Improvement of a computer-based surveyor-training tool using a user-centered approach

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Abstract

This paper presents the experiences of improving an existing surveyor-training tool, called SimuSurvey, using a user-centered approach. As few users were involved during the initial development of SimuSurvey, many instructors and students were skeptical about the innovative application of SimuSurvey in actual surveying classes. To address this problem, we proposed and applied an iterative and incremental user-centered design method to redevelop the tool. Three hundred and forty-six users including 5 instructors, 4 surveying experts, and 337 students, with different backgrounds were introduced at different stages of the redevelopment process. After two iterations of complete redevelopment cycles with five intermediate prototype systems generated, a much improved version of the tool, namely SimuSurvey R2, was developed. From the final interviews with students and the field observation on user groups, SimuSurvey R2 has been shown to be more practical for use in actual surveying classes. In addition, the proposed user-centered approach and several techniques it employs, such as storyboards and content diagrams, paper-based prototyping, high-fidelity prototyping, and usability tests, have been found to be effective for improvement (or redevelopment) of software systems.

1. Introduction

The surveying course is one of the important core courses for students majoring in civil engineering and architecture in most vocational schools and universities. A typical surveying course includes both indoor instruction, which covers surveying-related theories, and field training, which provides students with opportunities to familiarize themselves with the proper use of surveying instruments.

The main purpose of field training is to help novice surveyors become familiar with the use of surveying instruments. However, to manipulate a surveying instrument requires a clear understanding of the spatial relationship between the instrument and the target objects. Such spatial relationships involve many imaginary lines and other abstract concepts, such as the zenith angle, azimuth, and line of collimation. Surveying instructors often encounter difficulties when providing clear explanations of such abstract concepts to novice surveyors.

Traditionally, instructors conduct the field training component of a surveying course by following three steps: (1) explain the theoretical background either by using an example from the course notes or by illustrations on a blackboard; (2) demonstrate the manipulation of an actual instrument; and (3) instruct the students to practice in groups using actual instruments in the field.

Although this three-step teaching approach has been applied for years, it has three major drawbacks. First, the course requires many surveying instruments because each group of students requires at least one instrument on which to practice. The expenses of purchasing and maintaining the instruments can be burdensome. Second, the effectiveness of the lesson is often influenced by external factors including the weather, location, and time of day. Third, because many operations involve delicate actions, instructors often face the difficulty of demonstrating every step clearly and in detail to each student in the field within the allotted class time.

To overcome these drawbacks, several computer-based teaching aids have been developed specifically for improving the teaching in surveying courses. For example, some videos have been provided on Internet for demonstrating detailed surveying procedures and principles (e.g., setting up a level, theodolite, and total station) [1–3]. These videos highlight the critical procedures by zooming in on the detailed finger motions that are cumbersome to be demonstrated in the field. Ellis et al. [3,4] employed Flash and QuickTime VR to create an interactive multi-media learning environment for leveling surveys. Li et al. [5] created a virtual reality learning system for surveying practice on digital terrain model using a virtual total station. These teaching aids can assist instructors in explaining the concepts regarding the spatial relationship between the surveying instrument and the targets.
Although recent advancement of information technologies has greatly eased software-programming tasks, development of a useful and practical computer-aided instruction tool still requires significant efforts on designing the tool to fit user requirements, especially on designing the tool’s user interfaces. Several research efforts have addressed the issues of acquiring user requirements (e.g., [6,7]) and improving system design either incrementally or adaptively to satisfy evolving user needs (e.g., [8,9]). Development of a computer-aided tool for surveyor-training also needs to pay attention to the above system analysis and design issues.

Recently, a computer-based surveyor-training tool, also known as SimuSurvey, was developed [10]. SimuSurvey was developed using C# with OpenGL to simulate actual surveying instruments. A simulated surveying instrument allows users to design surveying task with more flexibility than using commercial virtual reality software. SimuSurvey provides virtual surveying instruments (e.g., theodolite, lever, total station) in a virtual environment for assisting teaching and learning in surveyor-training courses. In such an environment, students are allowed to manipulate the instrument using a computer mouse and obtain instant visual feedbacks. Since the execution of SimuSurvey requires only mid-range personal computers, students can easily practice surveying skills on their own computers as many times as necessary and even at home, benefits difficult to achieve in traditional surveying courses. In addition, because operations of the virtual instrument can be rendered and visualized on a computer screen, the teaching activities are greatly facilitated especially when the instructor would like to demonstrate the detailed manipulation of the surveying instrument.

Kuo et al. [11] conducted a feasibility study on the application of SimuSurvey in surveyor-training and evaluated the effectiveness of SimuSurvey. They summarized eight advantages of introducing a virtual instrument using the likes of SimuSurvey in surveyor-training. The advantages include: (1) using a virtual instrument with an actual instrument can enhance interaction between the instructor and students in surveying training and help collecting students’ feedback; (2) using a virtual instrument makes demonstration of the concept of abstract spatial relationship more graphical and easier via computer projector or computer screen; (3) teaching with virtual instrument makes classroom management easier; (4) virtual instruments provide students with opportunities to practice reading the measured data after class; (5) the virtual surveying instrument is unaffected by weather conditions; (6) virtual instrument enables the instructors to trace the learning processes; (7) surveying training with virtual instruments reduces the set-up time of the instrument; (8) surveying training with virtual instruments reduces the overall costs of owning and maintaining the real instruments.

