Integrating Design and Construction with Wearable Computers

George Elvin

IJAC 2-2_3 proof 16-7-04 3:46 pm Page 178

Integrating Design and Construction with Wearable Computers

George Elvin

Wearable computers can help bridge the gap between design and construction. They can integrate these traditionally separate cultures by improving the flow of information between them. Using a wearable computer, design and construction personnel can now exchange design information quickly and continuously between the point of work on the construction site and the remote design office. The improved iteration between design and construction and much stronger connection between design personnel and construction site afforded by wearable computers may point the way to a new kind of integrated architectural process. In this study, the goal was to determine the value of wearable computers in integrating design and construction by measuring specific performance characteristics. The results include findings on productivity, rework and communication quality. They reveal that wearable computers can improve communication quality and reduce rework, but may have an initially negative impact on productivity. These findings suggest that wearable computers may play a key role in future building projects, helping to bridge the current divide between design and construction.

1. Introduction

New technologies are redrawing the path we take from design concept to built form. One of the most promising technologies is wearable computers. With a wearable computer, a designer and builder can exchange design information instantaneously between the point of work on the jobsite and a remote design office. Rapid information exchange at the point of work could radically alter the processes we currently employ in designing and making buildings. In the current paradigm, an architect completes a design and hands it "over-the-wall" to a contractor for construction. Continuous information exchange via wearable computers on the jobsite could break down this wall and overcome many of the obstacles to design quality and construction efficiency that this wall has created. In 2003, the University of Illinois at Urbana-Champaign School of Architecture and Building Research Council undertook a study comparing wearable computers with tablet computers and paper documents in order to determine the potential of wearable computers for integrating design and construction. The results indicate that wearable computers can improve interdisciplinary communication and reduce rework on construction projects.

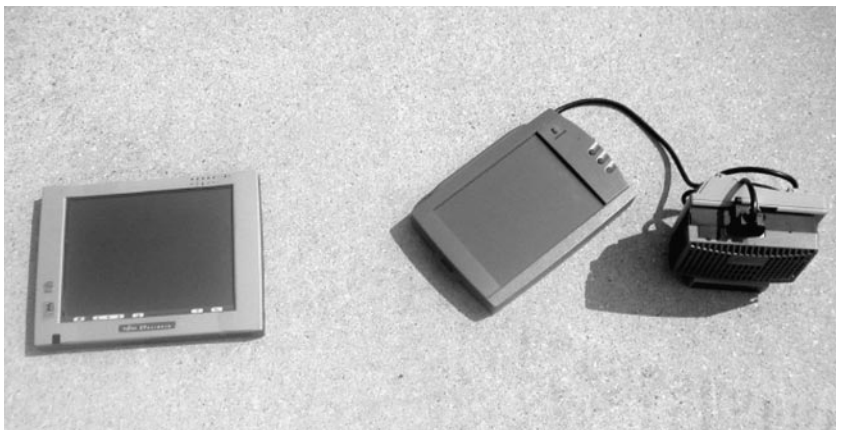
2. Commnuication quality

Architecture is the transformation of an idea into a built object. Currently, that process of transformation faces considerable criticism from both inside and outside the culture of design and construction. Architects complain that it prevents them from achieving the level of quality they desire, contractors feel held back from efficiently completing their work, and owners find the whole process too slow and too expensive. The most commonly cited reason for these problems is the separation of design and construction [1], [2]. The separation of design and construction as the process is currently structured makes collaboration and coordination difficult, undermining both the constructability of design ideas and the compliance of built work to original design intent.

The separation of design and construction makes communication between the two disciplines difficult. As the speed and complexity of the building process increases, the role of communication between disciplines becomes increasingly important. New process models like design-build and fast-track production only increase the need for faster, more frequent, and more complete communication across disciplinary boundaries. Communication is the key to improving the design-construction process, and improvements in communication can even lead to improvements in resulting building quality [3]. But where does communication break down? The weakest link in the communication process is between the design office and the point of work on the construction site [4]. The large sets of construction documents required in the "over-the-wall" paradigm are unwieldy on a jobsite, and typically out of date. A much more rapid, informal means of communication is required in order to improve the integration of design and construction.

