-flows after the Renaissance involved a third party at the construction site to mediate between the architect and construction workers

During the Industrial Revolution, as projects became even larger in scale and scope, the exchange of information between the design and construction teams became more formalized and sophisticated. This led to the emergence of construction documents, which were a paper-based communication process. “This method of communication led to unanswered questions and unanticipated situations in the field, since the person who had developed the project drawings did not work on-site, ready to address these issues.” (Kymmell 2008, 5)

The separation of the architect from the construction field lead to a lack of understanding of processes in the construction site. New speciality fields such as structural engineering, mechanical engineering and lighting consulting, emerged to support the architect in preparing the construction documents and to answer questions from the construction site. The building contractor, on the other hand, began dividing the scope of the actual construction between other smaller...
contractors, extending the distance between the architect and the construction worker even further. (Fig 3) The input coming from the architect had to go through many levels before reaching the front-line builder.

Fig 3. During the Industrial Revolution, new speciality fields emerged to support both architects and general contractors in translating the project design intent into a physically buildable undertaking.

In the early 20th century, the separation between architects and construction workers became even more pronounced. New professional disciplines emerged to support both the architecture and construction teams. Architects needed more consultants to develop design and construction documents while general contractors came to increasingly depend on sub contractors, site superintendents and foremen for the proper performance of construction workers. (Fig 4) The use of paper drawings and written instructions as the main form of communication led to greater incidents of misunderstandings, errors, delays in addressing problems and wasted time due to the replication of information. “A 2D document (drawing) is used to communicate each exchange of information between persons: this 2D communication results in a 3D visualization with each transaction, and thus each step requires a translation in
someone’s head, until the resulting instructions finally need to be visualized correctly by the person constructing the project. These transitions between persons may let oversights and errors go undetected until it is too late to address them effectively.” (Kymmell 2008, 7)

Fig 4. In the early 20th century, communication between architects and construction workers became further intermediated.

Over the past decade, construction projects have been increasingly designed and visualized in 3D virtual environments. Building Information Modeling (BIM) has provided a common platform for owners, architects, consultants and general contractors to better communicate among one another. (Fig 5) BIM models have already proven to be quite beneficial for better visualizing information, detecting mistakes while still in the
design process and eliminating duplication of information. Yet when it comes to the construction site, the process of conveying information still relies on paper drawings and written documents. 3D BIM models are defragmented and traditional 2D drawing information are extracted, printed and sent to site.

Fig 5. In the late 20th century, BIM models emerged to provide a common platform for owners, architects, consultants and general contractors
Recent advances in technology, namely the Internet and BIM, have the potential to break down the barriers to communication that have evolved in the construction process. (Fig 6) While we cannot go back to the master-builder format given the scale and complexity of contemporary projects, we can recover some of the communication benefits of earlier ages while maintaining the deep specialization and extensive teams necessary.

**Fig 6.** Advances in technology can assist in breaking down barriers of communication between different teams involved in a construction project
2. Current state of technology

“Our dilemma is that we hate change and love it at the same time; what we really want is for things to remain the same but get better.”

Sydney J. Harris
Over the past decades, technologies have evolved both in hardware and software to enable better visualization and navigation of information. These advances have the potential to revolutionize the way buildings are designed and the way instructions are relayed to construction workers on site. As technology improves, it becomes crucial to revisit the communication methods between design and construction teams and propose new applications to streamline the construction process.

**Building Information Modeling (BIM)**

Different forms of visualization and simulation have been used historically to communicate design intent and instructions in the construction process. “The wooden project models built in the 15th-century Renaissance period were simulations, and so are the diagrams, drawings, and specifications that have been used for hundred of years as instructions for building. The information contained in these examples is, however, very limited and fragmented (disconnected from other parts of the information).” (Kymell 2008, 26) Currently, BIM models are being used to visualize and simulate construction projects. (Fig 7) There is still debate on what the term “Building Information Modeling” means but according to Chuck Eastman, one of the pioneers in this field, BIM is defined as: “a modeling technology and associated set of processes to produce, communicate and analyze building models. Building models are characterized by:

- Building components that are represented with intelligent digital representation (objects) that ‘know’ what they are, and can be associated with computable graphic and data attributes and parametric rules.
- Components that include data that describe how they behave, as needed for analyses and work processes, e.g., take-off, specification, and energy analysis.
• Consistent and non-redundant data such that changes to component data are represented in all views of the component.
• Coordinated data such that all views of a model are represented in a coordinated way.” (Eastman et al. 2008, 13)

BIM models contain information that is stored explicitly in a formal, computer-interpretable format and consist of components with embedded properties and behaviors. (Fig 7) Some of the advantages of BIM derives from providing a platform where different teams can come together and develop a consistency in the exchange of information. This enables an input in the development of the model which can be visualized by other teams, provides transparency into the overall process and minimizes duplication of information by eliminating inconsistency and errors. “Explicit storage of building information enables meaningful exchange and sharing of building information between all involved in, affected by or those that can exert influence on a building project, throughout the entire building project life-cycle. This provides a state of constant transparency of processes and functions in order to reduce process conflicts, information clashes and information redundancy.” (Underwood and Isikdag 2010, 3) While design teams, owners, consultants and general contractors benefit from the advantages of BIM models; teams in the construction site still use the traditional defragmented methods of communication and therefore have no input into the BIM model.
Fig 7. Examples of BIM models (http://hvacadrafting.wordpress.com/page/2/)
Currently 3D BIM models are becoming accessible on hand-held computers through the Internet. GoBim is an iPhone application which enables users to upload a Rhinoceros or Revit model onto a server and access these files for viewing and basic manipulation online. (Fig 8) Users can view models and select specific objects or layers within the model. They have the opportunity to see the properties of each object thereby providing them extensive information on the 3D model in the field.