By interviewing five experienced surveyor instructors, Kuo et al. [11] also revealed several usability problems in SimuSurvey. Their common concern was whether this software tool provides sufficient functions to support the surveyor-training, especially features that address the manipulation details critical for surveying practice. They were skeptical about the effectiveness of the user interface and were concerned whether the computer-generated virtual instrument and scenarios are easy to use. Further, they were also concerned whether the virtual instrument provides interactive feedback with the virtual environment as well as the actual surveying instrument.

The original design of SimuSurvey was developed following only software engineering and instructional technology principles, without considering usability. Using SimuSurvey in the actual class setting usually lead to many problems and the way the interface is designed makes it difficult to use.

In this study, we focus particularly on addressing the usability problems of SimuSurvey. We desire to improve this educational software by seriously considering the needs of various user groups including students, surveying experts, and experienced instructors. Users with different backgrounds were involved in each step of the redevelopment processes. Through continual improvements, it is hoped that SimuSurvey will finally meet all users’ needs. This paper summarizes the two iterative cycles of redevelopment. The results and experiences are also summarized and presented herein.

2. User-centered design and I&I development

The principles of user-centered design (UCD) [12–14] have been established for many years. They are used to manage the usability problems due to increasing complexity of computer systems. Many computer systems today are designed following software engineering principles and domain knowledge. They are typically difficult to learn and use especially for those who have little knowledge about computers [15]. UCD is a process in which the needs, expectations, and concerns of the end users of the system are considered at each stage of the design process. Many investigators (e.g., [12,16–20]) have found that UCD can effectively identify and foresee the usability problems in the design stage and results in a more considerate final product.

Iterative and incremental (I&I) development (IID) [21–25] is a software-building approach in which the overall development life-cycle is composed of several iterations in sequence. Since the users are seldom fully satisfied with the result in a traditional development workflow, many investigators (e.g., [26–28]) started using the IID process. They found that IID could systematically help improve the product. After several development iterations, IID is more likely to bring the product to a state which achieves the desired goal and satisfies the users’ demands.

In this research, we integrated the principles of both iterative and incremental development and user-centered design, resulting in a software redevelopment (or improvement) approach called here I&I-UCD. Fig. 1 illustrates the features of the proposed I&I-UCD approach. From the figure, it is seen that the redevelopment

![Fig. 1. I&I-UCD approach.](image-url)
The process is a sequence of iterations, each of which is composed of five incremental stages: (1) plan; (2) analysis; (3) design; (4) implementation; and (5) release. Two sub-iterations exist in both the design and implementation phases in which user tests are performed to evaluate the result of design on implementation until all identified usability problems are addressed. The input of each iteration is a given version of software for redevelopment or improvement with new requirements from users whereas the output is a new released version, resulted from the redevelopment process. The released version of one iteration cycle becomes the starting version of the next iteration. The iterations proceed until all users are satisfied with the results or until the resources for software redevelopment are exhausted.

To better meet the needs of SimuSurvey users of different backgrounds and while simultaneously achieving the educational goals of SimuSurvey applications, we employed the I&I-UCD approach to redevelopment. As mentioned previously, the I&I-UCD approach includes five major phases: plan, analysis, design, implementation, and release. Table 1 shows the major activities involved in each phase of SimuSurvey redevelopment. In the plan phase, both the potential users and design goals are defined. In the analysis phase, a feasibility study and multiple user tests (i.e., interview, questionnaire, observation, usability tests, and field tests) are performed to refine the original users’ requirements from the education standpoint. In the design phase, usability tests are carried out to specifically evaluate the design result, i.e., the low-fidelity prototype [14] and its interaction with users. In the implementation phase, field tests and usability tests are conducted to verify the implementation result, i.e., the high-fidelity prototype [14] and its interaction with users. We focus especially on users’ behaviors and the manipulations of SimuSurvey in the field because it is more likely to identify the actual usability problems when the environmental aspects are considered in the user tests. The following sub-sections discuss the implementation details of the I&I-UCD approach for SimuSurvey redevelopment in each phase.

### 3. Realization of I&I-UCD approach for SimuSurvey redevelopment

This section presents the realization of the proposed iterative and incremental user-centered development (I&I-UCD) approach to redevelop SimuSurvey. As mentioned previously, the I&I-UCD approach includes five major phases: plan, analysis, design, implementation, and release. Table 1 shows the major activities involved in each phase of SimuSurvey redevelopment. In the plan phase, both the potential users and design goals are defined. In the analysis phase, a feasibility study and multiple user tests (i.e., interview, questionnaire, observation, usability tests, and field tests) are performed to refine the original users’ requirements from the education standpoint. In the design phase, usability tests are carried out to specifically evaluate the design result, i.e., the low-fidelity prototype [14] and its interaction with users. In the implementation phase, field tests and usability tests are conducted to verify the implementation result, i.e., the high-fidelity prototype [14] and its interaction with users. We focus especially on users’ behaviors and the manipulations of SimuSurvey in the field because it is more likely to identify the actual usability problems when the environmental aspects are considered in the user tests. The following sub-sections discuss the implementation details of the I&I-UCD approach for SimuSurvey redevelopment in each phase.