3. Wearble computers in design and construction

What technologies best support the rapid exchange of design information between the jobsite and design office? Cell phones allow quick, informal conversation but do not support the complex graphic media necessary to convey design information. Paper documents via fax or hand delivery are completely incompatible with the hostile conditions of most jobsites and are difficult to keep up to date. Laptop computers are too fragile, and keyboards quickly fill with dust and dirt. Tablet computers may hold some promise, and were included in this study. However, one of the most promising technologies for on-site communication remains relatively unknown. Wearable computers are in use today by emergency medical personnel, firefighters, utilities workers, and other field workers requiring instant access to large volumes of information in rugged environments. They consist of a processing unit and batteries worn on a belt accompanied by a variety of data input and display options [5], [6]. In this study, a Xybernaut MaV wearable computer was used which is commercially available for about the cost of a high-end desktop computer. It included a pen-based handheld display with a 7" screen for input.



◀ Figure 1. Tablet computer (left) and wearable computer (right)

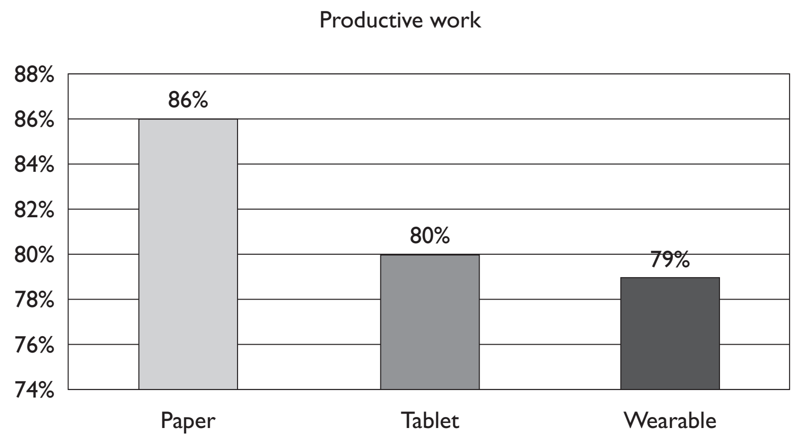
4. Testing wearable computers on site

While wearable computers appear to hold great promise for facilitating interdisciplinary communication in architecture, studies on their use have so far been largely anecdotal proof-of-concept explorations [7]. Thus, a decision was made to undertake a more rigorous study and gather detailed data on the performance of wearable computers relative to other technologies. To achieve this involved experimenting with actual construction conditions. In this experiment, a research assistant with a wearable computer was assigned the role of constructor while the principal investigator assumed the role of a remote designer. A second research assistant, present on the construction site but not engaged in construction, collected detailed data on information exchange and task performance, recording minute-by-minute the activities of the constructor. Variables in communication, design-construction task iteration, and general task performance were measured. Three small structures were designed and built, each using a different technology: paper, tablet computer or wearable computer. Design was varied with each structure to avoid the risk of increased efficiency resulting from repetition of tasks in the course of the experiments. At the outset of each structure's construction the constructor was provided with only thirty percent of the design information required to complete the project. This strategy ensured the need for considerable information exchange during construction.

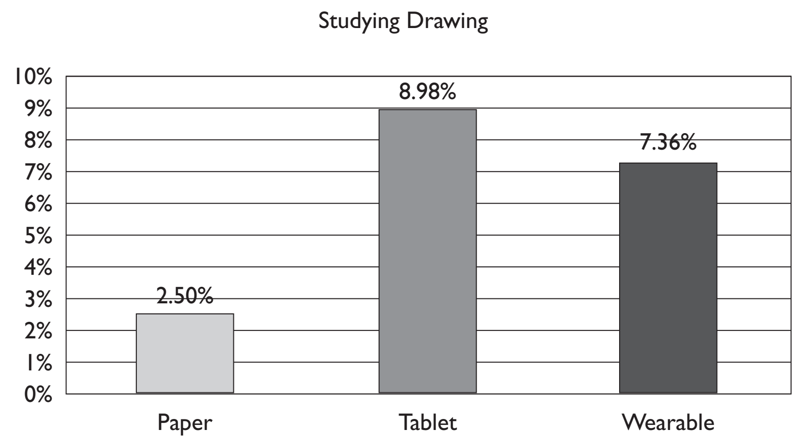
► Figure 2. Wearable computers allow construction personnel access to project information at the point of work on site; here the computer is tucked into the constructor's nail pouch