Fig 8. goBIM iPhone and iPad application (http://go-bim.iankeough.com/wordpress/?page_id=69)
Augmented Reality

Improvements in 3D virtual environments have led to the development of other technologies such as Augmented Reality, which is the visual augmentation of the real world through the superimposition of virtual computer-generated imagery. (Fig 10a, b) “Augmented reality systems, integrated with shape recognition and global positioning software, can track a user’s view and location in the real world. For example, when a user walks through a real environment, pre-recorded digital imagery can be juxtaposed onto the user’s view, thereby continuously matching synthetic views on top of the human vision.” (As and Schodek 2008, 125)

Many projects have been conducted under academic settings to demonstrate the benefits of augmented reality in the construction field. These systems promise to improve the optimization of construction operations and to allow checks of constructability and maintainability before building materials are ordered (Virtual 1995, Oloufa 1993). Integrated structural, architectural, and mechanical building databases are being combined with engineering expertise to create knowledge-based systems for improving the design process (Myers et. al. 1992). Robotics systems, mostly adapted from the automotive industry, have also been used recently in experimental and commercial attempts to automate various aspects of building construction (Webster 1994, Richards 1994).

A research project at Columbia University successfully illustrated how augmented reality could assist in the construction of space frame structures as well as in visualizing building systems for maintenance purposes. (Fig 9) Developments in hand-held computing can begin to incorporate augmented reality as a novel way of delivering information to the construction site.
Fig 9. Augmented reality for construction (http://graphics.cs.columbia.edu/projects/arc/arc.html)

Hand-held computers

Recent years have witnessed dramatic change in portable computing with respect to their durability, integrated hardware and interfaces. Laptop computers have long found their niche in construction sites and architecture firms but mostly as devices used by managers. Size, cost, relative fragility and restrictions of a keyboard interface have limited the widespread application of laptops at the construction front-line.

The last decade has also seen the evolution of tablet computing, or laptops with stylus-based touch-screen interfaces. Tablet PCs became widely promoted in the early 2000s as a way to make computing more accessible to front-line workers. (Fig 11) For the construction industry, manufacturers such as Motion Computing, Panasonic and Xplore have developed rugged casings to render the hardware more resilient and prevent damage in the event of drops, bumps, water spills and extreme temperatures. Enhanced computer screens enable clear visibility both indoor and outdoor despite direct sunlight. These computers, which normally weigh between 3 to 5 pounds, come equipped with cameras, RFID scanners and audio speakers with noise cancellation capabilities. While battery life lasts typically for about 4 hours, much research is going into better power storage technology to enable longer battery duration. For the time being, many users opt to carry two or more batteries to last through an 8 hour shift.

In parallel with the evolution of laptops and tablet computers, more compact hand-held devices such as personal digital assistants (PDAs) and smart-phones have also grown in functionality and sophistication in recent years. While originally constrained by limited processing power and paltry software libraries, smart-phones have gained dramatically in functionality, versatility and popularity with the Blackberry, the Apple iPhone and the Google Android phone. These devices feature high resolution touch
screens, megapixel video cameras, embedded GPS, magnetometers, accelerometers, long lasting batteries and software application stores that support a vast library of 3rd party applications. By many measures, current smart-phones exceed the processing power of laptop computers from 5 years ago.

Smart phones, however, have been limited in their relevance to construction due to the relatively small size of their screens and lack of 3rd party applications for the construction industry. With the convergence of tablet computers and hand-held devices, this is starting to change. As an example of a convergent device, the Apple iPad (Fig 12) is revolutionizing the way we interact with computers and the way we navigate information. Its relative low price, long battery life, light-weight form and ubiquitous connectivity to the web make it a good candidate for quick adoption in the construction industry. Currently GoBim is the only application developed for the iPad which addresses the building industry so there is an unmet need for new applications that can utilize the touchscreen capabilities for navigating information in the construction site.

Fig 11. Motion J 3400 (http://www.motioncomputing.com/)

Fig 12. iPad (http://www.apple.com/ipad/)
Google Earth

Google Earth is a geographic information system that provides users with a zooming web interface to navigate information relevant to where they are located and their area of interest. (Fig 13) Through the use of a GPS system, the viewer can locate themselves on a map and easily navigate the surrounding area. Search queries can be conducted such that information from the web can be overlaid onto the map. The implementation of such systems can be of great value in the construction site.