#### 3.1. Plan phase

The goal of the plan phase is to develop an overall plan for improving the given software to meet users’ requirements. Usability and software engineers collaborated in this phase to categorize the users into groups. Four groups were defined including instructors, surveying experts, experienced students, and novice students. These groups were involved in different phases of the redevelopment iterations.
Table 1
Major activities, requirements gathering methods and participants in each redevelopment cycle

<table>
<thead>
<tr>
<th>Redevelopment lifecycle/major activities</th>
<th>Requirements gathering methods</th>
<th>Participants of first iteration</th>
<th>Participants of second iteration</th>
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<tbody>
<tr>
<td>Plan</td>
<td></td>
<td>Users (number)</td>
<td>Developers (number)</td>
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<tr>
<td>Define potential users</td>
<td></td>
<td></td>
<td>Usability engineers (3)</td>
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<tr>
<td>Define design goals</td>
<td></td>
<td></td>
<td>Software developers (2)</td>
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<tr>
<td>Plan requirements gathering procedure</td>
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<tr>
<td>Analysis</td>
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<tr>
<td>Evaluate original interface</td>
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<tr>
<td>Gather user requirements</td>
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<td>Plan</td>
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<tr>
<td>Define potential users</td>
<td>Usability engineers (3)</td>
<td></td>
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<tr>
<td>Define design goals</td>
<td>Software developers (2)</td>
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<tr>
<td>Plan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define potential users</td>
<td>Feasibility study: interview</td>
<td>Instructors (5)</td>
<td>Usability engineers (1)</td>
</tr>
<tr>
<td>Define design goals</td>
<td>Feasibility study: questionnaire</td>
<td>Novice students (323)</td>
<td>Usability engineers (1)</td>
</tr>
<tr>
<td>Plan</td>
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<td></td>
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<tr>
<td>Gather user requirements</td>
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<tr>
<td>Plan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define potential users</td>
<td>User tests: interview</td>
<td>Instructors (4)</td>
<td>Usability engineers (3)</td>
</tr>
<tr>
<td>Define design goals</td>
<td>Expert tests: interview</td>
<td>Experts (4)</td>
<td>Software developers (2)</td>
</tr>
<tr>
<td>Plan</td>
<td></td>
<td>Experienced students (14)</td>
<td>Instructors (1)</td>
</tr>
<tr>
<td>Gather user requirements</td>
<td></td>
<td>Novice students (26)</td>
<td>Students (5)</td>
</tr>
<tr>
<td>Plan</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gather user requirements</td>
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<tr>
<td>Plan</td>
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<tr>
<td>Design/paper-based prototype</td>
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<tr>
<td>Model tasks</td>
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<tr>
<td>Create storyboards and content diagrams</td>
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<tr>
<td>Create low-fidelity prototype</td>
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<td></td>
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<tr>
<td>Iteratively improving functional and interface design</td>
<td></td>
<td>User tests: usability tests</td>
<td>Experienced students (3)</td>
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<tr>
<td>(based on results from usability tests)</td>
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<td></td>
<td>Usability engineers (3)</td>
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<tr>
<td>Implementation/evaluation</td>
<td></td>
<td></td>
<td>Software developers (2)</td>
</tr>
<tr>
<td>Identify usability problems and gather suggestions on innovation</td>
<td></td>
<td>User tests: usability tests</td>
<td>Experienced students (4)</td>
</tr>
<tr>
<td>Iteratively refine high-fidelity prototype</td>
<td></td>
<td>Novice students (86)</td>
<td>Usability engineers (2)</td>
</tr>
<tr>
<td>Release</td>
<td></td>
<td>Usability engineers (1)</td>
<td></td>
</tr>
<tr>
<td>Apply to a real training class</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Identify new usability problems and gather new requirements</td>
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</table>
Usability and software engineers also worked together to define the design goals from the user requirements. Since these requirements were provided only by users from their experiences, they need to be further verified and elaborated to become concrete design principles. In this study, the usability and software engineers developed a testing plan (i.e., feasibility study and user tests) for the following phases.

3.2. Analysis phase

The major goal in the analysis phase is to define concrete and detailed requirements that need to be achieved by the end of the redevelopment iteration. There are two major tasks in this phase. The first task is to evaluate the performance of the given software for redevelopment. Developers interviewed instructors who have extensive experience in surveyor education and conducted questionnaire surveys on students to understand their attitudes toward SimuSurvey. The second task is to gather and analyze the usability problems of SimuSurvey which were then addressed in the design phase. We conducted detailed user tests especially with those users who have negative attitudes toward SimuSurvey. From more in-depth interviews, detailed questionnaires, and observations, we then summarized a list of usability problems and a list of pros and cons for SimuSurvey. Software developers were involved in the analysis process as we expected that they could better understand the users’ requirements and be aware of usability problems during the design and implementation phases.