5. Results

Productivity was slightly lower in the projects using tablet and wearable computers than in the project using paper documents. Productive work accounted for 86% of the total project time when paper documents were used, 80% with a tablet computer, and 79% with a wearable computer (Table 1). The reduced productivity found in projects using tablet and wearable computers may be attributable to the greater time required to navigate CAD documents on site on a device with a relatively small screen. In the case of the paper document project, 2.5% of total project time was spent studying the project documents. In the case of tablet computers, 8.98% of project time, and for wearable computers, 7.37% of total project time (Table 2). These findings may reflect the difficulty of performing construction work while using a computer. However, the experiments did not measure the productivity impacts of managing a large volume of documents, as would be necessary on a large building project. Using a tablet or wearable computer it is possible to manage a large volume of project data, whereas an accumulation of paper documents at the point of work could begin to reduce productivity.



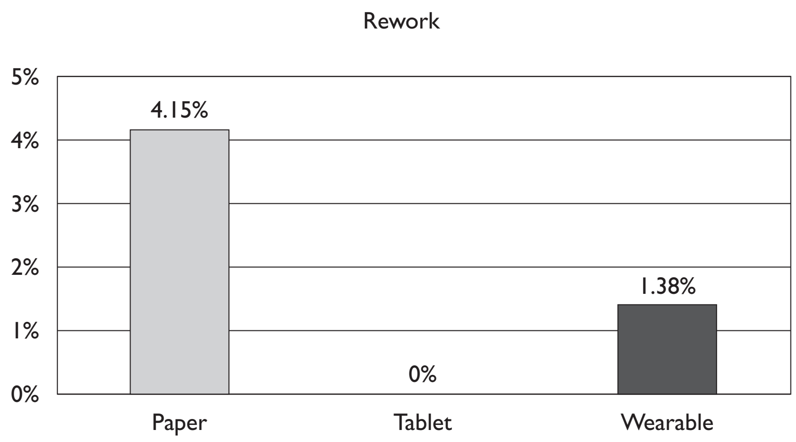
◀ **Table 1. Productive work as a percentage of total project work**



◀ **Table 2. Percentage of time spent studying and navigating project documents**

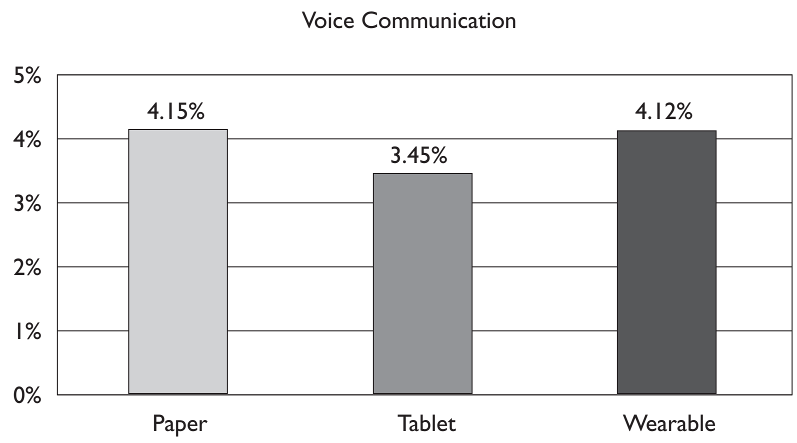
Rework required was significantly lower in the projects employing tablet and wearable computers than in the project employing paper documents. In the case of paper documents, 4.15% of total project time was spent engaged in rework; in the tablet computer case, 0%, and in the wearable case, 1.38% (Table 3). There are several possible causes for the reduction in rework when computers are employed on site. Paper documents were faxed to the site as is typical in contemporary construction projects, and the quality of the documents received is extremely unreliable. Also, CAD documents may be enlarged on screen to any level of detail, making their details clearer to the person interpreting them than paper documents allow. The tablet computer's larger screen (10.75" diagonal) may have been a factor in its slight improvement in rework reduction over the wearable computer with its 8.5" screen.