Fig 13. Google earth (http://earth.google.com/)
Current interfaces in the construction industry

Several companies are working to address the issue of how best to deliver information to the construction site. Firms such as Vela Systems, Meridian Systems, Procore and BidCom have developed project management suites with diverse features, but a common limitation has been that each interface system relies on the traditional folder structure schema for storing and accessing information. (Fig 14) Considering that people on site need access to a vast amount of information and data, the traditional folder structure has significant limitations. There is an opportunity for project management software to integrate new navigation methods such as augmented reality, zooming map interfaces (Google Earth) and touch screen technology to facilitate the manipulation of construction-relevant data.

Another common limitation of existing software is that it often provides all users, including workers on site, access to all information available on the project. Such overabundance of information can be irrelevant and confusing. In the spirit of maximizing efficiency and minimizing errors, there is an opportunity to develop new interfaces that provide only the data needed by each user - no more and no less.

Fig 14. Software interface (http://www.meridiansystems.com/)
3. Requirements for a next-generation solution

"The most successful people in life are generally those with the best information."

Benjamin Disraeli
Interview process

To better understand problems in the construction process and how a new software application could address them, I conducted approximately 20 interviews with professionals involved in various aspects of the construction industry. These incorporated a diversity of roles and perspectives including architects (Fig 15), general contractors (Fig 16) and foremen (Fig 17). The purpose of these interviews was to obtain information on the current state of communication in the construction process and to better understand the needs of the main players.

The interviews were informal and the questions varied from person to person. Each conversation was recorded either via iPhone or by handwritten notes. Much of the discussion centered on understanding the interviewees' responsibilities at the construction site, their methods of retrieving and communicating information as well as problems they perceived and the ideal work conditions they desired.

From conducting the interviews and shadowing some of the interviewees around the construction site for a day, several common themes emerged. Main problem areas often pertained to time inefficiencies and errors.
Roles and responsibilities at the construction site

- Ensure finished product matches the vision presented to the owner
- Make certain project is delivered on time, within budget and at the best agreed quality

Fig 15. Architect

- Manage project efficiently with regard to time, people, materials and cost
- Manage quality control to ensure recurring business

Fig 16. General contractor

- Understand list of tasks and ensure sufficient resources (man power, tools, materials, information) to execute them
- Ensure construction teams are working optimally at full utilization and minimum down time
- Add value to construction manager

Fig 17. Foreman
I don't bring drawings with me anymore. They are too heavy for me to carry.

The trick when you are on site is to be able to visualize what will be there.

I take photos and notes and when I go back to the office I type them up and put them in folders with the date.

Fig 18. Architects at the construction site
Activities on site:

- Conduct meetings
- Coordinate work with owner/project manager/consultants
- Manage site visits
- Ensure broad familiarity with what is happening on site
- Track progress and quality of work and inform the owner
- Guard the owner against defects and deficiencies in the work
- Determine if the work being done properly and, once finished, whether it will be in accordance with the contract documents
- Evaluate work against contract documents
- Conduct on site testing and inspection

Information and tools on site

- Construction drawings and information
- Camera
- Drawing pad to take notes
- Measuring tools
- Cell phone

Desired software requirements:

- Quick access to site productivity/stage of construction
- Active Requests for Information (RFI)
- Quick access to construction documents
- Quick access to specs
- Quick access to regulations
- Quick and clear way to point out problems in the construction site
- Quick access to people involved in the project
We spend a lot of time checking with the subs that orders for the materials have been placed and there are no delays.

Fig 19. General contractor at the construction site
Activities on site:

- Conduct meetings
- Coordinate work with owner/architect/foreman
- Track construction schedule
- Distribute tasks amongst different foremen
- Inform foremen on project changes
- Track site progress and quality of work
- Order materials
- Answer questions

Information and tools on site

- Construction drawings and shop drawings
- Drawing pad to take notes
- Camera
- Cell phone

Desired software requirements:

- Clear sense of overall productivity
- Quick way to answer questions
- Quick and clear way to ask questions to problems
- Access to most up to date construction drawings
- Quick access to tagging information or questions to construction drawings
- Quick access to people involved in the project
Moving materials and tools through the site is challenging because we don’t know beforehand what areas are inaccessible.

I wish the RFI process would be faster. Sometime I have man on site killing time until we hear from the architect and some other time we go ahead with the job before we hear back. We can’t afford waiting.

Fig 20. Foremen at the construction site
Activities on site:

- Conduct meetings
- Coordinate work with general contractor and other foremen
- Distribute tasks, materials and tools
- Coordinate sequence of tasks
- Order materials
- Coordinate where the material will be on site
- Track progress and inform the construction manager
- Answer questions
- Report problems

Information and tools on site

- Paper Drawings relevant to tasks
- Oral communication of tasks
- Construction tools
- Drawing pad to take notes
- Cell phone

Desired software requirements:

- Have a clear sense of what needs to be done
- Know who is doing what and at what time
- Know who is not working and why
- Know where all the materials are
- Know where tools are and how/when to get access to them
- Have access to most up to date construction drawings
- Have access to internet to get more information on products
- Quick accessibility to asking questions and getting answers
- Quick access to people involved in the project
- Demonstrate productivity
Interview excerpts:

Brian Guerrero (architect)
(this was a phone interview and I took down notes to record it.)

me: What do you usually bring with you when you go on site?
Brian: I review the problems that need to be resolved on site and then I bring drawings relevant to that problem and a notebook to take notes.

me: Are there times when you wished you had access to other information you have in the office?
Brian: Yes. I can not bring with me everything when I go on site. I have to be selective.
The other day I was missing information on code compatibility so I had to go back to the office and then back out on site.

me: what are some areas where you would like to see change in your communication with people on site?
Brian: RFIs. I wish there was a way of making them more active. Currently I receive a pdf form via email with a due date. They don’t promote discussion between the parts in order to solve the problem.