3.3. Design phase

In the design phase, the conclusions about software performance and usability obtained from the analysis phase were used to redesign SimuSurvey. The major activities in this phase include:

1. The creation of storyboards and content diagrams to illustrate the expected interaction between users and SimuSurvey. The storyboards include sequences of sketches or screen layouts that focus on the main actions and interactions with users in possible scenarios. Textual descriptions of task flows are turned into visual illustrations of interactions in the storyboards. We also developed content diagrams to describe task details because information flows and logics of SimuSurvey cannot be presented well by just using storyboards alone.

2. The creation of low-fidelity prototype by sketching a set of user interfaces that can support further usability tests. After storyboards and content diagrams are created, software developers create low-fidelity prototypes by sketching the user interfaces on paper. This method is also called paper-based prototyping. Although detailed system functions are not specified, users can interact with the system interface with the assistance of the developers. The major benefit of the paper-based prototype is that, it allows designers to develop multiple solutions in a relatively shorter time and with lower cost [29]. Therefore, it gives them more freedom to explore the design alternatives.

3. Running usability tests to determine whether the new design is able to solve the identified usability problems. Tests were conducted to verify the usability of the low-fidelity prototype. Three students who had taken fundamental surveying courses were selected as the participants of the usability tests. During the tests, we in particular observed their behaviors when they interacted with the paper-based interfaces, to confirm whether the interface can support user activities and envisage how it might be further developed to meet their information and interaction needs. During this interactive process, many usability problems were identified and solved.

The second and third steps were performed iteratively until we obtained a satisfactory design that resolves all usability problems found in the analysis phase.

Fig. 3 shows an example of a paper-based prototype developed in this study. Since the designers and users have various ideas about the interface for controlling the vertical angle in SimuSurvey, the main purpose of this prototype is to evaluate the appropriateness of the design of the vertical angle controller. In the original version of SimuSurvey, the vertical angle controller was designed based on a drive screw controller of real survey instrument (Fig. 3a). However, after several design and prototype iterations, the design illustrated in Fig. 3b was found to be more suitable. The users found that adjusting the vertical angle of SimuSurvey using

![Fig. 3. An example of a low-fidelity prototype for SimuSurvey. (a) The drive screw of a surveying instrument for vertical angle control and its corresponding simulated control icon in SimuSurvey R0. (b) The vertical angle control drawn in the low-fidelity prototype.](image-url)
a scrollbar (as in Fig. 3b) was more intuitive than using a virtual 3D drive screw. This is one example where a low-fidelity prototype helped the designer to efficiently determine the user requirements.

Fig. 4 shows two snapshots of usability tests using low-fidelity prototypes during the design phase. In this phase, we sketched the planned user interface elements of SimuSurvey (menus, buttons, icons, windows, dialogue sequences, etc. as shown in Fig. 4a). Once the paper-based prototype has been prepared, a developer sat in front of a user, played and subsequently played the role of the computer by moving interface elements around in response to the user's actions. This interactive communicating process refers to usability tests (Fig. 4b). The difficulties encountered by the user and their comments were noted down by an observer and recorded on video. The paper-based prototype approach can be useful for demonstrating the interface layouts and iteratively exploring design alternatives with users in a relatively short time frame. After several design interactions, we finalized the design of the user interfaces.

3.4. Implementation phase

In the implementation phase, the major activities include: (1) creation of a high-fidelity prototype based on the finalized low-fidelity prototype; (2) use of the high-fidelity prototype to gather usability problems and innovation suggestions from field tests and usability tests; and (3) iterative and incremental refinement of the high-fidelity prototype until participants of the field tests are satisfied. High-fidelity prototypes are built using software tools and have the appearance of the working software products. The high-fidelity prototype, because it is more detailed than the low-fidelity prototype, gives the users greater opportunities to explore all the possibilities of using the software system in real cases [30].

After the low-fidelity prototype has been finalized, we used the Microsoft Visual Studio.NET [31] development environment with C# programming language [32] to implement a high-fidelity prototype of SimuSurvey that included most functions required for the surveyor-training. Since we had tested and finalized the user interface during the iterative paper-prototyping, in the implementation phase we just need to follow the design shown by the paper-prototype to create the interfaces on the computer.

When the high-fidelity prototype (i.e. prototype on computers) has been completed, we again conducted usability tests with students. The high-fidelity prototype of SimuSurvey was deployed in an actual surveying class for a field tests. Students were separated into two groups. One group was taught using only physical instruments. The other group was taught using both physical instruments and SimuSurvey. The instructor adopted SimuSurvey in the classroom to introduce surveying concepts and to demonstrate manipulation of the instruments. Students were allowed to download SimuSurvey from internet to their laptop or standard build PC for practice after class. Fig. 5a shows a scenario of using a surveying instrument in the field and Fig. 5b shows the scenario of using SimuSurvey in the classroom. During the study, a developer participated in the class and observed the students’ learning processes. Through close observation, the developer was able to directly collect suggestions from the users.