► Table 3. Rework as a percentage of total project time

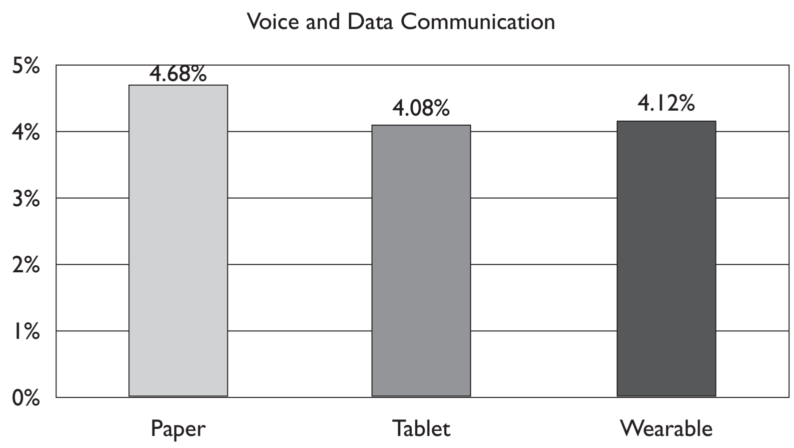


Voice Communication accounted for 4.15% of total project time in the paper-based project, 3.54% in the tablet computer project, and 4.12% in the wearable computer project (Table 4). No significant difference was found in the amount of voice communication required in the three projects. This indicates that computer-based data exchange between the designer's office and the point of work on site may not be a substitute for voice communication between designer and builder. When voice and data communication are combined, they account for 4.68% of total project time in the case of paper documents, 4.08% when using tablet computers, and 4.12% when using wearable computers; again, not a significant difference

► Table 4. Voice communication as a percentage of total project time



(Table 5). This result indicates that fetching faxes from a jobsite office roughly balanced with the time required to send and receive documents over the computer using a wireless Local Area Network. However, while the time required to fetch faxes would remain constant with more experience, the time required to exchange documents via the computer could decrease with improvements in data transfer speed and user experience.



◀ **Table 5. Voice and data communication as a percentage of total project time**

6. Conclusion

The results confirm that wearable computers can improve communication between disciplines in building design and construction. They also point to some areas of concern in the adoption of these new technologies. The most serious concern was the 8% decline in productivity observed when using tablet or wearable computers as opposed to paper documents. However, this decline is typical of the initial decline in productivity observed when a new technology is introduced to a workforce in any field. Further study is needed to determine the long-term productivity impacts of tablet and wearable computers once the user has become proficient in their use. The largest factor in the productivity decline was the increased time spent navigating and studying drawings when using the tablet or wearable computer. Time spent navigating and studying drawings when using the wearable computer was almost three times that spent navigating and studying paper documents, and even greater when using the tablet computer. The finding that productivity showed a similar decline when either a tablet computer or wearable was used suggests that the pen-based interface used by both devices may slow document navigation and study. Currently, users are accustomed to the more traditional keyboard and mouse interface. Productivity may improve if the recent promotion of pen-based tablet computers by Microsoft and several hardware manufacturers is successful and users become more familiar with this interface.

The time required to navigate and study drawings was undoubtedly influenced by the small scale of the experimental projects. Eighteen A4 paper documents were needed to complete the paper-based project – a fairly manageable quantity. However, on more complex projects requiring hundreds or thousands of documents, the results could differ; a tablet or wearable computer could, in principle, provide access to a large number of drawings which would be unmanageable in paper form at the point of work. Further study is recommended measuring the productivity impacts of electronic versus paper document management at the point of work on larger project.

The tablet and wearable computer achieved similar results in most of the tests. Productivity, voice and data communication, and time spent studying and navigating project documents were all similar when using either the tablet or wearable computer. However, the small scale of the project and its secure laboratory environment allowed the constructor to set the tablet computer down while working. On a larger project damage or theft could be a greater concern, and the wearable computer, which can be stowed in a workbelt, could lead to improved productivity.