John Kennedy (contractor)
(this interview was in person and was recorded.)

me: Do people get lost in big construction sites?
John: I don’t think they get physically lost as much as they are confused about where they should be going, what they are supposed to be doing and where it is. This is a big problem in big buildings for mechanical systems on which pipe is which and so forth.
They will figure it out but the question is how long will it take to figure it out.

me: Who is responsible for showing them where they need to go on site?
John: That is the trouble. It is another problem. You can not have the superintendent show everybody. It is their job to find it. So you usually say “go find it.”

Andy Deschenes (contractor)
(this interview was in person and was recorded.)

Andy: There are a few of us at Skanska that have been part of this BIM thing for a while but the more we have been part of it the more some of us are keying into the same thing: how do we get it out into the field?

me: What are other functions you would like to see on a hand held device?
Andy: I wish it was a lot easier to track the progress of the schedule on the job. The
ability to track schedule proposed verses actual visually and to be able to see more of the two weeks ahead through a model would be really helpful.

**me: How would you like the process of RFIs to be visually presented?**

Andy: To be able to see the thread of the problems: When did it get posted? What did that look like? Who was on the distribution list? Who answered it? How long did it take them? What was the ultimate solution? Did it work? If you are a superintendent on site and you open your iPhone to see what are the open RFIs this morning, or pick your topic and see if these things are pending or is someone looking at them right now, is someone working on this right now or has this been lingering for 17 days. That seems to be to be a very powerful thing. That is the kind of thing that the guys out in the field deal with every day. We have an issue. I told somebody about it last week. How come we don’t have an answer yet?

**David Conner (contractor)**

(this interview was in person and was recorded.)

**me: How do you keep track of materials delivered on site?**

David: typically the subcontractors are responsible for ordering the materials related to their scope of work. We are responsible that it arrives on site on time.

**me: How do you assure that the order has been placed and will arrive on time?**

David: All we can do is rely on the information that the subcontractors are giving us. This is typically verbal. Even if they have purchased materials there is no way of showing how long it will take for the materials to get there. We have to keep checking with the subcontractors and the manufactures on the status of the delivery.

**Arben Kalenja (foreman)**

(this was a phone interview and I took down notes to record it.)

**me: what are some of the problems you encounter in your day to day job?**

Arben: The information provided on the drawing is different form the site conditions. For example the floor is not levelled so the distance between the two walls once you start laying out tiles is different from what the architect has marked on the drawings and therefore effecting the layout design of the tiles.

Other issues have to deal with material sizes. The architect will order tiles thinking they are a perfect square. In reality in most of the cases tiles are cut at a smaller dimension then what they are marked in a brochure pamphlet. I wish there was more interaction with the architect so I could inform them of the material conditions earlier on.
4. Prototype proposal

“Until one is committed, there is hesitancy, the chance to draw back... Whatever you can do, or dream you can do, begin it. Boldness has genius, power, and magic in it. Begin it now.”

Goethe
Fig 21. Proposed software user interface
Upon evaluating the interviews, I identified 5 areas which were of crucial importance to architects, general contractors and foremen. These areas pertained to information on the project, schedule, people, meetings and materials. Focusing on these categories, I developed a prototype software interface which would identify each individual and based on their area of interest and location would tailor the information to each of them. (Fig 21)

The navigation system of the interface is divided into three main parts. The first section consists of buttons at the top of the interface which direct the user to individual windows with specific information categories, such as project, persons, meetings and materials. The second consists of information on the schedule which is always present regardless of the window of navigation. And last, is a set of applications which are always accessible for performing common activities such as making phone calls, sending email, accessing the web, etc.

Before entering the system, each user will be required to log in. This identifies the user and determines their data access rights. In this case, Wendy will be provided with information relevant to the role of the architect. (Fig 23)
Fig 22. Log in interface
Fig 23. Interface/Log in for the architect
<table>
<thead>
<tr>
<th>Project Name</th>
<th>Location</th>
<th>Map</th>
<th>Size</th>
<th>Completion date</th>
</tr>
</thead>
<tbody>
<tr>
<td>H Urban House</td>
<td>Manhattan, New York</td>
<td>![map_icon]</td>
<td>5,605 m²</td>
<td>July 2010</td>
</tr>
<tr>
<td>Brooklyn College</td>
<td>Brooklyn, New York</td>
<td>![map_icon]</td>
<td>25,548 m²</td>
<td>May 2011</td>
</tr>
</tbody>
</table>

**Fig 24. Interface/Project selection**
Upon entering the system, the user is asked to locate the project of interest. A connection with Google Earth will give the viewer a broader perspective of the project's location as well as her own. (Fig 24) Through the use of a GPS system and a sensor network set up in the construction site, the viewer can be located inside the structure of the building.