We also conducted rigorous usability tests on the high-fidelity prototype of SimuSurvey. In this study, we evaluated the usability

Fig. 4. Usability tests by using low-fidelity prototypes. (a) Low-fidelity prototypes. (b) Testing prototype with users.

Fig. 5. Field tests. (a) Physical instruments. (b) Virtual instruments.
in five dimensions: efficiency, effectiveness, degree of engagement, fault-tolerance, and ease-to-learn, referred to as 5Es [33]. The efficiency dimension is used to indicate the speed in which the modeled tasks can be completed. Effectiveness deals with the completeness and accuracy with which users achieve teaching and learning goals. Degree of engagement is indicated by how pleasant, satisfying or interesting a used interface is. Fault-tolerance is about how well SimuSurvey prevents errors and helps the user recover from mistakes that might occur. Ease-to-learn is used to indicate how easily the students can learn the system based on the hints provided by the system.

Fig. 6 shows the setup of usability tests. Fig. 6a illustrates the testing setup of the room while Fig. 6b shows a snapshot during the usability tests. The users were assigned simulation surveying tasks and to perform the task using SimuSurvey. This setup allows two participants in the test. A facilitator sat beside the participants to guide them through the test. Two observers, one sitting in front and the other behind, observed and recorded the users' behaviors during the test. The results were then used to improve the high-fidelity prototype in preparation for an release version of SimuSurvey.

3.5. Release phase

After finalizing the high-fidelity prototype, a release version of SimuSurvey was created. In this research, the release versions of SimuSurvey from the two redevelopment iterations, SimuSurvey R1 and SimuSurvey R2, respectively, have been made public on the internet at www.simusurvey.net for users to download. The users are also encouraged to post feedback, technical problems encountered, and suggestions for SimuSurvey. One usability engineer was assigned to maintain the website, reply to the users' postings and troubleshoot the technical problems of the software.

4. Results of simuSurvey improvement

In this section, the results of SimuSurvey improvement that evolve through two redevelopment iterations are presented. We first describe the original design of SimuSurvey (i.e., SimuSurvey R0) [10] and report the redevelopment experiences of the first iteration (i.e., redevelopment of SimuSurvey R1). We then report the experiences of second redevelopment iteration (i.e., redevelopment of SimuSurvey R2). Fig. 7 illustrates the evolution of SimuSurvey throughout the two redevelopment iterations using the screenshots of representative interface designs of different SimuSurvey versions.

4.1. Original design of simusurvey

Fig. 7a shows the original design of SimuSurvey. It includes a simulation view, scope view, user control interface and a learning behavior recorder.

The simulation view displays the major elements in a survey environment, including a survey instrument and multiple measurement poles (survey targets).

On the other hand, a view controller is provided to allow users to change the viewpoint of the scene. Users may select the top view, front view, right view, or perspective view anytime during operation. The surveying tasks can easily be displayed in each of these views, which assists instructors in demonstrating examples and clarifying surveying concepts.

The scope view, displayed at the top-right of the original user interface, shows what a user would see when operating a real survey instrument. This scene changes as users change the telescope orientation or height of the tripod. Users are also able to zoom in and out of the scope view by adjusting the telescope focus value on the virtual instrument.

The user control interface allows users to manipulate the virtual instrument. The manipulation functions are grouped into six categories with associated functions on a separate tab. The control tab contains the functions for controlling the telescope. The tripod tab contains the functions for controlling the angles between each leg of the tripod and their lengths. The other tabs contain functions for setting lighting, view, measurement pole positions, and the ground level.

The learning behavior recorder, as provided in the original SimuSurvey, allows users to record, and playback operations they performed on the virtual instrument. Instead of recording the animation frame by frame, SimuSurvey parameterizes the operations, and stores the data on the computer hard disk. In this way, the required storage space is significantly less than that using recording screen films.

When a user selects the replay function, SimuSurvey reads and decodes the time history of the parameters from the hard disk, and renders the animation in real-time. This function allows the instructor to review the details of each trainee's operations and locate when and where they erred. Students can also use this function to review standard procedures and practice for each trainee's operations and to locate when, for perfect command (or perfection).

Because SimuSurvey R0 was not developed with UCD and the users were not involved during the development processes, several problems have been reported when the tool was applied in actual surveying classes [11]. This also motivated us to have
gone through two iterations of redevelopment processes for addressing these problems and more others discovered during the iterations. In the rest of this section, we share our experiences on two iterations of redevelopment of SimuSurvey using the proposed I&I-UCD approach. The focuses of discussions are placed on how we identify the needs of users and usability problems of SimuSurvey, and address them for improving the software tool through the incremental and iterative design-implementation-evaluation processes.