Using a wearable computer rather than paper documents for information exchange in building construction reduced rework by 66%. If this result may be applied to the construction industry as a whole, where rework accounts for 12% of total construction costs [8], the use of wearable computers could reduce total construction costs by 8%. The reduction in rework may be due to the wearable computer's ability to bring up-to-the-minute electronic project documents directly to the point of work on site. CAD drawings are more accurate than faxed paper documents, and may be enlarged to any level of detail. Furthermore, the constructor need not leave the point of work to exchange data, whereas faxed documents require the constructor to leave the point of work in order to pick up the fax at a jobsite office.

Using a tablet or wearable computer did not significantly reduce the amount of time spent on communication; Project time devoted to voice and data communication remained relatively unchanged whether using paper, a tablet computer or a wearable computer. But the reduction in rework suggests that, while the tablet and wearable computers did not reduce the quantity of communication, they may have improved its quality. We therefore consider the initial research hypothesis that tablet and wearable computers can improve communication between the fieldworkers at the point of work on site and off-site collaborators in building design and construction verified. If tablet and wearable computers do improve project communication, this may lead to a more efficient design-construction process and to savings that may be dedicated to improving the quality of the built environment.

◀ Figure 3. One of the three completed structures

7. Future directions

With the complexity of project information going up and the cost of wearable computers coming down every day, we believe they will begin showing up on jobsites within five years. Their ability to improve interdisciplinary communication, together with the well-documented inefficiencies of current communication technologies makes the industry ripe for their introduction. They will most likely be used by contractors at the foreman level and on-site architects because these are the people most reliant on information access at the point of work on the jobsite. Their performance advantages are extremely compatible with the increased information exchange requirements of design-build and fast-track projects, and the continued growth of these two production methods may lend urgency to the wearable's introduction.

At a deeper, cultural level, wearable computers and similar technologies may even transform the way we design and construct buildings. As integrative technologies increase, many impediments to integration may fall away, leading to a new kind of architectural process, one characterized by much greater iteration between design and construction, much stronger connection between design personnel and construction site, and even greater quality in the buildings we produce. And this may be the most meaningful aspect of technological innovation, opening new possibilities in communication and cooperation between people, enabling them to create rather than conform to current limitations.

Acknowledgements

Research team members included the author and graduate research Assistants Joshua Klein, Rajpal Jain and Sachin Joshi. Funding was provided by the University of Illinois at Urbana-Champaign Campus Research Board.

References

1. Peña-Mora, F. and Li, M., Dynamic Planning and Control Methodology for Design/Build Fast-track Construction Projects, *Journal of Construction Engineering and Management*, January/February 2001, pp. 1-17.
2. Pietroforte, R., Communication and Governance in the Building Process, *Construction Management and Economics*, No. 15, 1997, pp. 71-82.
3. Fergusson, K. J., Impact of Integration on Industrial Facility Quality, *Center for Integrated Facility Engineering, Technical Report 84*, Stanford University, Palo Alto, CA, 1993, p. 84.
4. Hameri, A.-P., Nihtila, J. and Rehn, J., Document Viewpoint on One-of-a-kind Delivery Process, *International Journal of Production Research*, Vol. 37, No. 6, 1999, pp. 1319-1336.
5. Mann, S., Humanistic Intelligence/Humanistic Computing, *Proceedings of the IEEE*, Vol. 86, No. 11, 1998, pp. 2123-2151.
6. Siegel, J., et.al., Empirical Study of Collaborative Wearable Computer Systems. Human Factors in Computing Systems, *CHI – Conference Proceedings (2)*, ACM, New York, 1995, pp. 312-313.
7. Liu, L.Y. and Lustig, M., Digital Hard Hat for Construction Site Documentation, *Proceedings of the Sixth International Conference on Computing in Civil And Building Engineering*, Berlin, Germany, July 1995, pp. 1603-1606.
8. de la Garza, J., et. al., Value of Concurrent Engineering for A/E/C Industry, *Journal of Management in Engineering,* May/June 1994, pp. 46-55.

George Elvin,
University of Illinois at Urbana-Champaign School of Architecture, 611 Laredo Taft Dr., Champaign, IL 61820; PH 217-333-5870, USA

http://www.integratedpractice.com; elvin@uiuc.edu