Taking advantage of the touch screen, the viewer can choose to zoom in (Fig 25) and out of the 3D model by opening and closing her thumb and forefinger (Fig 26), switch between plan and axonometric views by using a rotation motion with her hand (Fig 29) as well as see a perspective view of the virtual model based on where she is located on site. (Fig 28)

When the viewer first enters the project, the information in the drawings is already focused on her profession. In this example, Wendy is presented with a plan view relevant to her as an architect. (Fig 27) However, if she wanted to get more information on the layout of the furniture, she could go under the trade specification (Fig 81) and select a view from the perspective of an interior designer. (Fig 82)
Fig 25. Interface/Project information
Fig 26. Interface/Project information
Fig 27. Interface/Project/User locate
Locate Trade Section cut Progress Tag History

Fig 28. Interface/Project/User locate/Perspective view
Fig 29. Interface/Project/User locate/View change
Fig 30. Interface/Project/User locate/Axonometric view
Fig 31. Interface/Project/Trade view
Fig 32. Interface/Project/Trade view
Fig 33. Interface/Project/Add Tags
Being able to quickly locate a problem on site and send that information to the foremen is of great importance to architects. In the current system, when architects go on site they take photos and write notes on problems they notice. Once they return to the office, they save these photos into folders and then write down their notes onto forms which are then sent back to the general contractor. By the time the foremen receive the note from the general contractor they might have already done much more work which would need to be torn down and redone.

Through this interface, if Wendy noticed that the installation of the wood flooring was completed incorrectly, she can tag the part of the model specific to where the wood installation is taking place, (Fig 34) she can write a note on why she thinks the wood flooring is being installed inappropriately and then take a photo to demonstrate her point. (Fig 35) In this case, everything is saved in connection to that specific part of the 3D model therefore eliminating fragmentation of information between unconnected folders.

Wendy can also choose to see overall problems happening on site. In this case, she would be presented with the wireframe of the building where the problematic areas would be highlighted with a color ranging from yellow to red based on the urgency of the response. (Fig 36) She could then tap on one of the highlighted areas and be presented with information on what the problem is, who identified the problem, whether they suggest any solutions and when the deadline is to address the question. (Fig 37)
Fig 34. Interface/Project/Tag RFI
Field Report:
Wrong installation of wood flooring. Not enough glue set set at the bottom. Already signs of wood warping.

Proposed solution:

Changes

Underground Floor

Fig 35. Interface/Project/Add photo to the RFI
Fig 36. Interface/Project/Site problems
Request:
The existing valve is too old and needs to be replaced. We have to change a section of the existing ductwork.

Proposed solution:

Response:

Changes

Fig 37. Interface/Project/Detailed information on site problems
Fig 38. Interface/Log in for the general contractor
One of the main problems that general contractors face on a day-to-day basis is keeping track of materials. They have to constantly check with the sub-contractors or foremen whether they have ordered the necessary materials and whether those materials will arrive on site on time without causing delay to the construction schedule. In one of the site meetings in which I participated, the challenge was that the curtain wall fabricator had misunderstood a conversation with the general contractor and had stopped the fabrication of the units. The general contractor had not found out about it until a few days before the units were due on site for assembly. Such a mistake risked throwing the construction schedule off by a couple weeks and therefore drastically increasing the cost of the project.

With the proposed application, the general contractor would have had clear visibility into the status of the materials, specifications and people involved with that specific material. (Fig 39) The general contractor could go as far as track the material through GPS on a Google map and see in real-time the position of the delivery. (Fig 40) In case there were problems with the delivery the general contractor would know exactly who to contact and he could quickly locate the foremen affected by the delivery of that material.

Quick access to the construction schedule would also provide an immediate perspective on how the delay in the material could affect the construction sequence. (Fig 41)
<table>
<thead>
<tr>
<th>Materials ordered</th>
<th>Contact</th>
<th>Foremen</th>
<th>Spec</th>
<th>Date</th>
<th>Time</th>
<th>Status</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling grid</td>
<td>1 607 387 6545</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td>3:30pm</td>
<td>on time</td>
<td></td>
</tr>
<tr>
<td>Wall paint color</td>
<td>1 800 534 7856</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td></td>
<td>delayed</td>
<td></td>
</tr>
<tr>
<td>Window frames</td>
<td>1 607 432 6578</td>
<td></td>
<td></td>
<td>5/10/10</td>
<td></td>
<td>on hold</td>
<td></td>
</tr>
</tbody>
</table>