4.2. First iteration of redevelopment

The first iteration started with SimuSurvey R0. We first conducted a feasibility study and user testing to gather user

Fig. 7. The interface evolvement of SimuSurvey. (a) SimuSurvey R0. (b) Low-fidelity prototype. (c) High-fidelity prototype (SimuSurvey V1). (d) Release version (SimuSurvey R1). (e) SimuSurvey R1. (f) Low-fidelity prototype. (g) High-fidelity prototype (SimuSurvey V2). (h) Release version (SimuSurvey R2).
requirements and identify usability problems. Then, the original design of SimuSurvey R0 was developed into a low-fidelity prototype, followed by a high-fidelity prototype; from which the release version, SimuSurvey R1, was produced.

The effectiveness of using SimuSurvey R0 for instruction was evaluated by a feasibility study. Five experienced instructors and 323 novice students from four schools were involved. We first demonstrated the use of SimuSurvey R0 and then asked them to individually perform a basic surveying task using the virtual instrument. We then interviewed the instructors and conducted a questionnaire and a quiz after the demonstration. From the instructors' interviews we found that all five instructors had generally positive attitudes toward introducing SimuSurvey R0 in the surveying training. However, they pointed out many important features, such as the interface for customizing surveying scenarios, are still lacking and that this may impede the application of SimuSurvey in a real-life application.

The results from the student questionnaires and quiz [11,34] can be summarized as follows: (1) 91% of students have a positive attitude toward using SimuSurvey R0 for self-learning the concepts of surveying instrument operations, and (2) 60% of students passed the quiz after using SimuSurvey R0 to learn a basic surveying task. These results show that SimuSurvey can be a helpful tool for surveyor-training and is worthy of further development. More detailed results can be found in [34].

The major activities for user testing in the design and analysis phases include: (1) interviews with users; (2) a questionnaire about users' backgrounds and usability problems with the original system; and (3) observations of users' behavior on the system. Four instructors, 4 surveying experts, 14 experienced students who had taken a basic surveying course, and 26 novice students selected from the 323 students involved in the aforementioned feasibility study were involved in these user testing activities. The major usability problems found from the user tests [35,36] are summarized as follows:

- Because the mouse control (for navigation) in the simulation view is implicit, users without training could not intuit the navigation methods.
- The cross-hairs are missing from the scope view, even though the skill of aiming at a target using the cross-hairs are very important when students learning the surveying instruments.
- It was confusing for the users to control both the vertical and horizontal rotation of the telescope on a 2D display.

### 4.2.2. High-fidelity prototype

After finalizing the design of the low-fidelity prototype, we developed a high-fidelity prototype, as shown in [Fig. 7c], which is based on the final paper-based prototype. We used the C# programming language in the Visual Studio.Net development environment to implement the high-fidelity prototype. Since Visual Studio.Net provides a series of rapid application development (RAD) tools, we were able to reduce the time required.

To verify the design, we demonstrated the high-fidelity prototype to three experienced students and conducted usability tests during which we collected their feedback. The usability tests were conducted using the SEES usability tests approach [33], which is useful for requirements elicitation and can facilitate the identification of issues that need to be addressed.

The resulting suggestions from the usability tests are summarized as follows:

- Because the aiming and reading of the level-rod scale (a scale for height determination) is a critical skill, most experienced students suggested adding a detailed level-rod scale to the scene.
- The ability to manipulate the telescope with precision is necessary. A real instrument usually includes a set of clamps (clamps are tightened to lock the telescope) and fine motion screws (screws are turned to rotate the telescope) in both the horizontal and vertical directions. SimuSurvey R0 only supported a set of fine motion screws for rotating the telescope at the degree level. Whereas, we implemented a set of fine motion screws for rotate telescope at minute and second levels to improve on SimuSurvey R0.

To investigate the usability of SimuSurvey further, we conducted field tests on 86 novice students and collected their feedback. Our suggestions based on the feedback of the field tests are summarized as follows:

- There is a need to visualize the motion of the telescope to facilitate demonstrations and explanations.
- The scene in the virtual world needs to be more realistic to enhance students' interest.

### 4.2.3. First release version of SimuSurvey

Following the suggestions from both the usability tests and field studies, we implemented a new interface for SimuSurvey (denoted as SimuSurvey R1) as shown in [Fig. 7d]. The major improvements built into SimuSurvey R1 are listed below:

- A new level-rod scale was added. It is similar in appearance to a real ruler and displays detailed interval marks.
- A fine-tuning function for rotating the telescope vertically and horizontally was added. Because it is difficult to rotate a knob-type icon using a mouse, we designed buttons for adjusting the minutes and seconds of rotations in both the vertical and horizontal directions.
- A function to illustrate the motion of the telescope in the simulation view was implemented. As seen in [Fig. 7d], a series of red points show the trajectory of the focus of the telescope. Users can easily understand the motion path of the telescope.
- The virtual environment was enriched by adding texture; making the sky and ground look more realistic. A panel was also included for users to add, delete, select, and replace the texture in order to create a more visually pleasing interface for learning.
4.3. Second iteration of redevelopment

Many users downloaded SimuSurvey R1 and reported several previously unidentified problems. Hence, work began on the second iteration. We again followed the ISL-UCD procedure and developed both low-fidelity and high-fidelity prototypes for usability evaluations. Users were involved throughout the development. Finally, the second release version, SimuSurvey R2, was developed. The detailed processes and results are summarized as follows.