Materials to order

- Door frames
- Acoustic tiles

Suggestions

Fig 39. Interface/Material tracking
### Interface/Material tracking

**Materials ordered**

<table>
<thead>
<tr>
<th>Materials ordered</th>
<th>Contact</th>
<th>Foremen</th>
<th>Spec</th>
<th>Date</th>
<th>Time</th>
<th>Status</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling grid</td>
<td>1 607 387 6545</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td>3:30pm</td>
<td>on time</td>
<td></td>
</tr>
<tr>
<td>Wall paint color</td>
<td>1 800 534 7856</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td></td>
<td>delayed</td>
<td></td>
</tr>
<tr>
<td>Window frames</td>
<td>1 607 432 6578</td>
<td></td>
<td></td>
<td>5/10/10</td>
<td></td>
<td>on hold</td>
<td></td>
</tr>
</tbody>
</table>

**Materials to order**

- Door frames
- Acoustic tiles

**Schedule**

- 9:30 AM

**Fig 40.** Interface/Material tracking
### Interface/Construction Schedule

<table>
<thead>
<tr>
<th>Materials Ordered</th>
<th>Contact</th>
<th>Foremen</th>
<th>Spec</th>
<th>Date</th>
<th>Time</th>
<th>Status</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling grid</td>
<td>1 607 387 6545</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td>3:30pm</td>
<td>on time</td>
<td></td>
</tr>
<tr>
<td>Wall paint color</td>
<td>1 800 534 7856</td>
<td></td>
<td></td>
<td>5/6/10</td>
<td></td>
<td>delayed</td>
<td></td>
</tr>
<tr>
<td>Window frames</td>
<td>1 607 432 6578</td>
<td></td>
<td></td>
<td>5/10/10</td>
<td></td>
<td>on hold</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials to Order</th>
<th>Suggestions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door frames</td>
<td></td>
</tr>
<tr>
<td>Acoustic tiles</td>
<td></td>
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</tbody>
</table>

#### Schedule

<table>
<thead>
<tr>
<th>Day</th>
<th>Board walls &amp; soffits</th>
<th>Tape walls &amp; soffits</th>
<th>Prime paint</th>
<th>Paint concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5/6/10</td>
<td>5/7/10</td>
<td>5/10/10</td>
<td>5/11/10</td>
</tr>
<tr>
<td>5</td>
<td>5/8/10</td>
<td>5/9/10</td>
<td>5/12/10</td>
<td>5/13/10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Length</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board walls &amp; soffits</td>
<td>3 days</td>
<td>5/8/10</td>
<td>5/8/10</td>
</tr>
<tr>
<td>Tape walls &amp; soffits</td>
<td>4 days</td>
<td>5/6/10</td>
<td>5/9/10</td>
</tr>
<tr>
<td>Prime paint</td>
<td>2 days</td>
<td>5/10/10</td>
<td>5/11/10</td>
</tr>
<tr>
<td>Paint concrete deck</td>
<td>2 days</td>
<td>5/12/10</td>
<td>5/13/10</td>
</tr>
</tbody>
</table>

---

**Fig 41.** Interface/Construction schedule
Meeting: Owner/Architect/GC  
Date: 5/16/2010  
Start Time: 8:30 am

<table>
<thead>
<tr>
<th>Attendees</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Joe Collins (Owner)</td>
<td>Tom Quirk (D’Agostino Izzo Architects)</td>
</tr>
<tr>
<td>Massimo D’Aloisio (Flack &amp; Kurtz, Inc.)</td>
<td>John Morganate (Owner)</td>
</tr>
<tr>
<td>James Thomson (Commodore Builders)</td>
<td>Tom Comeau (Owner)</td>
</tr>
<tr>
<td>Bill Maddox (Commodore Builders)</td>
<td>Bill Maddox (Commodore Builders)</td>
</tr>
<tr>
<td>Wendy Magliozzi (D’Agostino Izzo Architects)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Responsible</th>
<th>Due Date</th>
<th>Record</th>
<th>Play</th>
<th>Text</th>
<th>Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Work</td>
<td>James Thomson</td>
<td>5/16/2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The existing gate valve will not close completely and CB will be unable to test the new service against this valve. CB has provided pricing to replace the valve and underground piping. Joe has not received approved added cost yet.

<table>
<thead>
<tr>
<th>Description</th>
<th>Responsible</th>
<th>Due Date</th>
<th>Record</th>
<th>Play</th>
<th>Text</th>
<th>Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanitary Piping</td>
<td>Bill Maddox</td>
<td>5/18/2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A hole had to be chipped out around an infilled floor drain after a sanitary line backed up and CB notes there is no associated cost to owner for the work.

CM is working on repairing the pipe and infilling the floor.

<table>
<thead>
<tr>
<th>Description</th>
<th>Responsible</th>
<th>Due Date</th>
<th>Record</th>
<th>Play</th>
<th>Text</th>
<th>Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWS Drawings</td>
<td>Thomas Quirk</td>
<td>5/20/2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Team reviewed cost of window changes. DAIQ asked if cost associated with drafting time can be reduced based on errors made by AWS. CB to investigate.