4.3.1. SimuSurvey R1

SimuSurvey R1, as shown in Fig. 7e, was the starting point for redevelopment in the second iteration. The download count of SimuSurvey R1 at that time was approximately 150. To collect user feedback, one of the usability engineers in the development team was assigned to maintain the download website, answer technical queries, and most importantly gather users’ opinions that might be useful for defining new requirements for the redevelopment iteration. The most significant user feedback collected are summarized below:

- Because a clear demonstration of the spatial relationship between the surveying instrument and targets is crucial in explaining the surveying principles, several instructors requested adding a new function to allow the visualization of the virtual environment (or space) from multiple viewpoints, such as simultaneously showing the top view and the front view of the site. This capability is especially helpful when an instructor uses a large projector screen or a smart board in the classroom.
- It was found that, without external help, novice students often encountered difficulty in using SimuSurvey R1 to practice surveying tasks before class because they have little experience manipulating a real surveying instrument and know little about where to start and how to perform the surveying tasks. Therefore, we need to provide a scaffolding system and a real-time help tool to facilitate self-learning. These additional functions will help them become familiar with the software, manipulations required and overall constructs of surveying.

We started the redevelopment process based on the above two new requirements. As with the processes in the first iteration, we conducted a usability evaluation to identify which new functions could satisfy the requirements. The user tests involved an experienced instructor with twelve years experience of teaching surveying and five students with various degrees of learning experience in surveying education. Of the five students, one had taken a basic surveying course with SimuSurvey R1, one had taken a basic surveying course without SimuSurvey R1, and two were in the process of taking their first basic surveying course without SimuSurvey R1. From the usability evaluation, we then defined specific design goals:

- An additional function needs to be implemented to allow users to freely change the view layout. That is, users should be able to change the display top view, side view, front view, rear view, perspective view, or any such combination on the screen according to their preferred layout. Additionally, the user should be able to manipulate each view window independently of the other windows. This multi-view function makes demonstration of 3D surveying scenarios more comprehensive and therefore provides better support for the teaching activities in surveying classes.
- A learning menu that lists the topics of surveying lessons is needed to guide students through the learning process. Students can select the topic they would like to learn from the menu and SimuSurvey will then setup the surveying scenario that includes the necessary surveying instrument, virtual environment, and surveying targets for the specific topic. This learning menu should reduce the problem of learning disorientation and give students more confidence to learn efficiently using a relatively complicated tool.

4.3.2. Low-fidelity prototype

Fig. 7f shows an example screenshot of a low-fidelity prototype created during paper prototyping in the second iteration. Using the prototype, we attempted to find solutions for the usability problems uncovered during the previous step. Three experienced students participated in helping verify whether the design fulfills users’ needs. The major improvements made to SimuSurvey R1, as demonstrated using the low-fidelity prototype, are summarized as follows:

- Four selection icons were added to allow users to select one of four display modes, i.e., single view, two-view, three-view, and four-view mode. As shown in the middle right of Fig. 7f, the icons were designed by illustrating different layouts of the multi-view. We found that users were able to identify the meaning of the icons easily.
- A learning menu was added in the prototype. The learning menu included four learning units and a function for creating customized learning units. The four learning units include the most important topics of a traditional surveying course, namely, (1) level surveying, (2) angle surveying, (3) reading a level-rod scale, and (4) transverse surveying. This menu automatically pops up when the user launches SimuSurvey for the first time. If they do not need the menu, they can check the check box with “In future, do not display the learning menu on startup”. From the user tests, we found that the learning menu effectively facilitates students to intuitively utilize SimuSurvey and to commit to the learning process.

4.3.3. High-fidelity prototype

Fig. 7g shows a screenshot of the high-fidelity prototype as developed based on the finalized paper-prototype in the second iteration.

To verify the design, we included 14 users in the development process. Of the 14 students, four were selected from those that participated in the usability evaluation of the first redevelopment iteration. These four participated in the usability tests in a controlled environment as shown in Fig. 6a. Ten students, also recruited from the participants of the first iteration, participated in the field study.

The conclusions drawn from both the usability tests and the field study are summarized as follows:

- Although the learning menu with a list of learning topics had been provided to guide students’ learning, students still found difficulties to use SimuSurvey after entering each topic. They suggested the addition of an onscreen help tool that guides the users through the surveying tasks in a step by step manner and gives hints to the users when they encounter either conceptual or manipulation problems.
- The elimination of errors is one of the important topics in surveying. However, instructors often face challenges to illustrate the concept of errors in the classroom situation. Therefore, the instructors suggested adding a module for error visualization in SimuSurvey.
- Many users pointed out the designs of some icons, such as buttons for multi-view functions, are not intuitive. Also, some controlling functions, such as the telescope controller, lack ease of use. It is suggested that developers apply more considerate designs for icons and controllers.
4.3.4. Second release version of SimuSurvey

Following the aforementioned suggestions from user tests, we improved the high-fidelity prototype and implemented a new release version of SimuSurvey, i.e. SimuSurvey R2, as shown in Fig. 7h. The major improvements of SimuSurvey R2 from the high-fidelity prototype are summarized as follows:

- A virtual tutor, manifested as a moveable pop-up window, was added to guide and help students using SimuSurvey to build their understanding of concepts and their skills for each surveying topic. The content in the pop-up window includes text and figures corresponding to the surveying scenarios and tasks. The virtual tutor provides hints and step-by-step guides.
- The Error module was developed and added to simulate and illustrate the instrumental errors existing in an actual instrument. As shown in the scope view in Fig. 7h, a sub-window was added on lower-right corner of the scope view to display instrumental errors. This function makes SimuSurvey significantly more realistic. Besides, having the option of turning the error module on and off, allows users to comprehend the influence of errors on surveying tasks more easily. The error module also provides an interface for users to modify and edit parameters related to the instrumental errors.
- Several icons were redesigned in SimuSurvey R2. For example, we used arrow image icons, instead of buttons, for users to rotate and move a virtual instrument in a more intuitive manner. We added the grid line on the ground (as shown in the telescope view in Fig. 7h), to help users understand the spatial relationships inside the virtual environment.

From the final interviews with students and the field observation on user groups, SimuSurvey R2 has been shown to be more practical for use in actual surveying classes [36].

5. Discussions

In this study, we used the I&I-UCD approach to redevelop SimuSurvey. Two iteration cycles were performed and two release versions of SimuSurvey, SimuSurvey R1, and SimuSurvey R2, were delivered. The redevelopment involved 346 users with different backgrounds and five developers with various expertise. After such an extensive experience, the following points are worthy of discussion:

1. Using storyboards and content diagrams in early design phases is effective for identifying user’s requirements. Because the application scenarios and workflow are illustrated, users can understand the design more easily and determine whether the design fulfills their needs.

2. We found that paper-based prototypes effectively aided the developers to iteratively obtain user feedback during the design process. Paper-based prototypes help developers to understand why design elements work or fail, and to identify new functions. We also found, however, that paper-based prototypes may only be suitable for qualitative evaluations. They are lack sufficient detail to support quantitative decisions. Besides, because developing low-fidelity prototypes is quick and inexpensive, we suggest developing multiple (more than five in our case) prototypes for identifying a complete set of user requirements.

3. High-fidelity prototyping is also a powerful technique. In this study, we found that high-fidelity prototypes were effective for discovering usability problems, especially those that can only be identified through observing interactions between the user and the computer system during the execution of a real survey task. Unlike paper-based prototypes, it is relatively costly to develop high-fidelity prototypes. We suggest developers start from one high-fidelity prototype and revise it recursively based on the results of usability tests.

4. In this study, we found that recruiting different users in each phase (including plan, analysis, design, implementation, and release) was extremely important because a computer-aided instruction tool like SimuSurvey needs to seriously consider the needs of both students and instructors. Conducting different kinds of user tests was also needed in each step of the redevelopment process. By iterative improvement, the final result eventually satisfies all identified user needs.

5. A surveyor-training tool should provide users with experiences similar to those of using a real instrument. However, based on the feedback from users, the interface design of controllers for the virtual instrument should place more emphasis on user-friendliness rather than on reality. When users manipulate the virtual instrument using the controllers, the virtual scene and the scope view should provide instant feedback. The design of the screen layout for displaying the virtual scene and the scope view should allow users to change vantage point and display method freely and synchronously.

6. Conclusions

Although many concepts in I&I and UCD approaches may not be new in software engineering, their realization and integrated application to real examples are seldom reported. This research proposes an integrated I&I-UCD approach for software redevelopment. The realization of this approach has been presented and discussed. The experiences of applying the approach to redevelopment of a computer-aided instruction tool for surveyor-training, called SimuSurvey, have been reported and shared.

During the redevelopment of SimuSurvey, we found that the proposed I&I-UCD approach is effective for developing or improving software systems. I&I-UCD involves many user tests (i.e., interview, questionnaire, observation, usability tests, and field tests) to gather integrated requirements for users of different backgrounds at different stages in the development. This approach is particularly suited for developing a complicated computer system such as SimuSurvey, which is designed to support users of various backgrounds, e.g. instructors and students at different stages of their study, for multi-objective tasks. By using I&I-UCD, in which different users are involved during the design process, the design evolves from coarse proposals to concrete targets. Such an evolution is typical in the development of a complex software project. In addition, we also find that prototyping techniques include paper-based prototype and high-fidelity prototype are effective for exploring design alternatives and efficiently obtaining user feedback that iterates back into the design and implementation process. Based on the results of this empirical study, the I&I-UCD approach could also be applied to develop or improve other complex systems.

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