<table>
<thead>
<tr>
<th>Description</th>
<th>Responsible</th>
<th>Due Date</th>
<th>Record</th>
<th>Play</th>
<th>Text</th>
<th>Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Shutdown</td>
<td>Bill Maddox</td>
<td>5/26/2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig 43. Interface/Log in for foreman
During my discussions with foremen, a recurring theme was the lack of communication between them and the architect. Foremen were frustrated with the fact that anytime questions came up on site, they had to wait for extensive time periods before they received an answer.

Currently, if a problem arises on site, the construction worker who identifies it asks the foreman who, in turn, asks the site supervisor who asks the assistant in the office to write a Request for Information (RFI) which is eventually sent to the general contractor. This RFI is then sent to the architect who, after reading it, decides if it can be answered immediately or whether it should be referred to one of their consultants. Once the question is answered, the response has to go through the same hurdles all the way back to the construction worker.

With the new interface, when a problem appears on site, the foremen could tag it in the overall model (Fig 44) sending an alert to the architect with information on location, severity and relevant context. (Fig 45)
Fig 44. Interface/Project/Problem tagging
Request: The existing valve is too old and needs to be replaced. We have to change a section of the existing ductwork.

Date reported: 05/14/10
Date required: 06/11/10
Date answered: [ ]

Priority: [ ] low [ ] mid [ ] high

Sketches: [ ]
Proposed solution: [ ]
Response: [ ]
Changes: [ ]
Fig 46. Interface/Project/Progress
Another concern from foremen was the lack of communication of activities among one another. Despite regular meetings to inform each other about the activities they would perform that week, there were frequent occasions for miscommunication, forgetting or changes in time-frame. One problem that was explicitly identified involved people trying to get materials through areas that were not accessible leading either to damage of recently completed work (i.e. newly laid tiles) or to delays in the delivery of materials and tools.

With the better application of hand-holds, construction workers could inform each other of different stages of construction so that everyone walking around the site could plan accordingly. Information would be entered into the system by clicking objects in the BIM model related to the work that needs to be performed (Fig 47) and then changing the status of those objects to unaccessible, under construction or completed.

These inputs would also help architects and general contractors have a better sense of processes in the construction site as well as overall on-site productivity. (Fig 48)
Fig 47. Interface/Project/Progress mark up
Fig 48. Interface/Project/Progress view
5. Analysis

“If you want something you’ve never had before, you’re going to have to do something you’ve never done before.”

Zig Ziglar
According to the Construction Management Association of America (CMAA), 30% of the cost of construction is wasted due to inefficiencies at the construction site. FMI, one of the largest companies in management consulting and investment banking in the construction industry, has stated that 75% of the construction cost occurs on site yet only 10% of the software applications are built for the construction field. Taking this data into account, it seems important that we look into further researching the potential for technology to minimize inefficiencies on site.

Were the system proposed in this thesis to be implemented, it would be beneficial in saving time, minimizing errors and creating a closer connection between the teams in the office and those on site. The software would allow for the rapid identification of problems on site and the communication of these issues. Currently, if a problem is identified, the construction worker has to inform the foreman, who informs the site superintendent, who in turn informs his assistant in the trailer to write a Request for Information. With the new system, many of these steps can be eliminated. The construction worker can inform the foreman who can post the problem into the system. The use of BIM models would allow for accurate positioning of the problem, therefore eliminating ambiguities in locating and contextualizing the issue. The built-in camera within the hand-held can also be used to take photos of the problem to better clarify the issue for people far removed from the construction site.

Another benefit of the system would be the delivery of accurate information based on location and craft. Currently people on site have to carry large sets of drawings which are printed on paper and often don’t reflect the latest changes in design. In many cases, construction workers execute instructions based on the information they had on their drawing only to find out later that the design has changed and it has taken over a week for those changes to reach them. As a result the work performed would need to
be demolished and redone. With the help of this system, people on site will always have access to the most up-to-date information. The 3D model saved on the server is the same for everyone therefore changes made by one team will be visible to all others.

Another benefit of the system would be with regards to tracking materials, people and tools. Currently, much time is spent tracking all the above by making individual phone calls to the suppliers and people on site. With the proposed system, there is visibility on the status of materials delivered, tools checked out as well as people present on site.

Communication of unaccessible areas on site is another challenge which can lead to safety issues, damage to work already completed and time delays. With the new software, the status of work on site would be easily entered into the system and everyone would be quickly alerted to off-limit areas.

Finally, such a system would provide a platform where people could collect information relevant to the work they are doing. Currently, many people on site carry notebooks, drawings and directories of people involved in the project. These handwritten notes are later transferred into file systems in their desktop computers or lost in the process. Taking advantage of the easy portability of the hand-held and the different applications that come with it people on site can quickly store information into the system and retrieve it later as needed.

The dimensions by which the software should be evaluated include reduction in waisted time, errors and cost. In order to quantify these advantages, however, the software should be prototyped and tested in the field.
6. Conclusions and Future work

"Even if you're on the right track, you'll get run over if you just sit there."

Will Rogers
Due to recent and dramatic advances in computing technology, we are fortunate to be in a time when hardware and software have evolved to the point of becoming powerful, intuitive, portable and ubiquitous. Whereas computers were traditionally bulky, fragile and expensive, portable devices today have achieved a form factor that can enable every professional on a construction site to have access to computing.

By providing hand-held computers to front-line construction workers that are integrated with the Building Information Models of architects as well as the logistical and project management tools of general contractors, technology has the potential to break down the communication boundaries that have emerged over centuries. The growing scale and complexity of construction projects have stretched construction teams to also expand in size and specialization. Barriers to communication between construction teams, general contractors and architects are a negative consequence of the compartmentalization and fragmentation driven by greater specialization and project scope.

Just as technology has enabled greater complexity in construction, it also has the promise of achieving greater simplicity and streamlining of communication. By applying innovations in hardware and software, front-line construction workers can have access to tools that can increase their overall understanding of a project, accelerate their access to information and greatly shorten the lead-time in communication among team members.

This thesis has identified some of the gaps in communication among professionals involved in the construction process and has outlined the problems inherent in not having all workers on a level informational playing field. Interviews have revealed some of the frustrations and unmet needs of professionals at every level of a construction
The application prototype proposed in this thesis is an attempt to leverage modern hardware and software to address these challenges. However, this solution is still hypothetical and merits further proofs of concept and field-testing.

A continuation of this research would require the completion of a working software prototype based on detailed requirements gathered from discussions with construction workers, their supervisors, general contractors and architects. A viable prototype would then need to be tested in a controlled environment against existing standards of communication in the construction field. In order to quantify the benefits of a hand-held based approach, a controlled study would require that projects be alternatively pursued with conventional tools and with the new application prototype. Such a pair-wise comparison of the impact of the hand-held prototype would enable a precise measurement of efficiency gains and quality improvements. Robust field-testing would also highlight further areas for improvement such that subsequent versions of the application would have even greater front-line impact.

As hardware and software continue to improve, so will the potential performance of their application in the construction field. Hand-held computers will continue to become more compact, powerful and durable. Enhancements in the range and accuracy of GPS, magnetometers, accelerometers and other sensors will advance augmented reality and enable greater precision in integrating virtual elements from BIM into renderings of the actual construction site. Finally, developments in hand-held navigation (touch screens, zooming interfaces, drag and drop, etc.) will continue to make sophisticated BIM models and complex information on construction projects much more accessible and widely usable.

The days of master builders, craftsmen well versed in all aspects of a design and
construction project, may be long over. However, technology has the potential to greatly increase understanding and information-flow among the various specialized roles of a modern construction project. While there may be no contemporary analog to the master builder, widespread and intuitive hand-held computing can bring the architect back into the construction field and front-line workers closer to the architect’s studio.
Figures

Fig 1. Traditional construction work-flows in the Middle Ages in Western Europe relied on the master-builder to coordinate both design and construction

Fig 2. Construction work-flows after the Renaissance involved a third party at the construction site to mediate between the architect and construction workers

Fig 3. During the Industrial Revolution, new speciality fields emerged to support both architects and general contractors in translating the project design intent into a physically buildable undertaking

Fig 4. In the early 20th century, communication between architects and construction workers became further intermediated

Fig 5. In the late 20th century, BIM models emerged to provide a common platform for owners, architects, consultants and general contractors

Fig 6. Advances in technology can assist in breaking down barriers of communication between different teams involved in a construction project

Fig 7. Examples of BIM models (http://hvacdrafting.wordpress.com/page/2/)

Fig 8. goBIM iPhone and iPad application (http://go-bim.iankeough.com/wordpress/?page_id=69)

Fig 9. Augmented reality for construction (http://graphics.cs.columbia.edu/projects/arc/arc.html)


Fig 11. Motion J 3400 (http://www.motioncomputing.com/)

Fig 12. iPad (http://www.apple.com/ipad/)

Fig 13. Google Earth (http://earth.google.com/)

Fig 14. Software interface (http://www.meridiantsystems.com/)

Fig 15. Architect

Fig 16. General contractor

Fig 17. Foreman

Fig 18. Architects at the construction site
Fig 19. General contractor at the construction site

Fig 20. Foremen at the construction site

Fig 21. Proposed software interface

Fig 22. Log in interface

Fig 23. Interface/Log in for the architect

Fig 24. Interface/Project selection

Fig 25. Interface/Project information

Fig 26. Interface/Project information

Fig 27. Interface/Project/User locate

Fig 28. Interface/Project/User locate/Perspective view

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Fig 32. Interface/Project/Trade view

Fig 33. Interface/Project/Add Tags

Fig 34. Interface/Project/Tag RFI

Fig 35. Interface/Project/Add photo to the RFI

Fig 36. Interface/Project/Site problems

Fig 37. Interface/Project/Detailed information on site problems

Fig 38. Interface/Log in for the general contractor

Fig 39. Interface/Material tracking

Fig 40. Interface/Material tracking

Fig 41. Interface/Construction schedule

Fig 42. Interface/Meeting notes

Fig 43. Interface/Log in for foreman

Fig 44. Interface/Project/Problem tagging

Fig 45. Interface/Project/Problem tagging
Fig 46. Interface/Project/Progress

Fig 47. Interface/Project/Progress mark up

Fig 48. Interface/Project/Progress view
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